Health Physics Vol. 45, No. 2 (August), pp. 525–537, 1983
Printed in the U.S.A.

0017-9078/83 $3.00 + .00
Pergamon Press Ltd.

AUTOMATED SYSTEM FOR MEASURING AIR-EXCHANGE RATE AND RADON CONCENTRATION IN HOUSES

W. W. NAZAROFF, F. J. OFFERMANN and A. W. ROBB
Building Ventilation and Indoor Air Quality Program, Energy and Environment Division,
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

Abstract—We have developed an automated system for continuously measuring the air-exchange rate and ^{222}Rn (radon) concentration in an occupied residence. The air-exchange rate is measured over 90-min intervals by tracer gas decay using sulfur hexafluoride as the tracer gas. The radon concentration is measured over 3-hr intervals using a flow-through scintillation cell. Temperatures at up to seven points are measured every half hour. A microcomputer system controls the measurements, performs preliminary data analysis, and logs the data and the results. Continuous measurement of ventilation rate and radon concentration permits the effective radon source magnitude to be calculated as a function of time. The first field application of this system was a study in Rochester, NY, of residential air-exchange rates and indoor air quality. For the 8 houses monitored, the mean values over 4- to 14-day periods ranged from <0.2 to 2.2 pCi l^{-1} for radon, from 0.22 to 1.16 hr^{-1} for air-exchange rate and from <0.05 to 0.75 pCi l^{-1} hr^{-1} for radon source magnitude.

INTRODUCTION

IN CHARACTERIZING the energy performance and indoor air quality of a building, the air-exchange rate is an important parameter. During the heating and cooling seasons, incoming air must be conditioned to a comfortable indoor temperature and humidity; in a residence, this load can account for as much as 50% of the energy used for space conditioning (Ro78). It is often very cost-effective to reduce energy use in a residence by lowering the air-exchange rate—in an existing building through tightening measures such as caulking and weatherstripping, or in a new building by using, for example, a plastic vapor barrier in the exterior walls. Too little ventilation, however, can result in unacceptably high concentrations of indoor-generated air contaminants: odors, water vapor, combustion pollutants, organics and ^{222}Rn (radon).

A common technique for measuring the air-exchange rate of a residential building is to inject a tracer gas into the building, mix it to a uniform concentration in the air, and then measure the rate at which the concentration of the gas decreases. Unfortunately, because the procedure requires a few hours and is somewhat disruptive to occupants, little data has been collected on the variation of air-exchange rates over time in occupied houses. Such data would, for example, advance our understanding of the dependence of air-exchange rates on occupant behavior. In addition, since the generation of many of the indoor air pollutants depends on occupant activity, it is useful in studying indoor air quality to have the capability of measuring the air-exchange rate of an occupied residence over time.

Radon is considered to be an important indoor pollutant in terms of potential health risk to occupants (Co81). The concern is based on studies showing the increased incidence of lung cancer among uranium miners to be correlated with their exposure to the radioactive progeny of radon (UN77). Although concentrations of radon in houses are typically lower than in mines, miners represent a small fraction of the total population and so it is very likely that the population dose accumulated in houses from exposure to radon progeny exceeds that accumulated in mines.

Fully characterizing radon in indoor environments is a complex task. For example, the radon concentration in a house has been shown to vary greatly over time; over a period of a few days, radon concentrations have been found to vary over an order of magnitude or more (Sp80). How much of this variability is due to changes in the air-exchange rate, and how much is due to variations in the radon source magnitude is not known. One approach to answering this question is to continuously measure the radon concentration and the air-exchange rate; from such measurements the radon source magnitude as a function of time can be estimated. One can then determine the relative contributions of the radon source magnitude and the air-exchange rate to the variability in radon concentration.

To facilitate the study of residential ventilation and indoor radon, we have developed an automated system for measuring air-exchange rate and radon concentration continuously in an occupied residence. The air-exchange rate is measured over 90-min intervals by tracer gas decay using sulfur hexafluoride (SF_6) as the tracer; the concentration of the gas in the house is measured by an IR analyzer. The radon concentration is measured over 3-hr intervals by passing filtered air through a scintillation cell and observing the light pulses produced by the interaction of the α particles generated by the radioactive decay of radon and that of its progeny with the phosphor. Thermistors are used to measure the temperature at up to 7 points at half-hour intervals. A microcomputer controls the measurement sequences and does preliminary data reduction, with the results being recorded on magnetic tape and on a printing terminal. The system, named the Aardvark, is shown in Fig. 1. This paper describes the design and operational characteristics of the Aardvark, and presents some of the results of a 6-month field project studying residential air-exchange rates and indoor air quality.

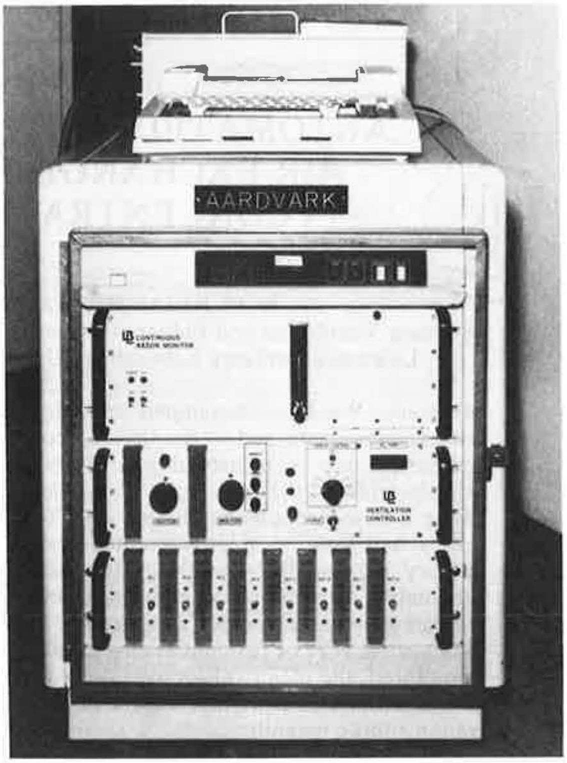

FIG. 1. The Aardvark system. The magnetic tape recorder and the metal cabinet that houses the gas cylinders are not shown.

AARDVARK COMPONENTS: DESIGN AND OPERATIONAL CHARACTERISTICS

Air-exchange measurement system

The procedure for measuring air-exchange rate by tracer gas decay involves two steps: injecting and mixing the tracer to a uniform concentration in the test space, then monitoring the concentration over time. The following mass balance equation describes the change in the concentration of the tracer over time (assuming a single, well-mixed volume):

$$\frac{dC_i(t)}{dt} = S(t) - \lambda C_i(t) + \lambda_v C_0(t) - \lambda_v C_i(t), \tag{1}$$

where $C_i(t)$ is the indoor concentration of the tracer, $C_0(t)$ is the outdoor concentration of the tracer, $S(t)$ is the production rate of the tracer per unit volume, λ is the rate of removal of the tracer by all means other than ventilation, and λ_v is the air-exchange rate, by which we mean the rate of replacement of indoor air with outdoor air.

If we choose a tracer gas that is inert and not naturally present in significant amounts, then after injection the first three terms on the r.h.s. of equation (1) are zero, and the solution becomes

$$C_i(t) = C_i(0)\exp(-\lambda_v t). \qquad (2)$$

Thus, a plot of the natural logarithm of the tracer gas concentration vs time is a straight line with a slope that is the negative of the air-exchange rate.

Air-exchange rate measurements can also be made using continuous injection of a tracer gas, either at a constant rate or at a rate which varies to maintain a constant concentration in the house (Sh80). Continuous injection techniques have the advantage of allowing one to determine the volume leakage rate, a parameter more appropriate to infiltration heating load calculations than the air-exchange rate. These techniques may also model more closely than the decay technique the behavior of some indoor air pollutants, including radon. On the other hand, instrumentation requirements are simpler for the decay technique as the injection rate of the tracer need not be measured or accurately controlled. Furthermore, mixing problems are likely to be less severe for tracer gas decay. After injection and initial mixing (assuming it is thorough) the maximum difference in tracer concentration between two parcels of air occurs between fresh outdoor air and indoor air containing the initial concentration of the tracer. With continuous injection techniques, unless mixing fans are on at all times thereby disturbing the state of the house, the maximum difference will be between the infiltrating air and the injected gas, which contains a very high concentration of the tracer. For these reasons we selected tracer decay rather than continuous injection as our measurement technique.

Figure 2 shows the mechanical system of the Aardvark. Air is drawn through as many as 4 sampling lines at a total flow rate of about 80 l./min. After passing through a low-pressure-drop filter, a flowmeter, and a flow-adjustment valve, the air in each sampling line is drawn into the sampling manifold. A spiral, regenerative blower (Rotron, Model SL1S2) draws air from the sampling manifold and delivers it back to the house through the delivery manifold and up to 4 delivery lines, each containing a flow-adjustment valve and a flowmeter.

To measure the SF_6 and radon concentrations in the house air, the sample/delivery loop is partially bypassed. About 20 l./min is taken from the exhaust side of the blower, passed through the SF_6 analyzer, then returned to the intake side of the blower. In a similar manner, 2 l./min is diverted to the radon monitor. Because of the bypass loop, only 80% of the flow rate through the analyzers is "fresh" air; however, since this reduced rate still provides 5–10 sample volumes per min to the analyzers, we are assured that the air in the analyzers accurately reflects the air at the sampling line intakes. To maintain a pressure of approx. 1 atm. in the sensitive volume of the analyzers, we have designed the mechanical system to have a low resistance to air-flow throughout: the total pressure drop around the sample/delivery loop, as determined from the blower specifications, is 0.03 atm.

Tracer gas for injection is provided from 2 cylinders of chemically pure SF_6. The delivery pressures on the regulators of the cylinders are set at 30 and 40 psig, and the delivery lines are coupled. A third regulator reduces the pressure on this line to 20 psig, the pressure at which the SF_6 is delivered to the injection control line. This cascaded-regulator configuration permits one tank to be exhausted before delivery of SF_6 from the other begins. In a house with a volume of 400 m^3 and an air-exchange rate of 0.5 hr^{-1}, one tank, containing 16 kg of SF_6, provides enough tracer for 20 days of operation. A solenoid valve in the injection line allows the computer to control the starting and ending times of the injection.

When installing the system we try to ensure that the Aardvark measures the average concentration of tracer gas in the house and that the tracer is well-distributed and well-mixed during injection. In a typical

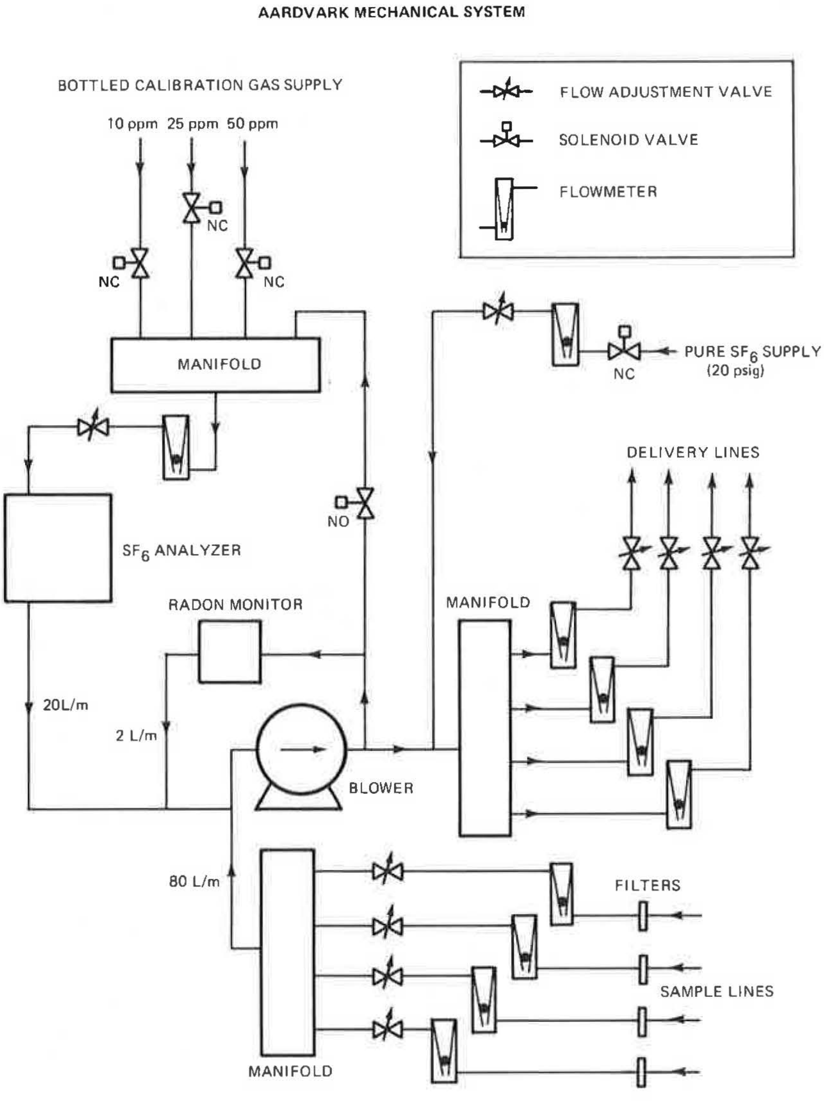

FIG. 2. Schematic diagram of the Aardvark sampling configuration.

house, we might place one sampling line in the basement, two on the first floor, and one upstairs for the bedrooms. The flow rate through each line is then adjusted to be proportional to the estimated volume served by that line. Depending on the volume of the house, the tracer gas injection rate is adjusted by a critical-orifice valve to allow the SF_6 concentration to be increased by approx. 10 ppm/min during injection. Thus, roughly 5 min is required to arrive at 50 ppm, the concentration at which we terminate injection and begin a decay measurement. The placement of and flow rate through the delivery lines depend on the floor plan and heating system of the house. In houses with a central forced-air heating system, we use one delivery line, installing its end in the return-air duct of the heating system. During injection a relay bypasses the thermostat and turns on the furnace fan allowing the air-distribution system of the furnace to be used for mixing and distributing the tracer gas. In homes that do not have an air-distribution system, the ends of the delivery lines are placed in the same areas as the sampling line intakes, but at some distance from them. The end of each delivery line is then fastened to a mixing fan which is turned on during injection to improve the initial mixing of the tracer gas.

For measuring SF_6 concentrations we use a commercially-available, infrared analyzer (Foxboro-Wilks, Model Miran-101), which measures the transmission of a specific wavelength of light through a path containing the air being sampled. The analyzer response is well-fitted by an equation of the form

$$C = -A_1 \ln (A_2 - A_3 V), \quad (3)$$

where C is the SF_6 concentration, V is the analyzer output voltage, and A_1, A_2 and A_3 are calibration coefficients. During system development, we found that the calibration coefficients varied substantially over time, so we decided to incorporate into the Aardvark the capability of automatically calibrating the SF_6 analyzer. We determine the three constants without any prior assumptions by a procedure that measures the response of the analyzer to three different concentrations of SF_6 drawn from compressed-air tanks. The concentrations we use are 10, 25 and 50 ppm, spanning the range we use in a decay. The Aardvark system performs an analyzer calibration after a user-specified number of air-exchange rate measurements; in our first field project we recalibrated every three hours.

Air-exchange rate measurements are performed by the Aardvak every 90 min. The measurement sequence begins with the calibration procedure, when necessary, which requires 1 min to sample each of the three calibration gases. (At 20 l./min, assuming perfect mixing in the analyzer, 99.9% of the change in the output voltage in response to a step change in the input concentration will occur in the first minute.) After the calibration is completed, the Aardvark begins the tracer gas injection by opening the injection solenoid valve and turning on the furnace fan or the mixing fans. The SF_6 concentration is measured roughly 4 times per min until the concentration reaches 50 ppm, at which time the injection is terminated. After 5 min have passed to allow for mixing, the concentration of SF_6 in the house is measured at 5-min intervals until the decay is terminated (either when the SF_6 concentration drops below 10 ppm, the lowest value for which the analyzer is calibrated, or at the end of the 90-min measurement period). After the decay measurement is completed, the microprocessor fits a straight line to the logarithm of the concentration vs time, using the method of least squares. The negative of the slope of this line is the air-exchange rate. The 90% confidence limits on the measurement of the air-exchange rate are also calculated, based on how well the data fit an exponential decay (Bo72).

Errors in measuring the air-exchange rate due to inaccurate determination of the tracer concentration in the analyzer are minimized in the Aardvark by frequent analyzer calibrations. However, other sources of error in the tracer decay technique can lead to inaccurate air-exchange rate measurements.

First, an error may result from bias in averaging over the time interval that the air-exchange rate measurement is made. Ideally, if the air-exchange rate changes during the measurement interval, one measures the time-weighted average. If only the beginning and ending concentrations are used to compute the air-exchange rate, then it can be shown that the variations over time are averaged without bias. The Aardvark, however, does a least-squares fit to the data to reduce the errors due to noise and imperfect mixing; under some conditions this procedure can result in a calculated air-exchange rate that is different than the average for the measurement interval. It would be difficult and perhaps impossible to estimate the resulting error for the most general case—an arbitrary time function of the ventilation rate. However, some indication of the magnitude of the averaging error that may occur can be obtained by considering the application of a least-squares fit to data from a measurement interval during which there are two distinct air-exchange rates: the result is too heavily weighted in favor of the air-exchange rate that persists longer. For example, if the air-exchange rate is $0.3\,hr^{-1}$ for 20 min, then $1.0\,hr^{-1}$ for 1 hr, a least-squares fit to the data would yield a result of $0.88\,hr^{-1}$ instead of the true average of $0.83\,hr^{-1}$. If, on the other hand, the ventilation rate were $0.3\,hr^{-1}$ for 1 hr, then $1.0\,hr^{-1}$ for the final 20 min of the measurement period, the air-exchange rate determined by the same procedure would be $0.42\,hr^{-1}$ instead of the true average of $0.48\,hr^{-1}$.

An error can arise from the common approximation that treats a residence as a single, well-mixed volume. If the configuration of the residence is such that air does not readily move throughout the house, and if the ventilation rate differs significantly from one part of the house to another, then, if the average concentration of tracer gas in the house has been accurately measured, the value obtained by tracer gas decay will always underestimate the true average ventilation rate. For example, assume (1) that a house consists of two cells of equal volume, each well-mixed but completely isolated from the other; and (2) that the air-exchange rates of these two cells are 0.5 and $1.0\,hr^{-1}$; then, if the initial SF_6 concentration in each cell is the same, analysis of the decay of the average concentration yields $0.71\,hr^{-1}$ rather than the actual mean air-exchange rate of $0.75\,hr^{-1}$ (assuming an 80-min measurement period).

A related and potentially important source of error when mixing is imperfect arises from the assumption that the measured concentration of tracer gas reflects the true average concentration. The magnitude of this error depends on the number and placement of the sampling lines. (It is for this reason that the Aardvark has four sampling lines.) Our field observations indicate that during the heating season this error is likely to be very small in the case where windows and doors are closed and the tracer gas is injected and distributed via an existing air-distribution system. Under these circumstances, a single sampling point would probably be sufficient for obtaining a reasonably accurate air-exchange rate measurement. In a home which did not have a forced-air heating system, however, we found relatively large differences in the SF_6 concentration at the four sampling points, indicating that the use of a single sampling point could result in significant measurement errors.

Radon measurement system

In the Aardvark system, the radon concentration is measured with a Continuous Radon Monitor (CRM) consisting of a scintillation flask, 170 ml in volume, through which filtered air is drawn, and a photomultiplier tube with associated electronics necessary to count the light pulses from the flask (Th79).

The CRM is calibrated following the procedure of Busigin *et al.* in which, after sampling radon-free air for several hours, the CRM samples air containing a known, constant concentration of radon over a period long enough for its counting rate to reach steady-state (Bu79). The radon concentration which the CRM samples is determined by analyzing several grab-samples taken with 100-ml scintillation cells. These scintillation cells, designed by Lucas (Lu57), and constructed at Lawrence Berkelely Laboratory (LBL), are from a batch of 25 cells calibrated with a standard- reference-method solution of ^{226}Ra (National Bureau of Standards). The response of this batch of cells is also compared with the response of radon detectors independently-calibrated at other laboratories. The sensitivity of individual cells is determined by filling several of them with a constant concentration of radon and comparing their response; the range of individual cell responses in this batch was found to be less than 5%.

We use an integration interval of 180 min for analyzing the CRM data. Given N counts observed during an interval, the radon concentration is computed as

$$\langle R_i \rangle_{t',t'+180m} = 2.19(N - 180b) - 0.13\langle R_i \rangle_{t'-180m,t'}, \tag{4}$$

where R_i is the indoor radon concentration in pCi/l., b is the background count rate in min^{-1}, and $\langle\rangle_{y,z}$ indicates an average over the interval y to z of the contents of the brackets. During the first field application of the Aardvark, the background count rate was measured once every 2–3 weeks over a period of several hours to 1 day. These eight measurements, when weighted by the inverse of their variance (i.e. the number of counts observed), yielded a mean value of 0.28 min^{-1} and a S.D. of 0.08 min^{-1}—values which were taken as the best estimates of b and the uncertainty in b, respectively, for the entire study.

We use the standard propagation-of-errors formula to estimate the uncertainty in the radon measurement (Be69). For 3-hr integration intervals, ignoring the contribution due to the calibration uncertainty (which we estimate to be on the order of 10%), the S.D. in the measurement of a constant radon level is 0.2 pCi/l. for concentrations below 3 pCi/l., 0.3 pCi/l. for a concentration of 5 pCi/l. and 0.4 pCi/l. for a concentration of 10 pCi/l. At low radon concentrations the measurement uncertainty is dominated by the variance in the background measurements, so that the measurement precision is not significantly improved by using longer integration intervals.

One of the most important features of the Aardvark is its capability of measuring radon concentration and air-exchange rate simultaneously; from these measurements we can calculate the radon source magnitude. The mass balance for radon in the residence can be written as

$$\frac{dR_i(t)}{dt} = S_R(t) + \lambda_v R_0(t) - \lambda_{Rn} R_i(t) - \lambda_v R_i(t), \tag{5}$$

where $R_0(t)$ is the outdoor radon concentration, $S_R(t)$ is the indoor radon source rate per unit volume, and λ_{Rn} is the time constant for radioactive decay of radon (0.00756 hr^{-1}). Since λ_v (almost always greater than 0.1 hr^{-1}), is much larger than λ_{Rn}, we ignore the third term on the r.h.s. of equation (5). We define the "effective" indoor radon source magnitude, Q_R, as the sum of the first two terms on the r.h.s. of equation (5), which is solved to obtain

$$\langle Q_R\rangle_{0,t'} \equiv \langle S_R\rangle_{0,t'} + \langle\lambda_v\rangle_{0,t'}\langle R_0\rangle_{0,t'} = \frac{R_i(t') - R_i(0)}{t'} + \langle R_i\lambda_v\rangle_{0,t'}. \tag{6}$$

The difference between the effective source magnitude, Q_R, and the value for indoor sources, S_R, is small if the indoor radon concentration is much greater than the outdoor concentration, as is often the case. Because we measure radon over 3-hr intervals, we do not know $R_i(t')$ or $R_i(0)$. We approximate these two quantities as

$$R_i(t') \simeq \frac{1}{2}(\langle R_i\rangle_{0,t'} + \langle R_i\rangle_{t',2t'}),$$

and

$$R_i(0) \simeq \frac{1}{2}(\langle R_i\rangle_{-t',0} + \langle R_i\rangle_{0,t'}). \tag{7}$$

We further approximate $\langle R_i\lambda_v\rangle_{0,t'}$ by $\langle R_i\rangle_{0,t'}\langle\lambda_v\rangle_{0,t'}$.

This approximation is accurate as long as there is no correlation between R_i and λ_v, or as long as both of these parameters do not vary significantly during a measurement interval. Our estimate of the effective radon source magnitude, then, is

$$\langle Q_R\rangle_{0,t'} = \frac{(\langle R_i\rangle_{t',2t'} - \langle R_i\rangle_{-t',0})}{2t'} + \langle R_i\rangle_{0,t'}\langle\lambda_v\rangle_{0,t'}. \tag{8}$$

Without knowing the accuracy of our approximations, we cannot determine precisely the uncertainty in our estimate of the radon source magnitude. The minimum uncertainty can be ascertained by applying the standard propagation-of-errors formula to equation (8). If the radon concentration is constant at 1 pCi/l. and is measured with a relative standard deviation (RSD) of 20%, and if the air-exchange rate is 0.5 hr^{-1} with a conservatively estimated RSD of 20%, then the radon source magnitude is 0.5 (pCi/l.)/hr with an RSD of 28%.

Temperature measurement system

The Aardvark is equipped to measure the air temperature at up to seven points once every 30 min. In a typical house, two probes would be used to measure indoor temperature and one to measure outdoor temperature. In our first field application of the Aardvark, we used the remaining four probes to measure the air stream temperatures of a mechanical ventilation system incorporating an air-to-air heat exchanger; from these data we calculated the "apparent" sensible effectiveness of the heat exchanger. In subsequent field applications we expect to use these four analog inputs to measure parameters other than temperature.

Computer system

The controller and data logger of the Aardvark are based on a commercial microcomputer system (Intel, iSBC 80/20-4). The microcomputer and the interfaces to the other Aardvark components are shown schematically in Fig. 3. The user interface is

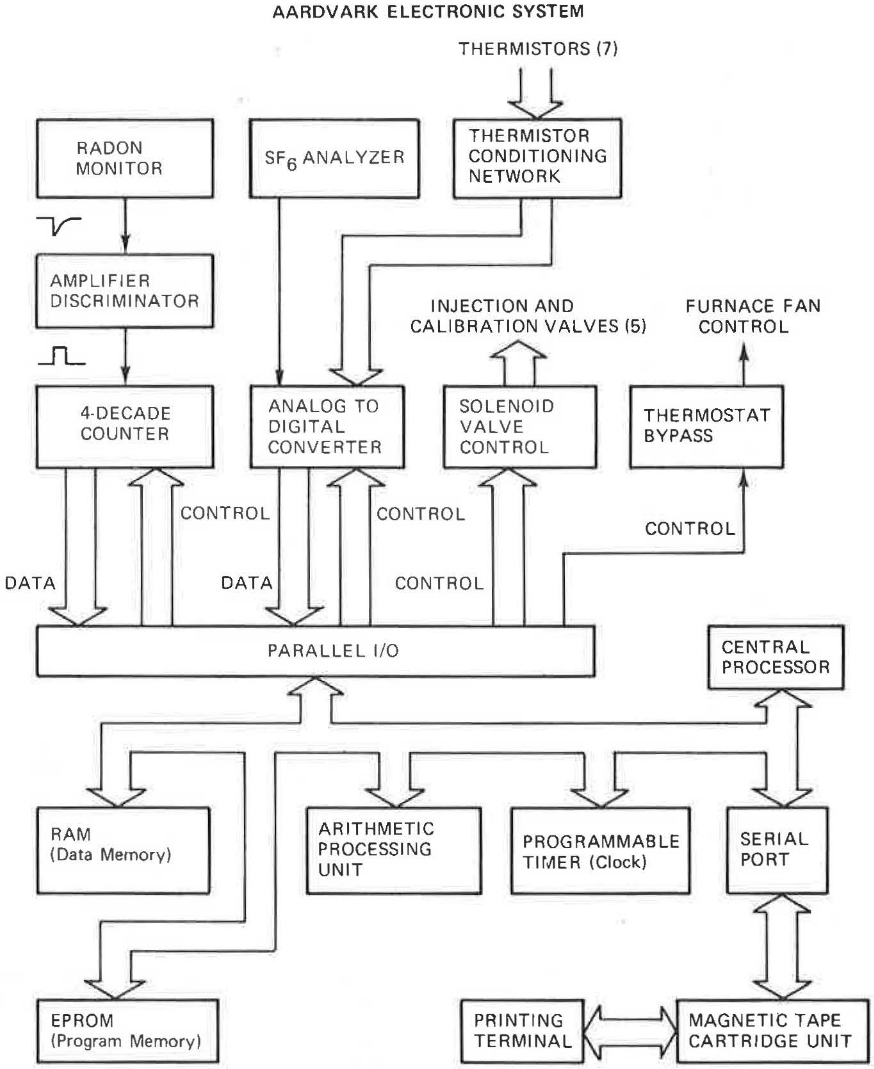

FIG. 3. Schematic diagram of the Aardvark electronic configuration.

provided through the serial port, which is connected to a magnetic-tape cartridge recorder (Columbia Data Products, 300D), which, in turn, is connected to a printing terminal (Texas Instruments, Silent 700). All data required by the system on startup are input via this terminal, and all output data are recorded on magnetic tape and printed by the terminal. Every few weeks the tape cartridge is sent back to our laboratory where we read it into a larger computer system for subsequent data reduction and analysis.

The Aardvark software was designed for ease of development and modification. The data-logging and control program is written in LLL Basic (Mc78) which has been modified to achieve a somewhat more powerful and flexible programming language. The interpreter, acting on the instructions in the Aardvark program, directs the operation of the computer. Our choice of having an on-line interpreter and programming the Aardvark in Basic was based primarily on the availability of the modified Basic interpreter and our experience with it. A major advantage of the on-line interpreter is that program development can be done directly on the Aardvark without requiring a separate development system. Another advantage is that the capabilities of the computer are readily accessible to the field operator for use in troubleshooting and data analysis.

The flow diagram for the Aardvark program is shown in Fig. 4. The central component of the software design is the action timetable—an array of $N \times 2$ elements. The elements in the first column are numerical representations in chronological order of the times at which some measurement action is to be taken, and the elements in the second

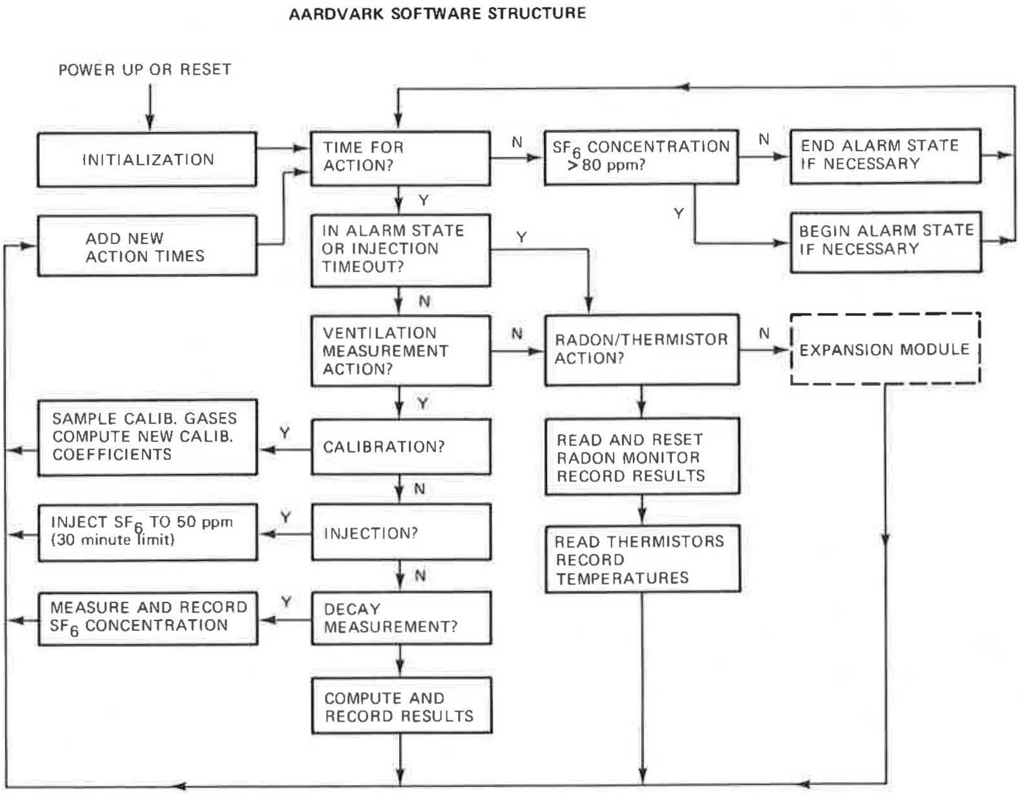

FIG. 4. Flow diagram for the Aardvark program, which is written in Basic.

column are code numbers that indicate what those actions are. In the central part of the Aardvark program the computer simply waits for the first time stored in the action timetable to pass, whereupon the measurement action specified by the first action code is performed, and the action timetable is updated. One of the important features of this software design is that many types of independent actions may be performed asynchronously. As a result, only minor modifications to the software would be required to add other measurement capabilities to the Aardvark.

ROCHESTER STUDY: SELECTED RESULTS

The first field experience with the Aardvark was obtained in a 6-month study of residential air-exchange rates and indoor air quality in Rochester, NY. The objectives of this study were (1) to assess the effectiveness of various construction techniques designed to reduce infiltration; (2) to monitor indoor air quality in selected homes with low air-exchange rates; and (3) to evaluate the thermal performance and impact on indoor air quality of mechanical ventilation systems employing air-to-air heat exchangers. A sample of 60 tract homes, with and without builder-designed air-tightening measures, was selected for the study. The effective leakage area of each house was measured by fan-pressurization (Gr81). On the basis of these measurements, eight houses were selected for detailed monitoring by the Aardvark over 2-week periods. Seven of these houses were relatively air-tight, incorporating special weatherization components such as polyethylene vapor barriers and joint seals; the eighth house, (designated as Roch37) having no special weatherization features, was selected for comparison with the other seven. The complete results of this study are reported elsewhere (Of81); here we present a summary of the radon and air-exchange rate data for the eight houses monitored by the Aardvark, as well as detailed data from one house showing the effect of weather on air-exchange rate.

In each of the houses studied, the monitoring period was divided into two 1-week intervals. During the "ventilated" interval a mechanical ventilation system with an air-to-air heat exchanger, which was installed in the house for the study, was operated. During the "unventilated" period the mechanical ventilation system was off, so air-exchange was only provided by infiltration (i.e. uncontrolled leakage through the exterior walls), by window and door openings, and by the occasional use of exhaust fans in the bathrooms and kitchen. Table 1 presents a summary of the measured radon concentration and air-exchange rate and the calculated radon source magnutide for each house during the unventilated period. The mean radon concentration ranges from <0.2 to 2.2 pCi/l.; in four of the houses the mean value is low—less than 0.5 pCi/l. The mean radon source magnitude ranges from <0.05 to 0.75 pCi $l.^{-1}$ hr^{-1}, and in each of the four houses with a mean radon source magnitude greater than 0.2 pCi $l.^{-1}$ hr^{-1}, individual determinations are seen to vary over a significant range. The results also show the mean air-exchange rate in the control house, Roch 37, to be much higher than those in the other seven houses, suggesting that weatherization measures can be effective in achieving low air-exchange rates in new houses.

The most interesting data from this study regarding the effects of weather on air-exchange rates was obtained in the control house. This house, built in 1974, has one main floor, covering 100 m^2, and a 55-m^2 basement used as a den. Heat is provided by a gas-fired, forced-air furnace with an energy consumption rating of 30 kW (100,000 BTU/hr). Supply registers are located in each room and a single return is situated in the middle of the main floor. None of the ductwork of the forced-air system passes through unconditioned space. The Aardvark was installed so that one sampling line would draw air from the living room–dining room–kitchen area, a second was divided into three branch lines to draw air from the three bedrooms, while the third sampled air from the basement den. The tracer was injected into the return duct of the furnace and the furnace

Table 1. Summary of data collected in first field application of Aardvark: measurements of radon concentration and air-exchange rate, and calculated radon source magnitude during unventilated periods in eight occupied houses in Rochester, NY

House ID	Monitoring Period	No. of Meas.	Radon Conc.[a,b] (pCi/l)	Air-exchange[a,c] Rate (h^{-1})	Radon Source[a,d] Magnitude (pCi l^{-1} h^{-1})
Roch 45	11/6 - 11/19/80[e]	30	2.0 (1.4-3.0)	0.36 (0.2-0.5)	0.75 (0.3-1.3)
Roch 1	12/7 - 12/15/80	61	0.4 (0.0-0.9)	0.22 (0.1-0.5)	0.05 (0.0-0.2)
Roch 10	1/6 - 1/13/81	55	1.2 (0.5-2.0)	0.30 (0.2-0.5)	0.35 (0.1-0.7)
Roch 56	1/28 - 2/9/81[e]	67	0.1 (0.0-0.5)	0.47 (0.2-0.8)	0.0 (0.0-0.3)
Roch 33	2/22 - 3/3/81[e]	42	0.3 (0.0-0.7)	0.41 (0.2-0.8)	0.15 (0.0-0.4)
Roch 37	3/13 - 3/20/81	49	0.0 (0.0-0.1)	1.16 (0.4-3.8)	0.0 (0.0-0.1)
Roch 52	3/25 - 3/31/81[e]	34	1.2 (0.6-1.8)	0.27 (0.1-0.6)	0.35 (0.1-0.8)
Roch 60	4/16 - 4/20/81	32	2.2 (1.3-3.0)	0.31 (0.2-0.5)	0.7 (0.4-1.3)

[a]Arithmetic mean values of measurements made over three-hour intervals; range of measured values in parentheses.

[b]Radon concentrations computed using the average CRM background of 0.28 min^{-1}. The background was measured at each of the eight houses over a total period of 9000 minutes. The weighted standard deviation in these eight measurements was 0.08 min^{-1}, yeilding a standard deviation in the measured radon concentration of 0.2 pCi/l for concentrations below 3 pCi/l.

[c]Air-exchange rates reflect the sum of infiltration (i.e., uncontrolled leakage through the building envelope) and occupant-influenced ventilation (e.g., open windows or fireplace drafts). A mechanical ventilation system, installed in each house, was off during the monitoring period.

[d]The mean radon source magnitude is rounded to the nearest 0.05 pCi l^{-1} h^{-1}.

[e]Lapses in Aardvark operation caused a loss of data for interval(s) longer than several hours during the monitoring period.

fan was turned on during injection to mix and distribute the tracer.

Figure 5 presents a plot of air-exchange rate, indoor–outdoor temperature difference, wind speed and the fuel consumption of the furnace for a 5-day period. These data illustrate the effect of weather, particularly wind speed, on air-exchange rate and heating load. The air-exchange rate is represented by horizontal line segments whose lengths correspond to the measurement integration interval. The maximum measurement interval of 70–75 min occurs for ventilation rates of less than 1.5 hr^{-1}. With greater air-exchange rates, the decay measurement terminates when the SF_6 concentration drops below 10 ppm, resulting in a total measurement time that is somewhat shorter than the maximum. The indoor–outdoor temperature difference represents the average of three consecutive measurements taken at half-hour intervals; each measurement is determined as the average temperature at two points indoors (one in the basement and the other on the main floor) minus the temperature at one point outdoors. Wind-speed values were obtained from a weather station located 20 km south-west of the house and represent single observations made 5 min before the hour for which they are plotted (NWS81). We use weather station observations as indicators; however, because of the distance

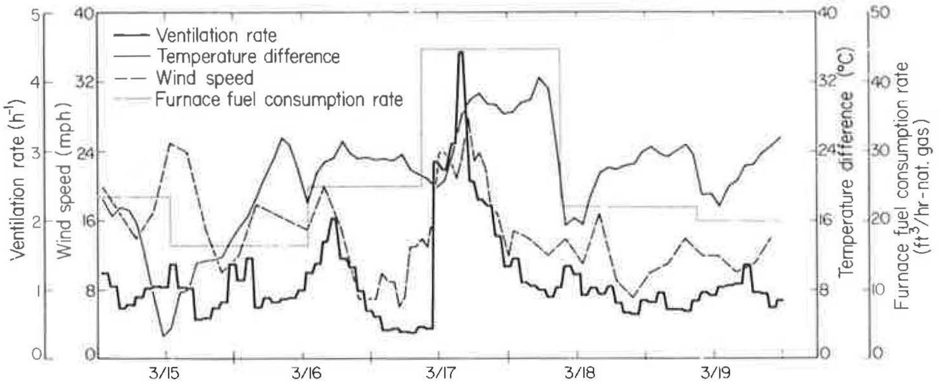

FIG. 5. Data obtained in Roch 37, an occupied house in Rochester, NY, during the first field project in which the Aardvark was used. The indoor–outdoor temperature difference is based on three observations made at half-hour intervals. Each observation represents the difference between the average temperature (measured at two points) indoors and the outdoor temperature. The wind-speed data represent observations at a weather station 20 km south-west of the house. The observations were made hourly; every third observation is plotted except for 17 March for which each observation is plotted. (Furnace fuel consumption rate of 1 ft^3/hr of natural gas equals 0.3 kW. 1 m.p.h. = 0.45 m/sec).

between the house and the weather station, the actual on-site wind speed can be expected to be somewhat different than the values plotted in Fig. 5. The average amount of fuel consumed for heating was determined from daily readings of a gas meter installed in the fuel supply line of the heating system.

The most dramatic effect of weather on air-exchange occurred on 17 March when the weather data indicate that from 9 a.m. to 6 p.m. the wind speed increased from 4 to 11 m/sec (8–24 m.p.h.). We observed that over this time period the indoor–outdoor temperature difference rose from 24 to 30°C, and that the air-exchange rate increased from less than 0.5 to 3.0 hr^{-1}. The fuel consumption rate for this day averaged about two times that of the other days in this period.

The data we collected in this house were also used to compute its heating load due to ventilation. With the same averaging intervals as used for determining the fuel consumption rate of the furnace, we calculated that the average heating load due to the measured air-exchange rate ranged from 1.5 to 5.4 kW for the 5-day period. Assuming that the furnace efficiency was 0.7, that the energy from all of the electricity used in the house (also measured daily) appeared as heat, and that other heat sources (e.g. solar gain and occupants) are negligible, then during this period ventilation represents 30–50% of the total heating load of this house.

CONCLUSIONS

We have described the design and operation of the Aardvark, an automated system for measuring air-exchange rate and radon concentration in an occupied house. Air-exchange rate is measured over 90-min intervals using tracer gas decay. Radon concentrations are measured over 180-min intervals with a flow-through scintillation cell; the measurement uncertainty for radon concentrations below 3 pCi/l. is 0.2 pCi/l. Taken in combination, the air-exchange rate and radon concentration can be used to calculate the radon source magnitude of the house.

The Aardvark system has a number of potential applications: (1) validation of infiltration models, using the effective leakage area and weather data to predict infiltration rate in buildings; (2) studies of the effect of occupant behavior on residential air-exchange rates; and (3) indoor air quality research. The Aardvark is expected to be particularly important in measuring the radon source magnitude in a building over time and correlating its variability with critical factors such as infiltration rate and weather. With this information, our understanding of the nature of radon sources in buildings could be considerably advanced.

Acknowledgments—We gratefully acknowledge the substantial assistance we received during the course of this project—in particular, from our LBL colleagues L. Davis, J. Koonce and G. Roseme, for their assistance in designing and fabricating the Aardvark; and from M. Lints and J. DeFrees of the Rochester Institute of Technology for operating the Aardvark during the field project. The manuscript was edited by L. Cook and reviewed by Dr. A. Nero, Dr. D. Grimsrud and K. Revzan.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division, and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48. The field project was sponsored in part by the New York State Energy Research and Development Administration and the Rochester Gas and Electric Corporation.

REFERENCES

Be69 Bevington P. R., 1969, *Data Reduction and Error Analysis for the Physical Sciences*, pp. 56–65, (New York: McGraw-Hill).

Bo72 Bowker A. H. and Lieberman G. J., 1972, *Engineering Statistics*, 2nd Edn (Englewood Cliffs, N.J.: Prentice Hall).

Bu79 Busigin A., Van Der Vooren A. W. and Phillips C. R., 1979, "Interpretation of the Response of Continuous Radon Monitors to Transient Radon Concentrations", *Health Phys.* **37**, 659–667.

Co81 Committee on Indoor Pollutants, National Research Council, 1981, *Indoor Pollutants* (Washington, DC: NAS).

Gr81 Grimsrud D. T., Sonderegger R. C. and Sherman M. H., 1981, "Infiltration Measurements in Audit and Retrofit Programs", Lawrence Berkeley Laboratory, Rep. LBL-12221, Berkeley, CA.

Lu57 Lucas H. F., 1957, "Improved Low-level Alpha Scintillation Counter for Radon", *Rev. Sci. Instrum.* **28**, 680–683.

Mc78 McGoldrick P. R., Dickinson J. and Allison T. G., 1978, "LLL 8080 Basic II Interpreter User's Manual", Lawrence Livermore Laboratory Rep. UCID-17752, Livermore, CA.

NWS81 National Weather Service Office, Rochester, NY, 1981, "Local Climatological Data", U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, NC.

Of81 Offermann F. J., Dickinson J. B., Grimsrud D. T., Hollowell C. D., Krinkel D. L., Lints M. C. and Roseme G. D., 1981, "Residential Air Leakage and Indoor Air Quality in Rochester, New York", Lawrence Berkeley Laboratory, Rep. LBL-13100, Berkeley, CA.

Ro78 Ross H. D. and Grimsrud D. T., 1978, "Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda", Lawrence Berkeley Laboratory, Rep. LBL-7822, Berkeley, CA.

Sh80 Sherman M. H., Grimsrud D. T., Condon P. E. and Smith B. V., 1980, "Air Infiltration Measurement Techniques", Lawrence Berkeley Laboratory, Rep. LBL-10705, Berkeley, CA.

Sp80 Spitz H. B., Wrenn Mc.E. and Cohen, N., 1980, "Diurnal Variation of Radon Measured Indoors and Outdoors in Grand Junction, Colorado, and Teaneck, New Jersey, and the Influence that Ventilation has on the Buildup of Radon Indoors", In: *Natural Radiation Environment III* (Edited by T. F. Gesell and W. M. Lowder), U.S. Department of Energy Publication CONF-780422, Vol. 2.

Th79 Thomas J. W. and Countess R. J., 1979, "Continuous Radon Monitor", *Health Phys.* **36**, 734–738.

UN77 United Nations Scientific Committee on the Effects of Atomic Radiation, 1977, *Sources and Effects of Ionizing Radiation*, Annex G, (New York: UN).