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Authors

Nazaroff, W.W.
Offermann, F.J.
Robb, A.W.

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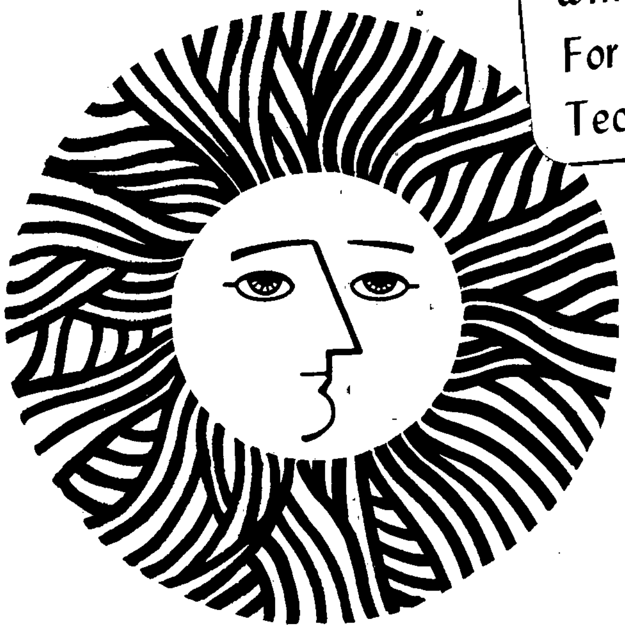

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Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
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University of California
Berkeley, California 94720

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W.W. Nazaroff, F.J. Offermann, and A.W. Robb
Building Ventilation and Indoor Air Quality Program
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Berkeley, California 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-minute intervals by tracer gas decay using sulfur hexafluoride as the tracer gas. The radon concentration is measured over three-hour 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, New York, of residential air-exchange rates and indoor air quality. For the eight houses monitored, the mean values over four- to fourteen-day periods ranged from 0.0 to 2.2 pCi l^{-1} for radon, from 0.22 to 1.16 h^{-1} for air-exchange rate and from 0.0 to 0.75 pCi l^{-1} h^{-1} for radon source magnitude.

Keywords: air-exchange rate, energy conservation, houses, indoor air quality, measuring instruments, radon

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. However, too little ventilation can result in unacceptably high concentrations of indoor-generated air contaminants -- odors, water vapor, combustion pollutants, organics, and ^{222}Rn (radon) -- if, as is often the case, the indoor concentrations exceed those outdoors.

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 one of the more important indoor pollutants, in terms of potential health risk to occupants, and, as such, has been receiving increasing research attention over the past several years. The concern stems largely from studies showing the increased incidence of lung cancer among uranium miners to be correlated with their exposure to the radioactive progeny of radon (UNSCEAR77). Although concentrations of radon in houses are typically much lower than in mines, miners represent a relatively small fraction of the total population, and so the total radiation dose from radon progeny is greater in houses than in mines. 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. The radon source magnitude as a function of time can be estimated by continuously measuring the radon concentration and the air-exchange rate. 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 such work, 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-minute 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 infrared analyzer. The radon concentration is measured over three-hour intervals by passing air through a scintillation cell and observing the light pulses produced by the interaction of the alpha 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 seven points at half-hour intervals. A microcomputer controls the measurement sequences and does preliminary data reduction. The results are recorded by a magnetic tape recorder and a printing terminal. The system, named the Aardvark, is shown in Figure 1. This paper describes the design and operational characteristics of the Aardvark, summarizes our initial operational experience with it during a six-month field project studying residential air-exchange rates and indoor air quality, and presents some of the results of that study.

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):

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

where $C_i(t)$ is the indoor concentration of the tracer, $C_o(t)$ is the outdoor concentration of the tracer, $S(t)$ is the injection rate of the tracer per unit volume, λ is the fractional 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 fractional rate of replacement of indoor air with outdoor air.

If we choose a tracer gas that is inert and not naturally present or produced in significant amounts, then after injection the first three terms on the right hand side of Eq. (1) are zero, and the solution becomes

$$C_i(t) = C_i(0) \exp(-\lambda_v t) . \tag{2}$$

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

Even though the procedure is simple, the instrumentation required to make automatic measurements of air-exchange rate using tracer gas decay can be relatively complex, as can be seen in the schematic diagram of the Aardvark mechanical system (Figure 2). As shown at bottom right, air is drawn through as many as four sampling lines at a total flow rate of about 80 l/m. 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 four delivery lines, each containing a flow-adjustment valve and a flowmeter. The sampling and delivery lines are made of polyvinyl chloride, have an inside diameter of 1.3 cm (1/2 in.) and are up to 30 m long.

To measure the SF_6 and radon concentrations in the house air, the sample/delivery loop is partially bypassed. About 20 l/m 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/m 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 minute 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 approximtely one 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 two 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 a air-exchange rate of 0.5 h^{-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 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 approximately 10 ppm/minute during injection. Thus, roughly five minutes 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, portable, non-dispersive infrared (NDIR) analyzer (Foxboro-Wilks, Model Miran-101), which measures the transmission of a specific wavelength of infrared light through a path containing the air being sampled. The analyzer response is well-fitted by an equation of the form

$$C = - A_1 \ln(A_2 - A_3 V) , \tag{3}$$

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. Although the gas concentrations are certified by the manufacturer to be accurate within 5%, we check the concentrations by comparing the analyzer response to these certified standards with the analyzer response to primary standards having the same nominal concentrations. The SF_6 concentrations in the primary standard tanks are specified by the manufacturer to be accurate to within 1% (Sc78). The Aardvark system performs an analyzer calibration after a user-specified number of air-exchange rate measurements; in the first field project for which we used this system we recalibrated every three hours.

Air-exchange rate measurements are performed by the Aardvark every 90 minutes. The measurement sequence begins with the calibration procedure, if necessary, which requires one minute to sample each of the three calibration gases. (At 20 l/m, 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 four times per minute until the concentration reaches 50 ppm , at which time the injection is terminated. After five minutes have passed to allow for mixing, the concentration of SF_6 in the house is measured at five-minute 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-minute measurement period). After the decay measurement is completed, the microprocessor fits a straight line to the logarithm of the concentration versus 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 fits an exponential decay (Bo72).

In selecting the range of concentrations over which to measure the ventilation rate, we had several considerations in mind. First, to keep the measurement cost down, we want to use the lowest concentration of SF_6 that we can measure accurately. At the same time, we want to allow as large a range as possible within a fixed measurement period so that the full measurement interval can be used even for high ventilation rates. Finally, the analyzer response drift we observed appears to have the greatest effect on the baseline, causing larger fractional errors in the measurement of low concentrations than high concentrations; for this reason, we selected 10 ppm as a lower limit for our decays.

The Aardvark is designed to verify that the ventilation measurement system is operating properly. For example, to avoid emptying two full tanks of SF_6 into a house in case of an analyzer malfunction, we limit the tracer gas injection period to thirty minutes. This time limit could also be reached because of an inadequate injection rate, exhausted SF_6 tanks, or an extremely high ventilation rate. If this limit is reached, a message is printed on the terminal, and no further ventilation measurements are performed until the problem is corrected and the system is reset.

To avoid emptying the SF_6 tanks in the case of a leak in the injection line, the system is designed to enter an alarm state whenever the concentration of SF_6 exceeds 80 ppm. In the alarm state, a bell rings and a message is printed on the terminal directing the homeowner to close the valves on the SF_6 tanks. During our recent field program, the only case in which the alarm was triggered occurred because poor mixing during injection caused the average concentration of SF_6 in the house to exceed 80 ppm before the concentration at the sampling points reached 50 ppm.

To conclude the discussion of the air-exchange rate measurement system, we now consider two sources of error that can arise whenever air-exchange is measured by tracer gas decay techniques: bias in averaging, and imperfect mixing. Air-exchange rates measured by tracer gas decay are always averaged over some time interval. (With the Aardvark system, that interval is typically 80 minutes.) 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 h^{-1} for 20 minutes, then 1.0 h^{-1} for one hour, a least-squares fit to the data would yield a result of 0.88 h^{-1} instead of the true average of 0.83 h^{-1}. If, on the other hand, the ventilation rate were 0.3 h^{-1} for one hour, then 1.0 h^{-1} for the final 20 minutes of the measurement period, the air-exchange rate determined by the same procedure would be 0.42 h^{-1} instead of the true average of 0.48 h^{-1}.

The mixing error can arise from the common approximation that treats a residence as a single, well-mixed volume. If, in fact, 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, if the house consists of two cells of equal volume, each well-mixed but completely isolated from the other, and if the air-exchange rates of these two cells are 0.5 h^{-1} and 1.0 h^{-1}, then, assuming the initial SF_6 concentration in each cell to be the same, analysis of the decay of the average concentration would yield 0.71 h^{-1} rather than the actual mean air-exchange rate of 0.75 h^{-1} (assuming an 80-minute 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 system 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 cylindrical cell (an aluminum cup), 170 ml in volume, with a glass window sealed to the open end and two air-flow fittings at the closed end through which filtered air is drawn (Th79). The inside of the cup is coated with a silver-activated zinc sulphide phosphor. When an alpha particle strikes the phosphor, a large number of photons are produced, some of which pass through the window and enter a photomultiplier tube producing a current pulse proportional to the number of incident photons. The output of the photomultiplier tube is converted to a voltage pulse, which is amplified; and -- if the peak exceeds a discriminator setting -- counted; the number accumulated over a 30-minute interval is recorded.

The alpha particles are produced by the decay of radon atoms and the radon progeny ^{218}Po and ^{214}Po in the cell. If the radon progeny were swept out of the cell before decaying and so did not contribute to the counting rate, then the average counting rate, less background, would be proportional to the average radon concentration, independent of the measurement period. Generally, this is not the case, and if one wishes to obtain measurements of the radon concentration over periods shorter than many half-lives of the radon progeny (i.e., several hours), their contribution to the count rate, relative to the contribution of radon itself, must be determined. To make this determination for the CRM, we followed 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 sampled was determined by analyzing several grab-samples taken with 100-ml scintillation cells. These scintillation cells, designed by Lucas (Lu57), and constructed at Lawrence Berkeley 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 minutes 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 two to three weeks over a period of several hours to one 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 standard deviation 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 three-hour integration intervals, ignoring the contribution due to the calibration uncertainty (which we estimate to be on the order of 10%), the standard deviation 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.

In operation, the CRM only requires service occasionally. Approximately once every two weeks, the scintillation cell in the CRM is replaced, flushed with nitrogen, and stored. Before beginning to measure radon in the air, the background count rate of the newly inserted cell is measured, usually overnight. The performance of the counting electronics and photomultiplier tube is checked by measuring the count rate of a scintillation cell containing a small amount of ^{226}Ra.

One of the most important features of the Aardvark 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

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

where $R_o(t)$ 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 h^{-1}). Since λ_v (almost always greater than 0.1 h^{-1}), is much larger than λ_{Rn}, we ignore the third term on the righthand side of Eq. (5). We define the "effective" indoor radon source magnitude, Q_R, as the sum of the first two terms on the right hand side of Eq. (5), which is solved to obtain

$$\langle Q_R\rangle_{0,t'} \equiv \langle S_R\rangle_{0,t'} + \langle\lambda_v\rangle_{0,t'}\langle R_o\rangle_{0,t'} = \frac{R_i(t') - R_i(0)}{t'} + \langle R_i\;\lambda_v\rangle_{0,t'} \; , \qquad (6)$$

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 three-hour intervals, we do not know $R_i(t')$ or $R_i(0)$. We approximate these two quantities as

$$R_i(t') \approx \tfrac{1}{2}(\langle R_i\rangle_{0,t'} + \langle R_i\rangle_{t',2t'}) \; , \text{ and } R_i(0) \approx \tfrac{1}{2}(\langle R_i\rangle_{-t',0} + \langle R_i\rangle_{0,t'}) \; . \qquad (7)$$

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

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

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 (12). 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 h^{-1} with a conservatively estimated RSD of 20%, then the radon source magnitude is 0.5 (pCi/l)/h with an RSD of 28%.

Temperature Measurement System

The Aardvark is equipped to measure the air temperature at up to seven points once every thirty minutes. 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" effectiveness of the heat exchanger. In subsequent field applications we expect to use these four analog inputs to measure parameters other than temperature.

The temperature probes (Yellow Springs Instruments, Model 705) contain two thermistors whose resistance varies with temperature. Two precision resistors of specified values are used with the probe to provide a two-terminal network with a total resistance that varies with temperature in an approximately linear manner over a range of -30 to 50 °C. A conditioning circuit was built for each probe to sense the resistance of this network and convert it to a voltage. The particular circuit we use provides an output that varies linearly from -0.1 V at -30 °C to 0.7 V at 50 °C. In the field, the calibration of the probes and the conditioning circuits is checked every few weeks by immersing the probes in water at 0 °C and 20 °C and comparing their response with that of two precision thermometers.

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 Figure 3. Most of the computer and interface hardware is built on three circuit boards, two of which are commercially available, the third being custom-designed and fabricated. One of the commercial boards (Intel, SBC 80/20-4) contains the microprocessor (Intel 8080), 8K (8096) bytes of programmable read-only memory (EPROM), 4K bytes of random-acccess memory (RAM), 48 bits of parallel input or output (I/O), a programmable timer, and a serial port. The second commercial board (Intel, iSBC 016) contains 16K bytes of RAM. The custom board contains 20K bytes of EPROM, an 8-channel analog-to-digital converter (ADC), an arithmetic processing unit (Advanced Micro Devices 9511), and pulse amplifier-discriminator and counter circuits for the CRM. The three boards communicate largely over the Intel Multibus (In77), although the interfaces to the CRM and ADC circuits use parallel I/O.

The arithmetic processing unit provides in hardware the mathematical functions found on a scientific calculator, such as 32-bit arithmetic, and trigonometric, exponential, logarithmic and power functions. The real-time clock for the computer system is implemented in software using interrupts generated by the programmable timer as a time base. The user interface is 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 is input via this terminal, and all output data is 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.

A memory map of the Aardvark system is shown in Figure 4. The 28K bytes of EPROM in the system are used for a monitor (2K), a Basic interpreter (12K), and the Aardvark program (14K) which is written in Basic. The 20K bytes of RAM are used for data storage and calculations, as well as for software development.

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 capabilities of the computer are readily accessible to the field operator, for use in troubleshooting and data analysis. An alternative we considered was to store only a compiled program, generated on a development system, in the Aardvark. The primary advantages of storing a compiled program are that the EPROM requirements (and therefore the hardware cost) would be lower, and program operation would be faster. These advantages are slight, however --

the first because the Aardvark is essentially a one-of-a-kind device, so that development costs dominate hardware costs in overall expense, and the second because even with an on-line interpreter, the execution time of each portion of the program is short compared with the shortest measurement interval, and therefore the computer is idle a large majority of the time.

The flow diagram for the Aardvark program is shown in Figure 5. The central component of the software design is the action timetable -- an array of N x 2 elements. The elements in the first column are numerical representations of the times at which some measurement action is to be taken, and the elements in the second 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. Separate action codes are provided for calibrating the SF_6 analyzer, initiating tracer gas injection, monitoring tracer gas injection, ending the tracer gas injection, monitoring tracer gas decay, checking for termination of the SF_6 alarm, calculating the results of a tracer decay, and reading the CRM and thermistors. Each of the measurement action routines can add (or remove) action times to (or from) the timetable by calling the appropriate subroutine. The subroutine for adding an element inserts it in its proper chronological position, moving all subsequent elements down in the table. To remove an element, the subroutine searches the action codes, beginning at the top of the list, until it finds the code to be removed. All elements subsequent to the one removed are moved up in the table. 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.

OPERATIONAL EXPERIENCE

The first field experience with the Aardvark was obtained in a six-month study of residential air-exchange rates and indoor air quality in Rochester, New York. 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 Roch 37), 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 some representative data to indicate the usefulness of the Aardvark and discuss some of the operational difficulties encountered in the field.

In each of the eight houses studied, the monitoring period was divided into two one-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 magnitude for each house during the unventilated period. The mean radon concentration ranges from 0.0 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 0.0 to 0.75 pCi l^{-1} h^{-1}, and in each of the four houses with a mean radon source magnitude greater than 0.2 pCi l^{-1} h^{-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/h). 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 fan was turned on during injection to mix and distribute the tracer.

Figure 6 presents a plot of air-exchange rate, indoor-outdoor temperature difference, wind speed, and the fuel consumption of the furnace for a five-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 minutes occurs for ventilation rates of less than 1.5 h^{-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 house and represent single observations made five minutes before the hour for which they are plotted (NWS81). We use weather station observations as indicators; however, because of the distance 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 Figure 6. 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 March 17 when the weather data indicate that from 9AM to 6PM the wind speed increased from 4 to 11 m/s (8 to 24 mph). We observed that over this time period the indoor-outdoor temperature difference rose from 24 to 30 ^{o}C, and that the air-exchange rate increased from less than 0.5 to 3.0 h^{-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 five-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 to 50% of the total heating load of this house.

In this field program, two student aides typically spent four hours installing the Aardvark in a house. (Much of this time was spent installing the sampling lines and thermistors.) Because all of the houses studied were occupied, considerable care was taken to install the system as neatly and inconspicuously as possible: The Aardvark was usually placed next to the furnace in the basement, and the sample lines were carefully placed along the base of the walls. The Aardvark operates relatively quietly and in none of the eight homes were there any complaints from the homeowners or their families concerning the operation of the system. All of the homeowners were volunteers and were compensated to cover the cost of the power consumed by the Aardvark.

We encountered a number of problems with the Aardvark during this six-month study, although no more than might be expected of any new system of comparable complexity. The computer aborted operation ("crashed") approximately 15 times during the study. Most of the crashes occurred in the first two houses; we presumed them to be a result of voltage fluctuations on the 115 VAC power line. These problems were solved by installing an isolation transformer on the power line of the computer and the tape deck, and by equipping the computer with a small, battery-powered, back-up power supply. During subsequent portions of this field study, most of the crashes were traced to one of the calibration gases not being delivered to the SF_6 analyzer. On these occasions the computer would abort when trying, for example, to take the natural logarithm of a negative number while calculating new calibration coefficients. We presumed that these failures were caused by malfunctioning solenoid valves. A software check has since been added to verify that the analyzer response to the calibration gases is within preset limits before new calibration coefficients are calculated.

We also encountered several operational lapses in the magnetic tape deck, either due to improper installation or an internal failure. On several other occasions the printing terminal either ran out of paper or jammed. (The data recorded on the tape was the same as that printed by the terminal, and so we lost no data because of these failures.)

Some of the indoor air quality instrumentation used in this project required daily servicing; we took advantage of this fact by having field personnel include a daily check of the operation of the Aardvark. In addition to verifying that the system was still operating, the distribution and mixing of the tracer gas was checked by measuring the concentration of SF_6 at each sampling point. As noted previously the mixing in houses with forced-air distribution systems was excellent; the difference among sampling locations was consistently less than a few ppm. In the one house without a forced-air heating system, we had difficulty in obtaining a uniform initial concentration of tracer. In that house, we installed the Aardvark to sample from the three main air spaces of the house, and we installed a delivery line in each area. The end of each delivery line was attached to the back of a mixing fan that was switched on by the computer during injection. To obtain a uniform concentration of SF_6 in the house, the relative flows through the three delivery lines had to be properly adjusted, a process that was not completed until a few days after the initial installation.

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-minute intervals using tracer gas decay. Radon concentrations are measured over 180-minute 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.

Acknowledgements

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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, New York.

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 for 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.

FIGURE CAPTIONS

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

Figure 2. Schematic diagram of the Aardvark sampling configuration.

Figure 3. Schematic diagram of the Aardvark electronic configuration.

Figure 4. Memory map for the Aardvark computer. The numbers to the left are addresses in hexadecimal notation.

Figure 5. Flow diagram for the Aardvark program, written in Basic.

Figure 6. Data obtained in 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 March 17 for which each observation is plotted. (Furnace fuel consumption rate of 1 ft^3/h of natural gas equals 0.3 kW. 1 mph = 0.45 m/s)

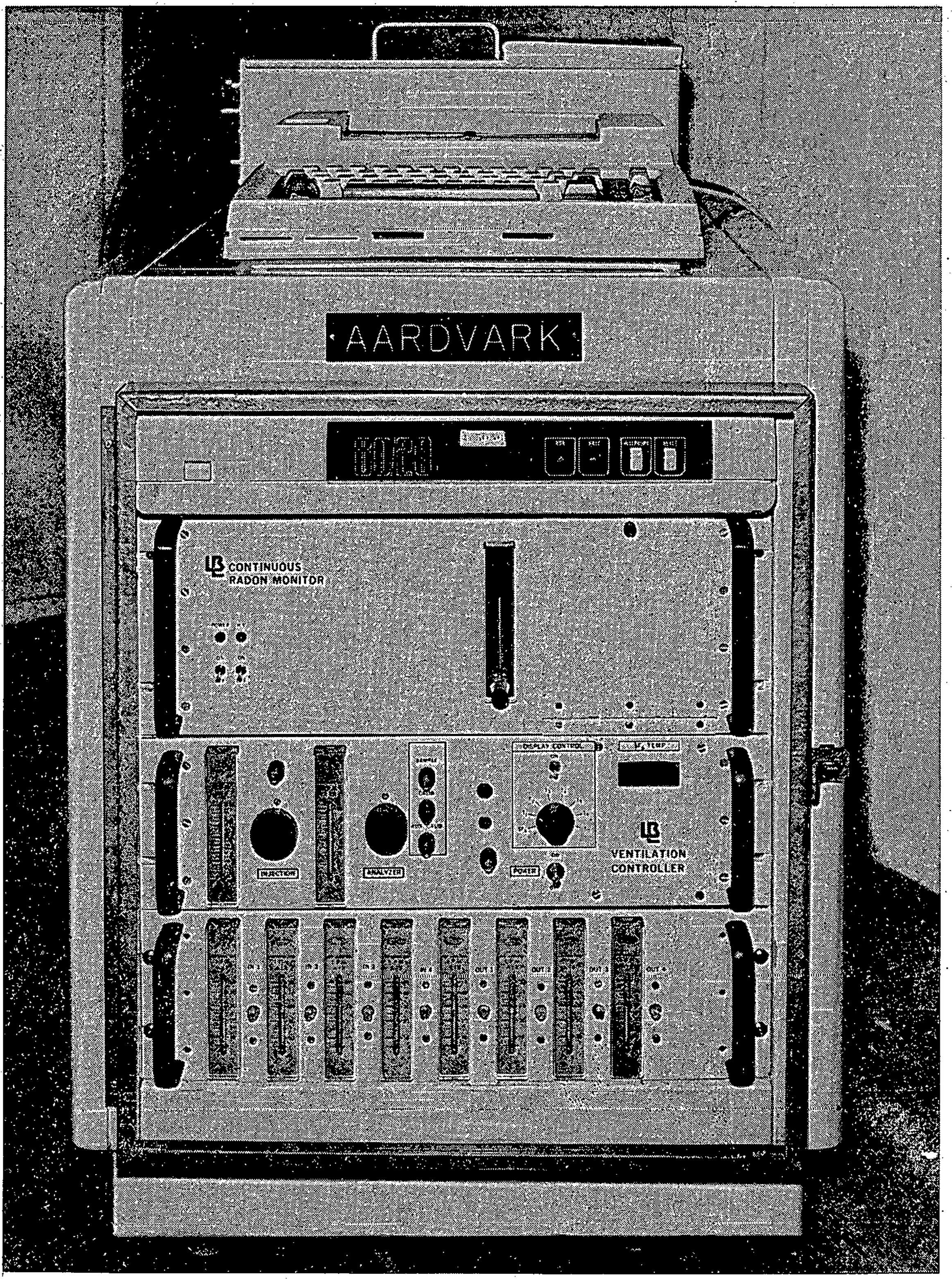


Figure 1

CBB800-12101

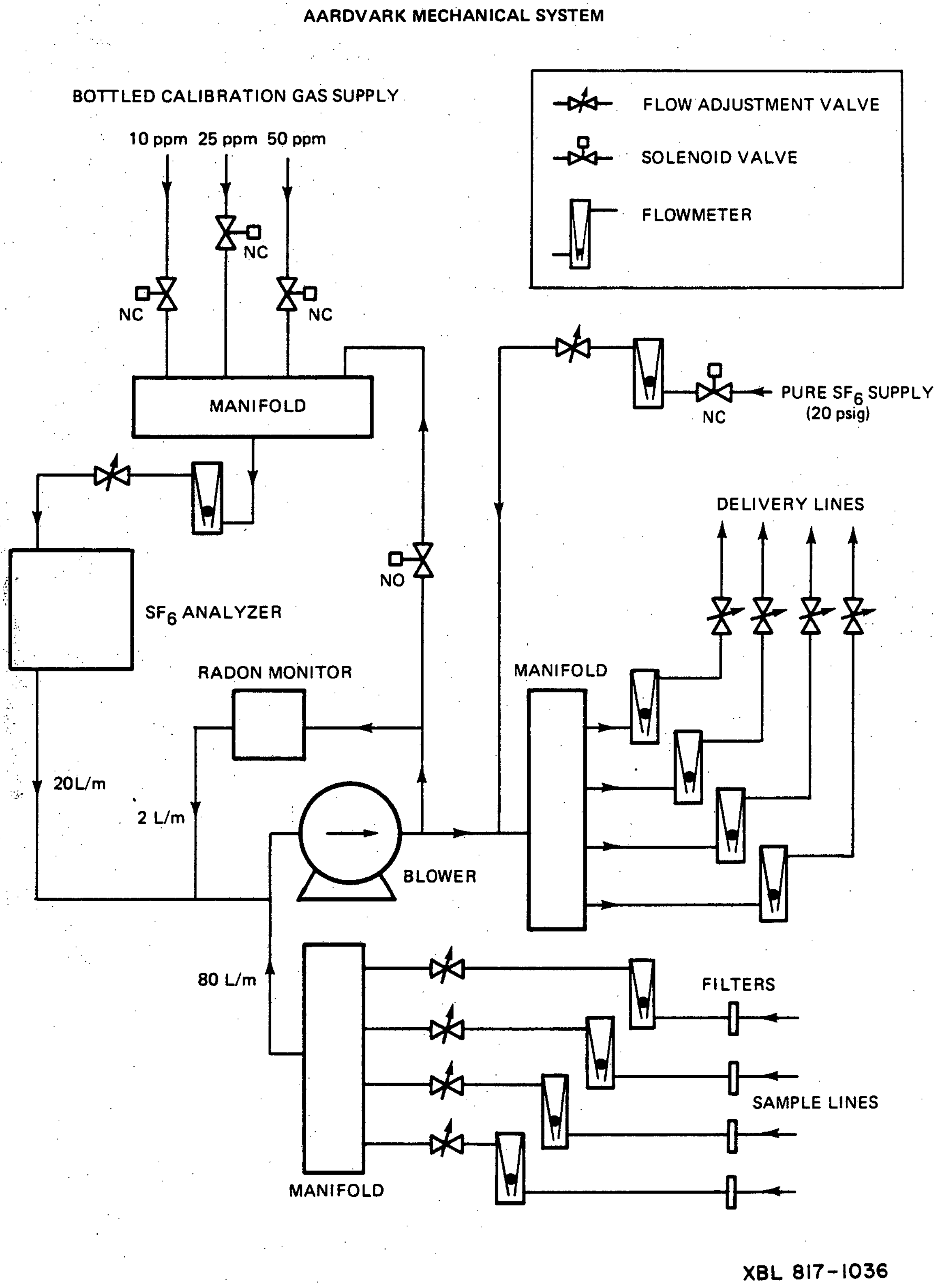
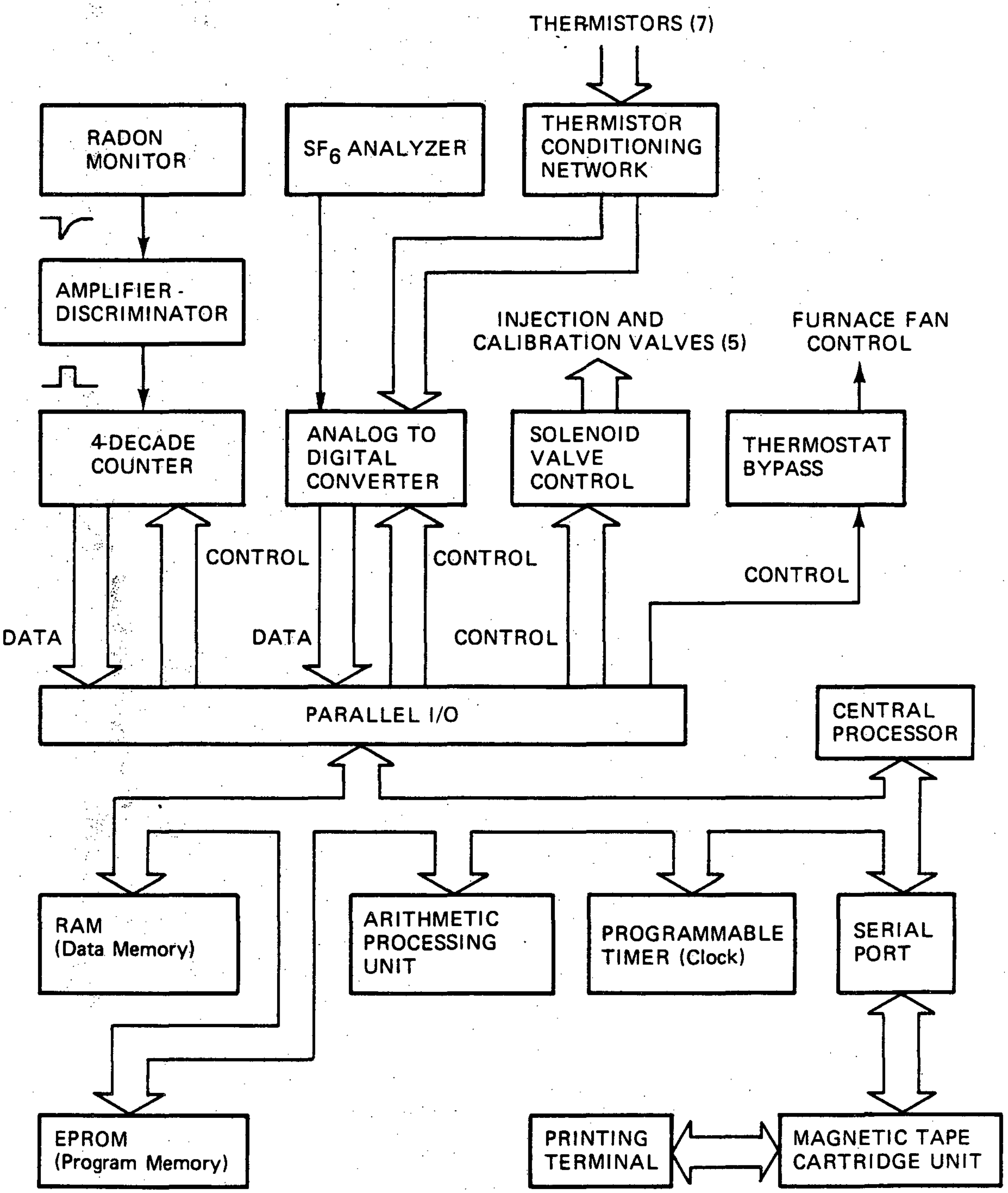

AARDVARK MECHANICAL SYSTEM
BOTTLED CALIBRATION GAS SUPPLY
10 ppm
25 ppm
50 ppm
NC
NC
NC
FLOW ADJUSTMENT VALVE
SOLENOID VALVE
FLOWMETER
MANIFOLD
PURE SF6 SUPPLY (20 psig)
NC
DELIVERY LINES
NO
SF6 ANALYZER
RADON MONITOR
MANIFOLD
20L/m
2 L/m
BLOWER
80 L/m
FILTERS
SAMPLE LINES
MANIFOLD
XBL 817-1036

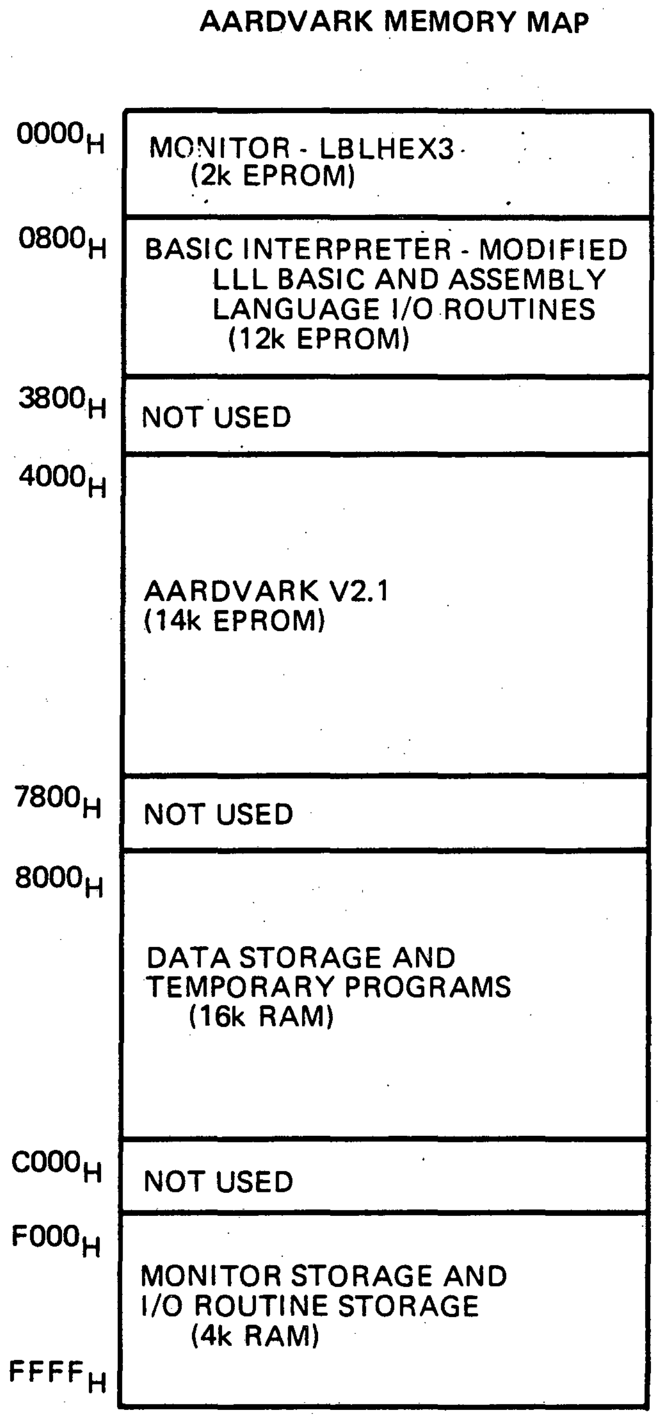
Figure 2

AARDVARK ELECTRONIC SYSTEM



XBL 817-1038

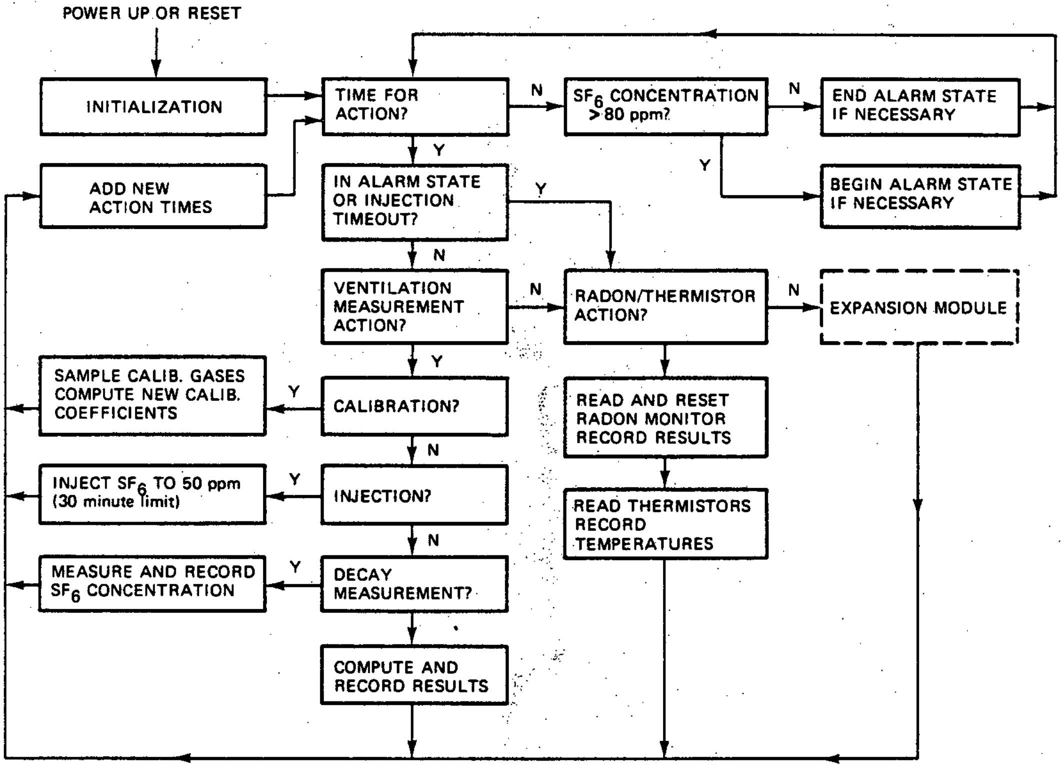
Figure 3



XBL 817-1035

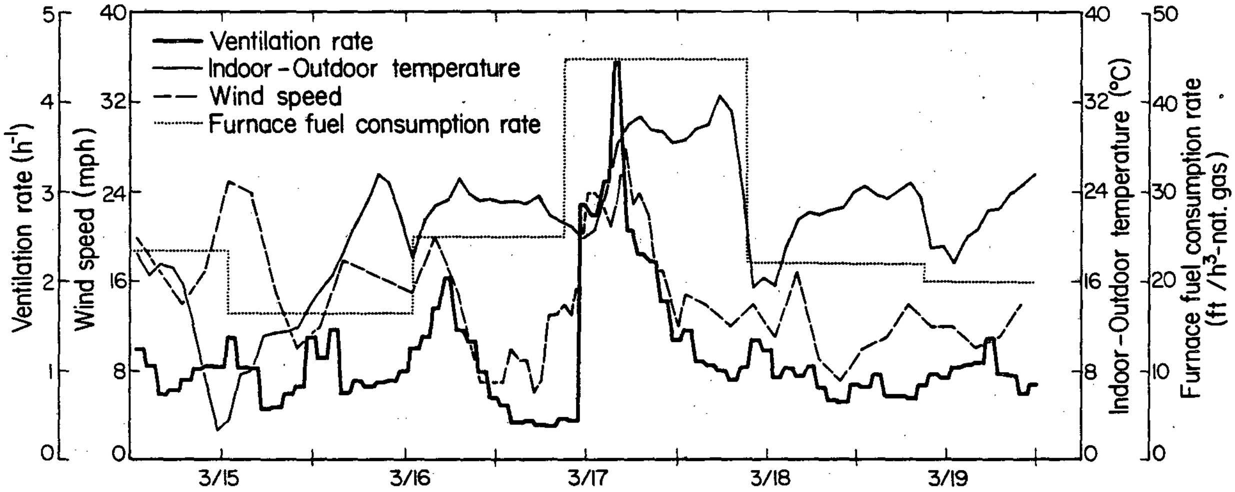
Figure 4

AARDVARK SOFTWARE STRUCTURE



XBL 817-1039

Figure 5



XBL 817-1037

Figure 6

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720