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D. MICHELL

K.L. BIGGS

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D. MICHELL and K.L. BIGGS

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION

DIVISION OF BUILDING RESEARCH

CSIRO
Division of Building Research
P.O. Box 56
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AUSTRALIA

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SUMMARY

Air infiltration, defined as uncontrolled leakage of air through the building envelope, affects the heating and cooling loads of houses, and the quality of air within them. Its magnitude is therefore of considerable importance. Continuous monitoring is an efficient method for obtaining the large amount of air infiltration rate data needed to characterize the infiltration behaviour of a house.

The principle of a method for continuous monitoring of air infiltration rate is explained and an outline given of an apparatus to implement it. The apparatus consists of an infra-red gas analyser with six air sampling tubes and a rotating multi-port gas valve; a gas distribution system comprising a gas cylinder, a gasometer, a flowmeter with needle valve, and six solenoid-operated gas valves; electronic control circuitry; a data logger and printer; meteorological instrumentation; and a multi-channel chart recorder.

The sequence of operations of the apparatus, the tracer gas distribution system, and the calculation of infiltration rates are discussed. An expression is given linking the maximum values of infiltration rate and building volume that may be monitored by the apparatus as it is presently adjusted.

Keywords: Infiltration, Continuous measurement, Constant concentration, Apparatus.

1. INTRODUCTION

Ventilation of buildings is essential in order to meet the oxygen requirements of the occupants and to keep the concentration of carbon dioxide sufficiently low. It also enables the control of factors such as tobacco smoke, odours, humidity, and indoor pollution arising from materials used in furniture, furnishings, and house construction.

Energy required in buildings to provide thermal comfort and hot water, and for cooking, lighting and the operation of appliances, accounts for more than 20% of Australia's primary energy consumption (National Energy Advisory Committee, 1980). About two-thirds of this energy is used in domestic buildings and in south-eastern Australia almost half the domestic energy usage is accounted for by space heating. Energy must be consumed to heat the air entering a house maintained above ambient temperature. Depending upon the extent to which the house is thermally insulated, this energy consumption can account for as much as 40 per cent of the total heating load. There is, therefore, a strong incentive to reduce air infiltration in houses. (Air infiltration may be defined as uncontrolled leakage of air through cracks and openings in the building envelope).

From either point of view, i.e. the provision of an adequate supply of air for health and comfort, or the restriction of air infiltration in order to reduce energy consumption, it is of basic importance to be able to measure the infiltration rate. Known values are necessary, too, for accurate calculations of heating loads.

The infiltration rate for a given building is dependent on, among other things, the speed and direction of the wind to which it is exposed, and on the temperature difference between indoors and outdoors. Thus to characterize the infiltration behaviour of a building, values of infiltration rate will be required for a range of wind speeds and directions, and a range of indoor to outdoor temperature differences. The data can be obtained efficiently by continuous, automatic monitoring.

The basic principles of measuring the rate of air infiltration into buildings by means of a tracer gas have been described by many authors including Kronvall (1980) and Grot *et al.* (1982), and a number of measuring systems using these principles have been developed (Condon *et al.*, 1980; Kumar, Ireson and Orr, 1980; Grot, Hunt and Harrje, 1980). The three basic approaches are (a) to observe the decrease in concentration of tracer gas initially distributed uniformly throughout a building, or (b) to determine the rate at which tracer gas must be added to the air in a building to maintain a constant concentration, or (c) to observe the gas concentration obtained when tracer gas is added to the air in a building at a constant rate (constant gas emission).

The apparatus outlined in this report was constructed at the CSIRO Division of Building Research to enable continuous monitoring of air infiltration, and simultaneous collection of climatic data. It is based on a combination of the constant gas concentration and constant gas emission techniques discussed by, among others, Kronvall (1980) and Grot *et al.* (1982). The apparatus is capable of operating for long periods (weeks) without supervision. Nitrous oxide was chosen for the tracer gas because its concentration is easily measured by an infra-red gas analyser, it is relatively cheap, readily available, has a density fairly close to that of air, and in the concentrations used is not hazardous to health.

2. PRINCIPLE OF THE METHOD

In this method tracer gas is released in a quantity proportional to the difference between the measured value of gas concentration and some higher set reference value. This results, for a particular value of air infiltration rate, in a constant value of gas concentration. Should the rate of air infiltration change, the concentration of gas is affected, so the quantity of gas released automatically changes too, and the interaction of the two influences (infiltration and gas release) establishes a new value of gas concentration.

In its purest form the constant concentration method would constantly adjust the flowrate of the tracer gas supply system to maintain a preselected, set gas concentration. On the other hand, the constant gas emission technique, by definition, maintains a constant flowrate from the supply system. The present apparatus is a 'hybrid' in so far as a reference gas concentration value is set, and tracer gas is supplied in 'bursts' of constant flowrate but with durations dictated by the degree to which the actual gas concentration falls short of the pre-set reference concentration. The advantage of this approach is that timed releases of variable duration (but constant flowrate) are more easily and more accurately arranged and recorded than variations in the flowrate.

For steady conditions the relationship between the rate of air infiltration γ (air changes per hour, ac/h), rate of gas release Q (m^3/h), gas concentration C (parts per million, [ppm], vol./vol.) and volume of the building V (m^3) is given by

$$\gamma = Q \times 10^6/CV. \tag{1}$$

The present equipment provides for monitoring and releasing gas at six locations distributed throughout the house being studied. The locations are normally within the three bedrooms, the kitchen, the dining room and the lounge. All internal doors, except the toilet door, are left open. The concentration of tracer gas is measured 15 times per hour at each location and, after each measurement, gas is released in that general location at a constant flowrate, q (mL/s) for a time, t (seconds) equal to the difference between the reference concentration (ppm) and the gas concentration measured at that location. The selected value of the reference concentration, C_R (ppm), is arbitrary and in our case is usually in the range 60–99 ppm.

Under these conditions the gas released per hour at each location is –

$$Q_i = 15\, q\, t_i \times 10^{-6}\ m^3/h$$

and the total gas released at the six locations is

$$15\, q \sum_{i=1}^{6} t_i \times 10^{-6}\ m^3/h.$$

When the concentration of gas is essentially uniform throughout the house, the total gas released per hour, Q, is given by –

$$Q = 15 \times 6\, q\, t \times 10^{-6}\ m^3/h$$

where $t = (C_R - C)$ seconds.

By substitution for Q in equation 1 an expression is obtained in which C is the only variable:

$$\gamma = 15 \times 6\, q\, (C_R - C)/CV. \tag{2}$$

By substituting for $C = (C_R - t)$ in equation 2 an expression is obtained in which t is the only variable:

$$\gamma = 15 \times 6\, qt/(C_R - t)V. \tag{3}$$

From these equations it is evident that it is necessary only to record either C or t in order to determine air change rate but, in fact, both quantities are routinely recorded. In practice Σt can be determined more simply than an average value of gas concentration, hence air change rates are calculated on the basis of number of seconds of gas released rather than from gas concentration values.

The variation of air infiltration rate, γ (ac/h) may be calculated as a function of T, the total time (seconds) of gas release per hour, by utilizing equation 3 and the relation T = 90t. This has been done for reference concentrations of 70 and 99 ppm, six gas sample and release locations, with fifteen gas releases per hour at each location (q = 11.6 mL/s), with a house volume of 250 m^3, and the results are shown in Figure 1.

It may be seen from Figure 1 that the calculated air infiltration rate, γ, increases non-linearly with T, the total time of gas release per hour, and that for a given value of γ the magnitude of T increases with the reference concentration C_R. The latter has practical implications. If the air infiltration rate of the house is low the value of T obtained by measurement will be low and the value of t, the number of seconds of gas released on each occasion, at each location, will be small, leading to possible inaccuracies. Thus C_R should be set at a relatively high value. On the other hand, if the air infiltration rate is high the value of t required to establish a stable concentration may exceed the time available for gas release on each occasion, so C_R should be set at a relatively low figure.

A block diagram of the apparatus is shown in Figure 2. The sequence of operations, which is controlled by the cycle control unit, is depicted in Figure 3. In outline, the sequence of events is to sample gas at position 1, compare the measured concentration C_M with the reference concentration C_R and use the difference in concentration $[C_R - C_M]$ to control the time of release of gas by means of the gas release unit acting on the gas distribution unit, which in turn releases the gas at location 1 in the general vicinity of that sampling point. A domestic exhaust fan with a capacity of 580 m^3/h, mounted near the floor (see Fig. 4) is used at each location to ensure dispersal of the gas and thorough mixing with the air. Before moving to position 2 the printer records the sample location, the time of day, gas concentration and the accumulated total number of seconds during which gas has been released. This sequence of operations is repeated for locations 2 to 6, followed by the recording of temperature and wind data. The time taken to complete one cycle of operations is set, by means of an adjustable delay at the beginning of the cycle, to be 4 minutes precisely, which ensures that there are fifteen releases of gas per hour at each location.

In addition to the printout, a multi-channel chart recorder provides traces of the indoor and outdoor temperatures, the wind speed averaged over two minutes, wind direction sampled at one minute intervals, and by means of a suitable circuit, the gas concentration at each of the six locations is sampled sequentially and each concentration recorded for approximately 30 seconds on a single trace. A sample of the chart recording is shown in Figure 5. This chart is particularly useful as a guide to the selection of times suitable for the processing of the air infiltration data; that is, when the weather conditions are stable and infiltration rates are within the range that can be measured with the apparatus (this latter aspect is discussed at the end of the next section).

3. SOME DETAILS OF THE APPARATUS

The concentration of tracer gas at a given location is determined by drawing a stream of the tracer gas/air mixture from that location by means of an inbuilt diaphragm pump, operating at approximately 1L/min., and passing it through a gas analyser which utilizes a double-beam system employing a gas-filled detector operating in the infra-red region at wavelengths between 2 and 15 μm. There it is compared with tracer-free air drawn from outside the building being tested. The particular location sampled is determined by the position of a multi-port, step-rotating gas port selector (Scanivalve Type S1265-1P/12T) which is under the direction of the cycle control unit. A separate pump, operating at about 17 L/min., maintains a flow of air through all the sampling tubes not coupled to the gas analyser at that time, in order to reduce the time to reach equilibrium when the gas valve is rotated to select the next location to be sampled. (Thirty seconds has been allowed for equilibration). The flowrates are low and have negligible effect on the distribution of tracer gas within the volume under consideration and on the air infiltration rates being determined.

At each of the six locations, tracer gas is released, via a solenoid-operated valve, on the inlet side of a fan mounted near the floor and directing its air stream vertically upwards, to ensure good mixing with the room air. (Smoke pencil tests have shown that all parts of a room are involved in the mixing process. Furthermore, four minutes elapses between the release of gas at a given location and the next sampling of the gas concentration there). For each location the number of seconds during which gas is released is added to the total number of seconds of gas release for the whole house being accumulated in a counter.

It is a requirement of this method for determining air infiltration rates that gas is released at a constant flowrate. Figure 6 shows the essential features of the gas distribution system designed to achieve this. An inverted, weighted, hollow cylinder 140 mm in diameter and 240 mm high, closed at the top, located in an outer, open-topped hollow cylinder partly filled with transformer oil, is used as a storage tank in a manner similar to a 'gasometer'. The storage tank is 'charged' by gas entering it from the N_2O cylinder via regulating valves and the solenoid-controlled gas valve. Intervals for charging (or 'topping up') are provided six times per cycle, as indicated in Figure 3, so that the storage tank is normally at or near its full capacity at the start of each period of gas release. The gasometer is shown in Figure 7. (Nitrous oxide is only sparingly soluble in the oil used and, within the limits of experimental error, no difference has been detected between infiltration rates obtained with the gasometer open to the room and those obtained with the gasometer in a gas-tight enclosure).

Charging ceases when a metal blade (B1, Figure 7) mounted on the top of the rising storage cylinder interrupts the beam of an infra-red 'photo'-cell (PC, Figure 7). There are two safety cut-offs; a microswitch mounted above the storage cylinder which interrupts the current to the charging valve solenoid should the storage tank rise past the normal 'fully-charged' height, and a logic gate in the gas release control circuit which cuts off the gas supply should the gas concentration exceed 100 ppm. For practical reasons the apparatus is used only in unoccupied houses and normally attendance, in order to replenish chart paper etc., lasts at most an hour or two a few times per week. This should not pose a health problem to the operators since the suggested time-weighted average value of nitrous oxide gas concentration, for an eight hour per day, five days a week exposure is 25 ppm. (National Institute for Occupational Safety and Health, 1977).

Release of gas occurs when one of the six release valves (R_1. . . . .R_6, Figure 6) is open. (Gating circuits make the operation of the charging and the gas release solenoids mutually exclusive). As the storage tank sinks into the oil bath, gas under constant pressure flows from the tank, via a needle valve and a flowmeter (Porter Rotameter Type F65A-V), to a six-port manifold and out through the particular release valve selected by the cycle control unit. The maximum time allowed for gas release per location is 21 seconds.

The flowrate corresponding to a particular setting of the Porter Rotameter flowmeter may be determined from a knowledge of the dimensions of the storage tank and the measured rate of settling of the tank.

There are practical limitations on the maximum value of air change rate that may be measured, or the maximum volume that may be studied, with a given rate of gas release. Equation (1) states that $\gamma = Q \times 10^6/CV$. The present apparatus has been adjusted to give a gas flowrate of 11.6 mL/s, and the maximum time for release of gas at each location has been limited to 21 seconds (see Figure 3), so the maximum value of Q, the amount of gas released in one hour, is

$$15 \times 6 \times 11.6 \times 21 \times 10^{-6} = 0.022 \text{ m}^3/\text{h}.$$

For accuracy, the value of the concentration being maintained should not fall below 20% of full scale of the infra-red gas analyser, in our case 20 ppm. Substituting for Q and C in equation (1) shows that the limiting values of air change rate and volume, on the basis of the above selected parameters, are governed by the expression $\cong 1000/V$, e.g. 3.3 ac/h for a volume of 300 m^3, and 20 ac/h for a volume of 50 m^3. However, the principle could be applied to any flowrate and time of gas release.

4. CALCULATION OF AIR INFILTRATION RATE

To obtain reliable values of infiltration rate, it is desirable that the weather conditions remain stable for periods of about one hour. Any short term instability in the weather tends to reduce the number of reliable values of infiltration rate, but on the other hand extended periods of stability in the weather reduce the range of values that may be deduced from the basic data. By reviewing the traces produced by the chart recorder it is a simple matter to select periods suitable for calculations of air infiltration rate.

For each of the six data-logging channels concerned with gas release, the printer records the channel number, time of day, gas concentration and the current total number of seconds of gas release.

Assuming steady conditions over a given elapsed time, H hours, and setting t = N/90H, equation 3 may be expressed as

$$\gamma = \frac{q\,N/H}{V\,[C_R - (N/90\,H)]}$$

where q is the constant flowrate during gas release (mL/s),
N is the accumulated number of seconds of gas release during the elapsed time,
H is the elapsed time (hour),
V is the volume of the building (m^3), and
C_R is the reference concentration (ppm).

For the chosen time interval the start and the finish times and the total accumulated seconds of gas release during that period are determined from the printout data. This information, together with the values of q, V and C_R, enables the average infiltration rate over the given time interval to be calculated from equation 4. A rigorous error analysis has not been carried out, but a consideration of the precision of measurement and accuracy of calibration of the quantities involved suggests an accuracy for determined values of γ of about ± 10%.

5. CONCLUDING REMARKS

The apparatus described in this report has been used successfully in a number of investigations of the air infiltration characteristics of houses in Melbourne and Sydney. In each of these cases the house was treated as a single space, sampled at six locations within the house volume. However, it would be possible with this equipment to determine separate air infiltration rates for up to six spaces simultaneously, provided that there was no transfer of tracer gas between the spaces.

As a check on the performance of the automatic apparatus, the release of tracer gas was stopped on several occasions, in different houses, and the decay in concentration of tracer gas measured over time periods of up to several hours. The air change rate was determined for periods during the decay of approximately one hour, from the expression

$$\gamma = [\ln C_o - \ln C_1]/H$$

where C_o is the initial gas concentration (ppm),

C_1 is the final gas concentration,

and H is the time for the decay (hours).

The values for the air change rates obtained by this method were within 10% of those using the automated gas release method for the same nominal wind velocity and approximate wind direction. This is considered good agreement since the wind conditions always changed to some extent over the comparison period and the air change rate is dependent on the precise wind speed and direction.

The equipment described here does not employ microprocessor technology, but the principle of the method could easily be adapted to such a system. The present 'hard wired' system has proved to be reliable; in one case a building was monitored for nine weeks and the apparatus operated continuously, without malfunctioning, throughout that period.

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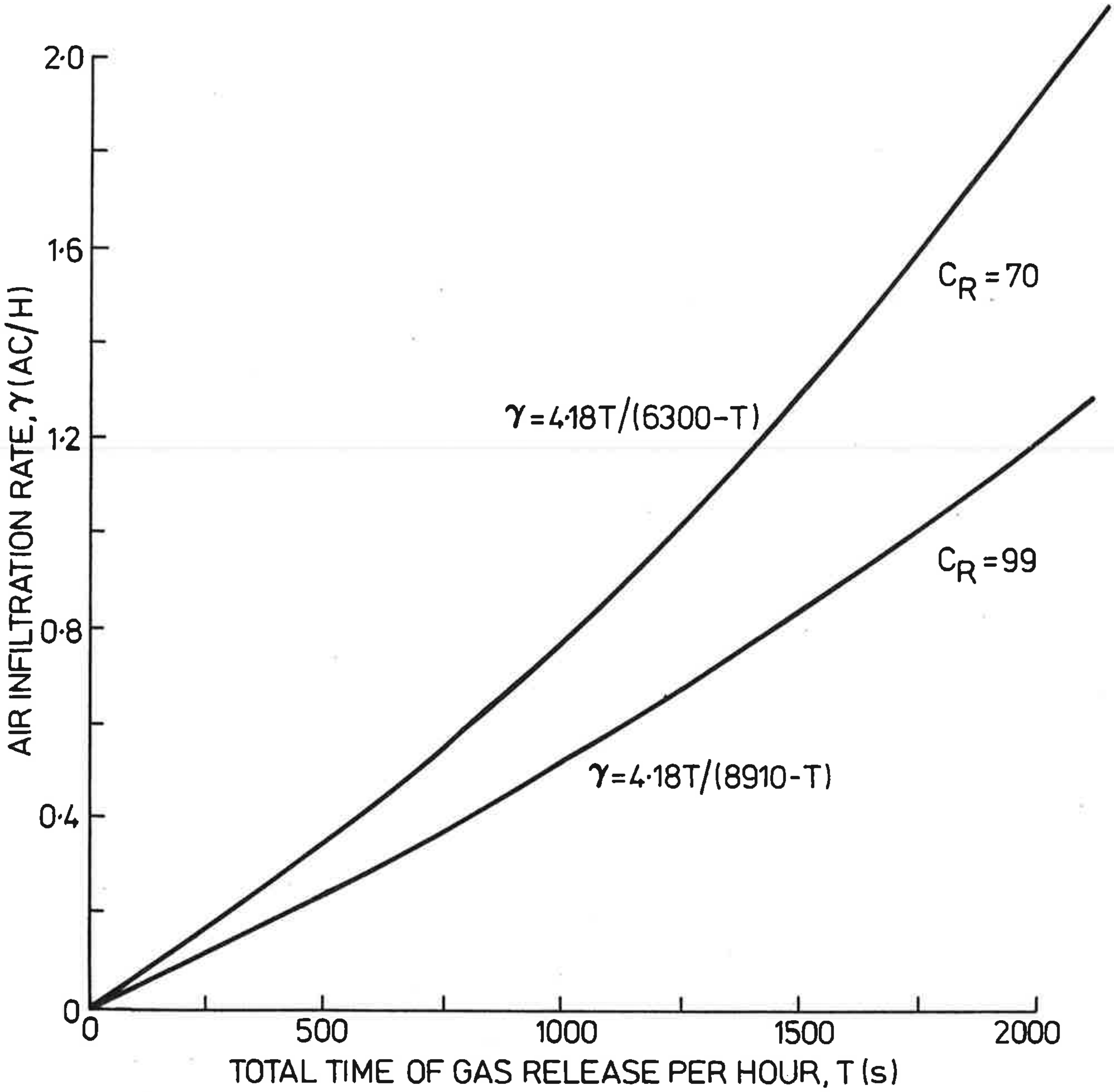

Figure 1. **Air infiltration rate calculated as a function of the total time of gas release per hour, for two values of the reference concentration, C_R (ppm).**

No. of release and sampling points = 6.
No. of gas releases per hour = 15 per location.
Gas flowrate q = 11.6 mL/s.
House volume = 250 m^3.

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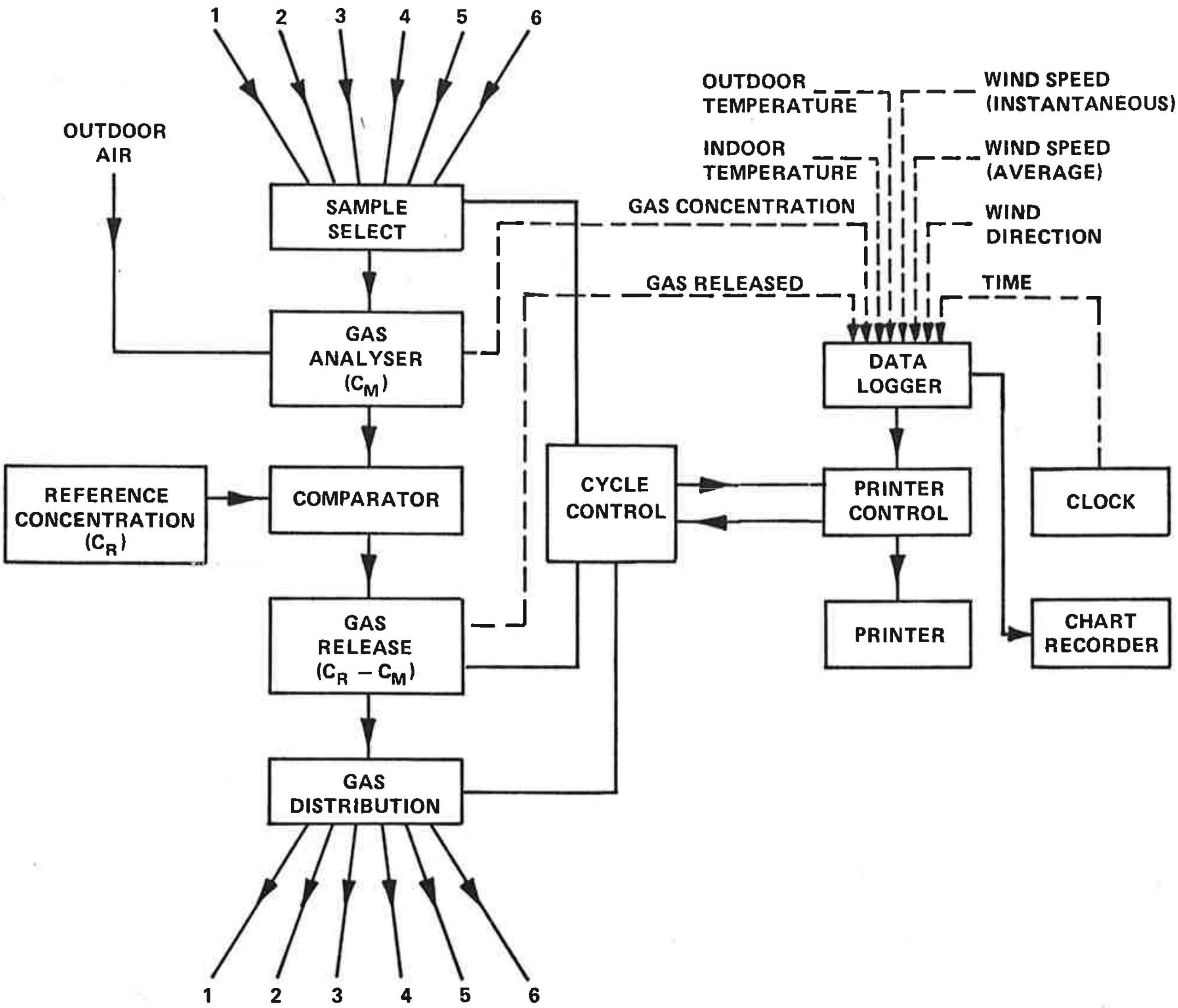

Figure 2. Block diagram of apparatus for continuous monitoring of air infiltration.

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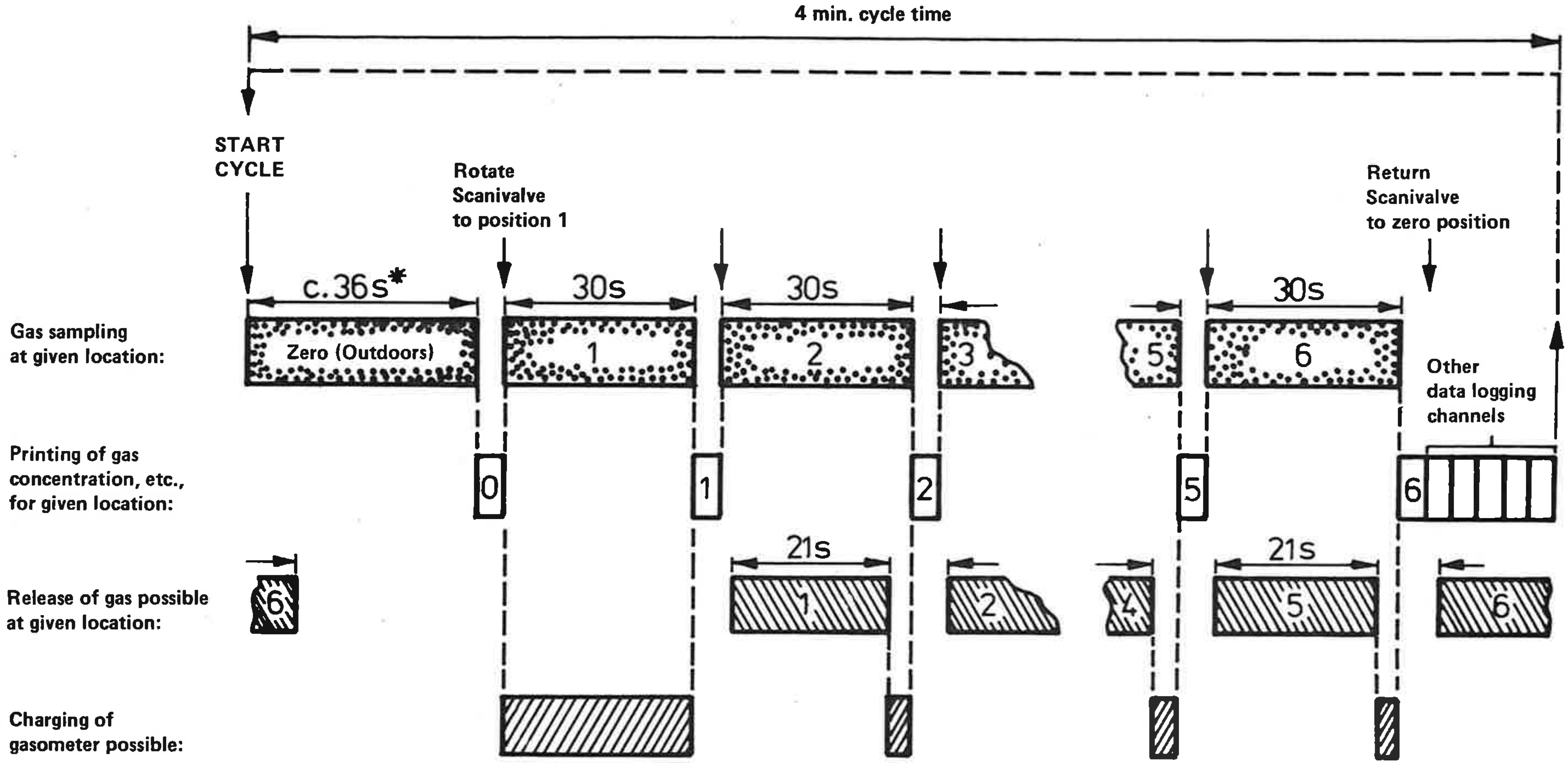

*Adjusted to give total cycle time of exactly 4 min.

Figure 3. Sequence diagram of the operations of the apparatus.

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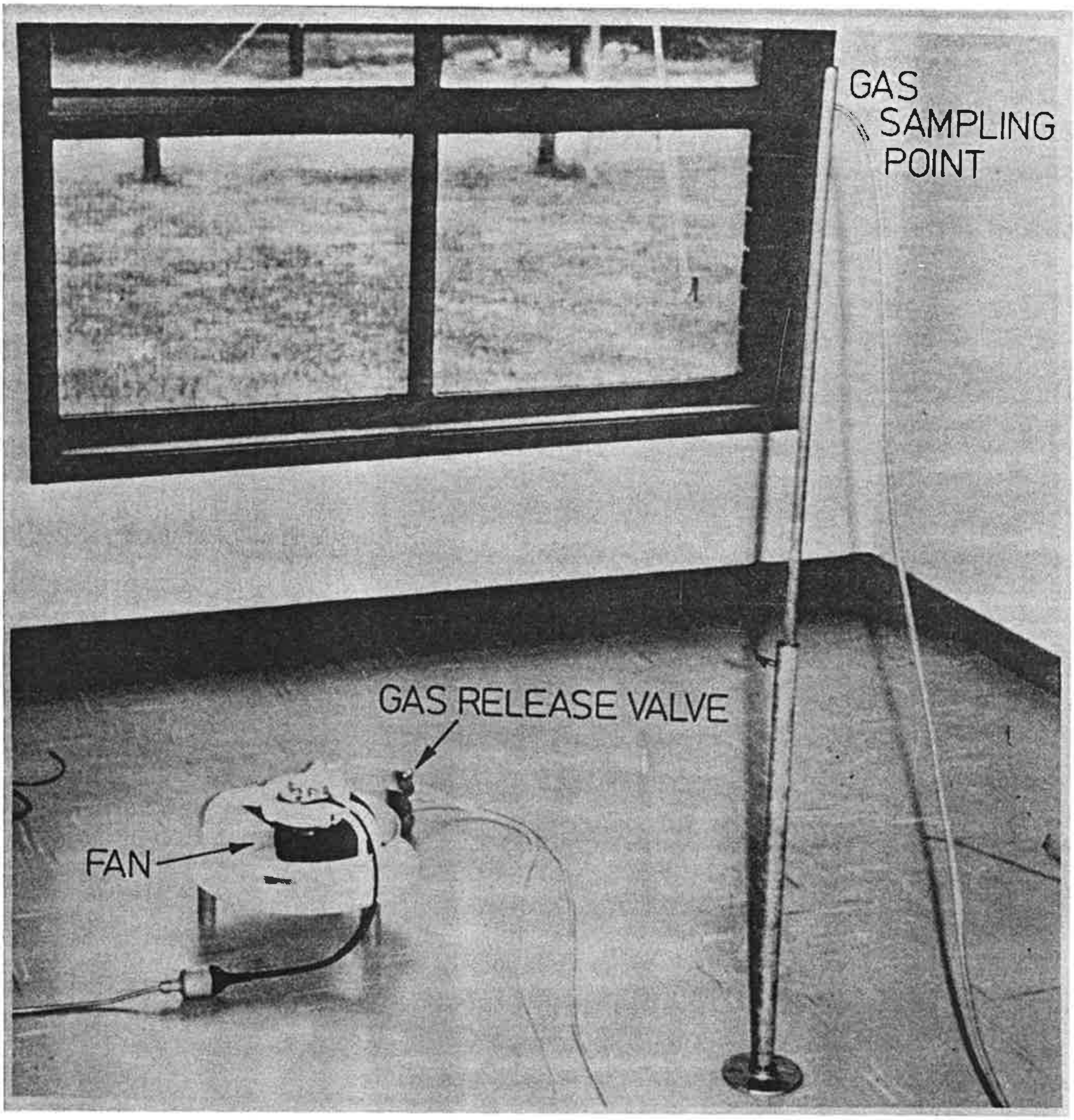

Figure 4. Typical arrangement of gas distribution fan and gas sampling tube in a room being monitored for air infiltration rate.

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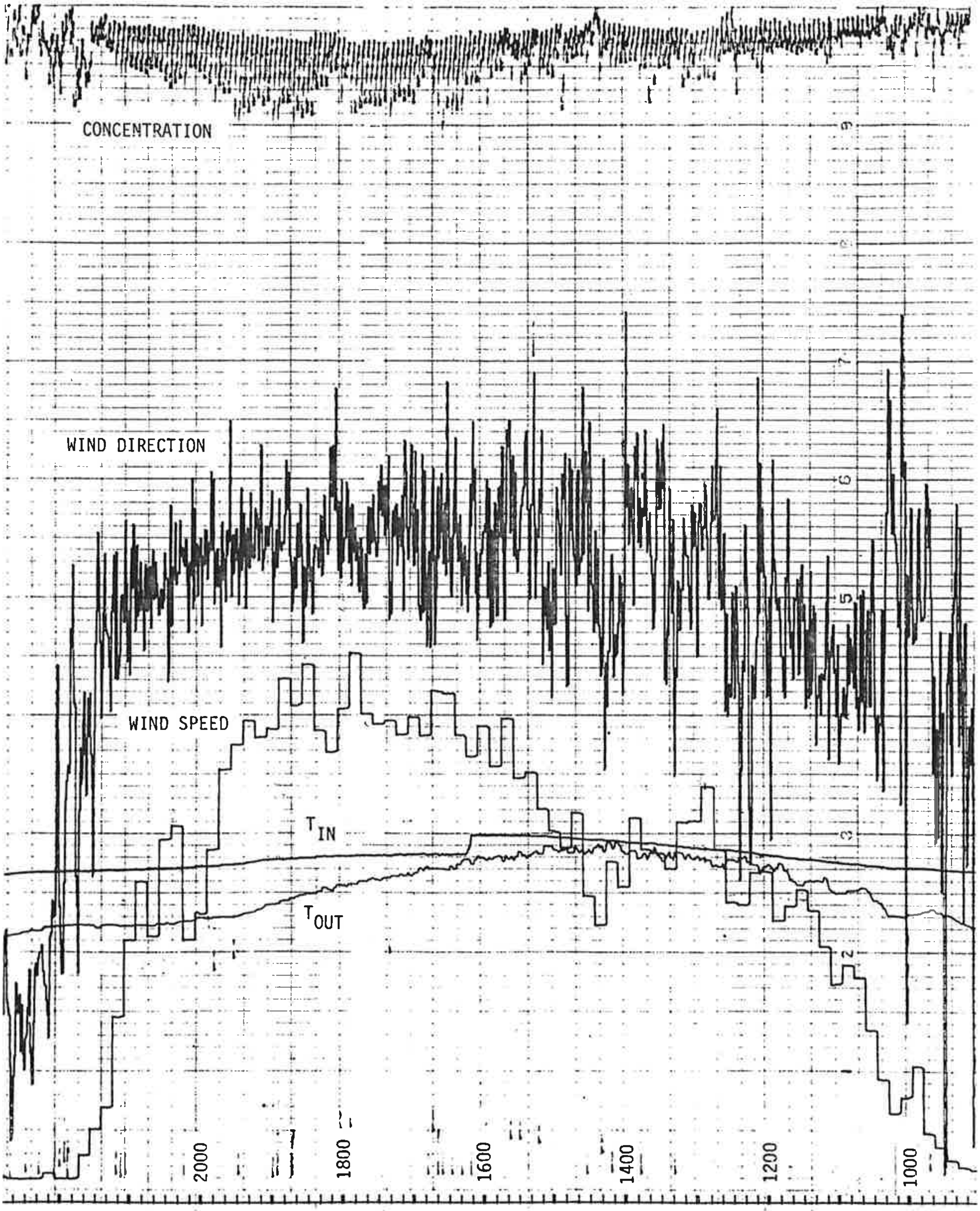

Figure 5. Chart recorder traces of gas concentration (100 ppm full scale deflection (FSD)), two-minute average values of wind speed (10 m/s FSD), wind direction sampled at one minute intervals (10 V FSD, 1 V equivalent to 45°), and indoor and outdoor temperatures (100°C FSD). Reference concentration 99 ppm.

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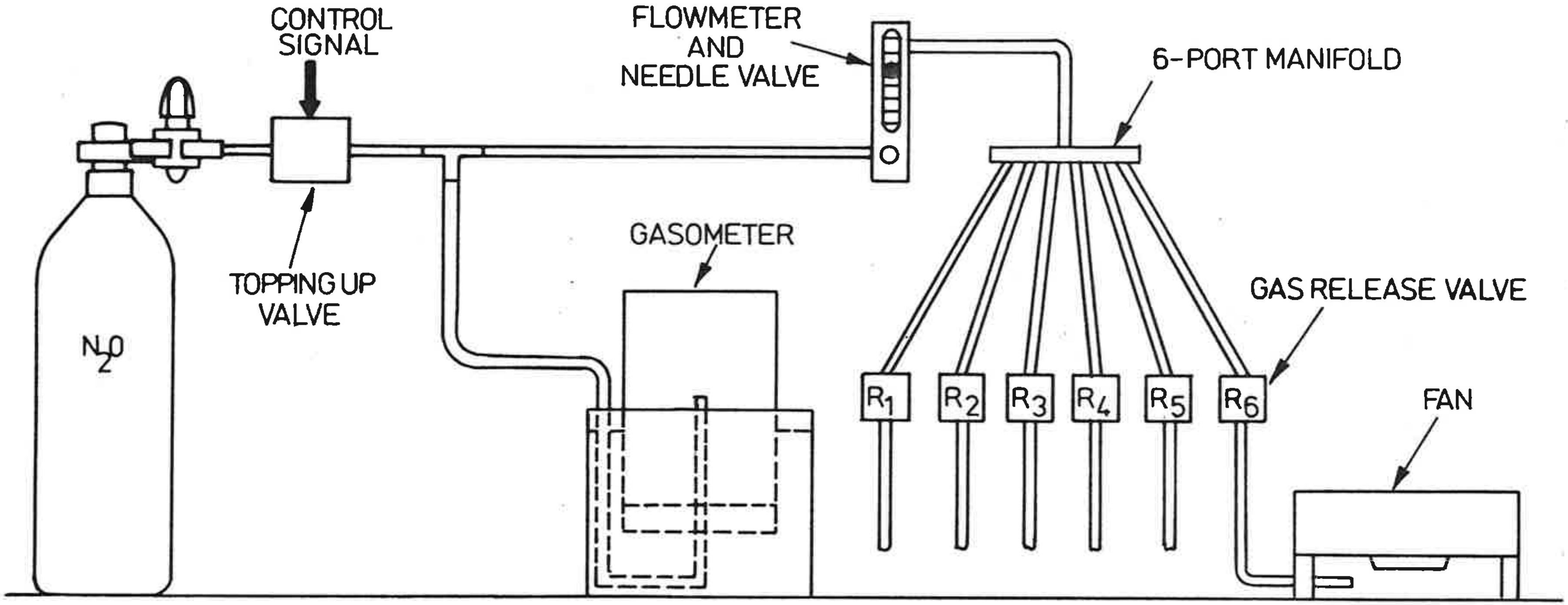

Figure 6. Schematic diagram of the apparatus for delivering tracer gas at a constant flowrate when a gas release valve is opened.

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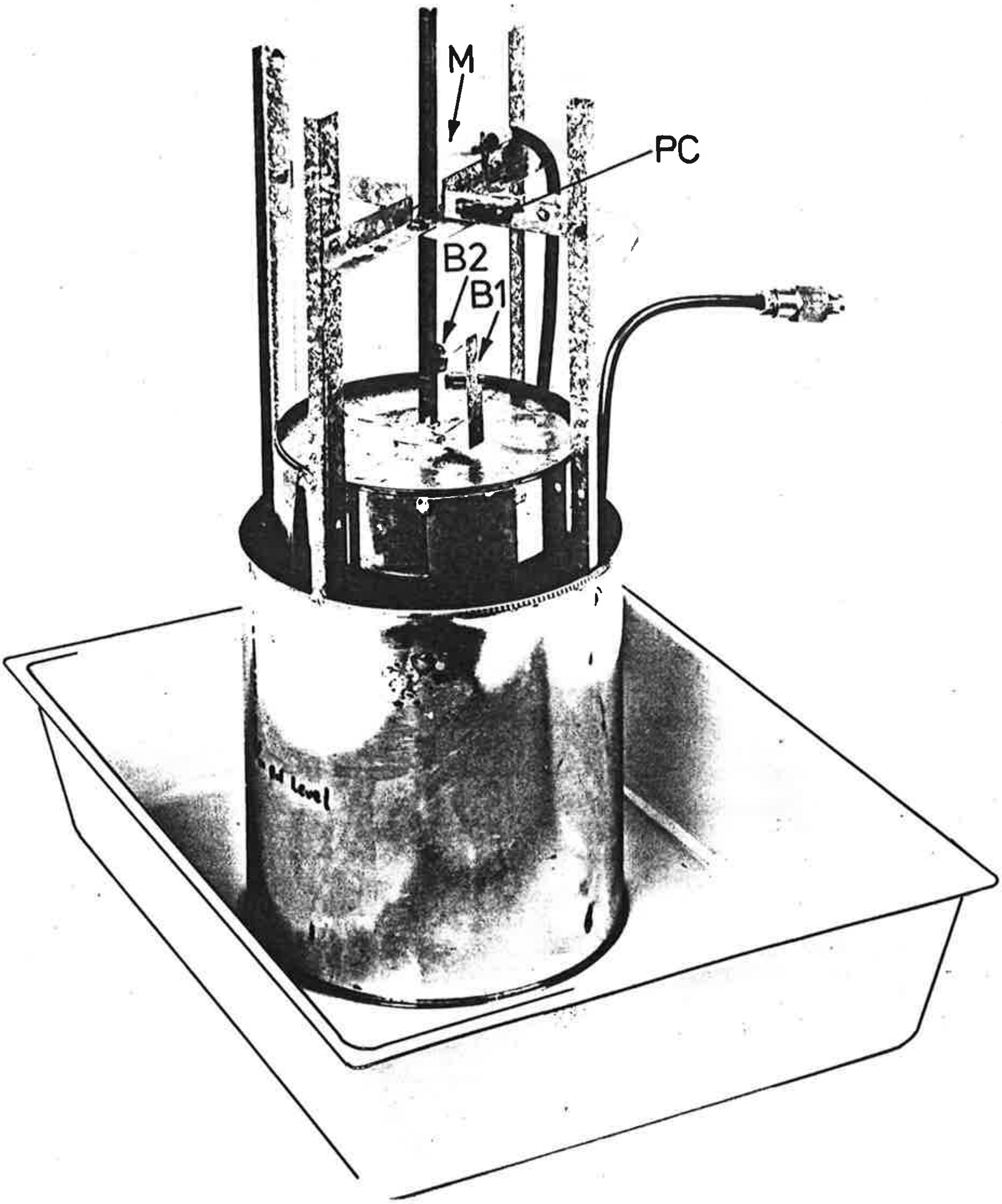

Figure 7. The gasometer used to supply tracer gas at constant pressure.

PC = infra-red 'photo-cell'.
B1 = blade to interrupt PC beam.
M = microswitch.
B2 = blade to trip M.

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