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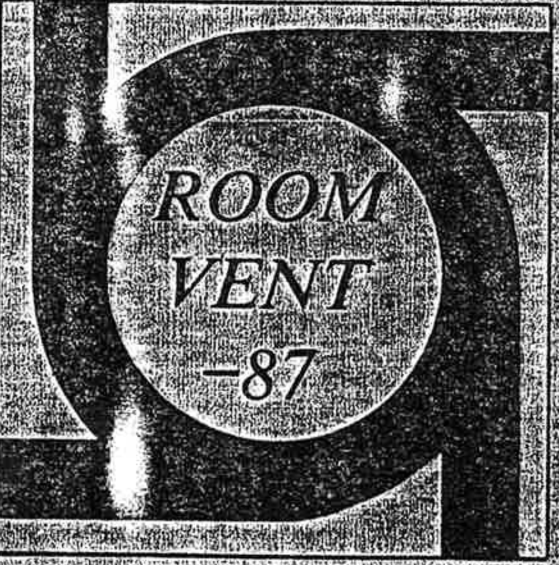

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THE MEASUREMENT OF AIR MOVEMENTS BETWEEN FOUR INTERCONNECTED CELLS BY A MULTIPLE TRACER GAS DECAY TECHNIQUE

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ABSTRACT

This paper describes the development and application of a multiple tracer gas decay technique for the measurement of the ventilation rates in, and the air movements between, four interconnected cells. The measurement equipment used is a refinement of the existing UMIST parallel separation column portable gas chromatograph. By the use of parallel electron capture detectors, it is possible to measure the concentrations of four tracer gases in four cells, within sufficiently short a time interval for an air movement calculation procedure, based on the previous procedures used for two and three cells, to be used successfully: this procedure is summarised in this paper. A typical set of results is presented, in order to demonstrate a situation in which the technique could be applied to complex air movements within the building envelope. The possible extension of the technique to five or more cells is also briefly discussed.

INTRODUCTION

It has been appreciated for many years that air infiltration losses can account for 30-40% of domestic energy consumption, given in well-insulated dwellings. Several authors, for example Dick[1] and Kronvall[2] have undertaken research in the field of ventilation and infiltration measurement, and have made determinations of the size of energy savings achieved by the sealing of structures. Ever increasing standards of air tightness and thermal insulation, whilst undoubtedly resulting in superior energy efficiency, have led to new difficulties which were not previously envisaged. Firstly, instances of condensation problems, with resulting damage to both house contents and fabric, have become more commonplace; secondly, there is now considerable concern about the effects of increased airtightness on air quality within dwellings, since reduced air infiltration inhibits the removal of pollutants such as odours and CO_2. Since both of these problem areas involve localised generation and dispersal of pollutants, it is clear that the study of such phenomena entails the measurement of air movements between internal spaces.

Ventilation and air movement research at UMIST has been in progress for seven years. In this time, the equipment used has evolved from the simple, single separation column gas chromatography as used by I'Anson et al [3] to the parallel column gas chromatograph developed by Irwin and Edwards [4]. This improvement in measurement equipment has led to an increase in the speed at which air/tracer gas samples can be analysed, which in turn has facilitated the successful implementation of a new, simplified interzonal air movement rate calculation procedure, for two [4] and three interconnected cells [5].

A three cell capability is not adequate for all cases. In many circumstances, a four (or perhaps even five) cell capability would be highly desirable. The existing equipment is barely capable of fulfilling such demands. This paper describes the construction of a new piece of air movement measurement equipment, and summarises the mathematical procedure necessary to analyse the data produced for the case of four interconnected cells.

EXPERIMENTAL

a) Equipment

In order to be able to make "real time" air movement measurements, the equipment used must be able to separate out the requisite number of tracer gas peaks within a sufficiently short time interval, whilst at the same time maintaining peak resolution and separation, particularly at lower tracer gas concentrations. These two criteria are in direct conflict with each other in gas chromatographic terms. However, the existing parallel column equipment can, for the case of three tracer gases fulfil both with no compromising of equipment performance. Using Freon 12, Freon 114 and bromo-chloro-difluoromethane, (BCF) a sampling interval of 45 seconds can be easily obtained, with no loss of resolution at lower concentrations. When the parallel column equipment is used for four tracer gases, however, problems are encountered. The maximum sampling interval desirable is 1 minute in order to achieve this chromatographic column operating conditions have to be adjusted to such an extent that tracer gas peak resolution is lost completely at concentrations below 5% of full scale reading. Such a limitation renders the equipment ineffective in situations where interzonal air movement rates are small in magnitude. It is therefore apparent that the parallel column equipment is of very limited use for the case of four interconnected cells or more, and that a substantial enhancement in measurement technique performance is required: furthermore, it is essential that this enhanced performance is obtained without sacrificing equipment portability, which is the principal advantage of the existing measuremement technique.

The problem is overcome by the rebuilding of an Analytical Instruments (AI) model 505 electron capture portable gas chromatograph (GC) which is the same basic instrument as used for the parallel column apparatus. However, in this particular case the degree of rebuilding is significantly greater. The manual prototype apparatus is shown in Figure 1. The GC now has two electron capture detectors fitted, which are capable of working simultaneously and independently. To each electron capture detector are connected two GC separation columns, in the same manner as the parallel column equipment. Five 4-part Whitey valves are used to direct sample flow through the system. Later work with the parallel column apparatus showed that, instead of using a pump to suck gas through the system a pump was used to pressurise the system, then problems of pressure equalisation throughout the system were all but elminated and the performances of the GC columns became more closely matched. As a consequence, the pump supplied in the AI 505 has been removed, and a Charles Austin Dymax 2 pump is used at the front end of the system.

The use of two ECDs in parallel has meant that the existing modulated power supply/amplifier board and socket on the AI 505 has been replaced by a specially made twin channel board. This new board fits in the same board connector socket as the original. Changes to the connector

ECD	Column	Time (seconds)							
		0	30	60	90	120	150	180	210
a	1	Inject	*Monitor	*Monitor	-	Inject	*Monitor	*Monitor	-
	2	* -	-	Inject	+Monitor	+Monitor		Inject	+Monitor
b	1	-	Inject	+Monitor	+Monitor	-	Inject	+Monitor	+Monitor
	2	+	+ -	-	Inject	+Monitor	+Monitor	-	Inject

* Live column to a

+ Live column to b

Table 1: Sample injection/monitoring sequence

socket contacts have been made such that each ECD has an independent zeroing potentiometer, and ammeter. The whole piece of apparatus is mounted in an instrument box which is not significantly larger than the original unit.

The GC columns used are 3 metres long and 6 mm diameter. The packing is 10% squalane on a ceolite non-acid washed support. In order to match column responses as closely as possible the same procedure for column preparation and operation was used as per reference (4), that is:

i) Columns to be purchased from the same manufacturer, and to be packed during the same production run from the same batch of packing material;

ii) All columns to be baked simultaneously in parallel in an over at 100°C for 12 hours prior to first use, with the purging gas (argon) to be drawn from the same cylinder;

iii) When not in use, all columns to be kept under a blanket of argon, (connected in parallel) with the purging gas to be drawn from the same cylinder.

When in operation, the GC columns are immersed in a thermostatically controlled water bath and stirrer unit at 40°C. This eliminates ECD sight baseline drift problems, and also minimised differences in response between columns. Calibration tests showed that the maximum difference in response between the two ECDs for the same air/tracer gas concentration (40% of full scale) was not greater than 0.5%.

Several tracer gases were assessed for use in four cell measurements. The final choice was made as follows: Freon 13B1, Freon 12, Perfluorocarbon PP1, and Freon 114. The gases are injected remotely into the relevant test cell and mixed with oscilating desk fans for a suitable length of time, typically 5 minutes. Gas air samples are drawn into the GC by means of multipoint sampling manifolds. A typical pipe layout is shown in Figure 2.

The sampling and monitoring sequence for the parallel detector apparatus is shown in Table 1. As can be seen, use of this apparatus enables one air/tracer gas sample to be injected every 30 seconds. Whereas the use of parallel columns effectively doubles the sampling interval by making use of the "retention time" associated with the passage of a sample through a column, the use of parallel detectors doubles the available time for which ECD output can be monitored for a given sample, before the next sample has to be switched on. This extra time reduces the urgency for rapid tracer gas peak throughput, and hence improves peak resolution at lower concentrations.

b) Mathematical analysis

The equations describing the variations in concentration with three of four tracer gases in four interconnected cells are extremely complex and are consequently very difficult to manipulate in order to give air movement rate values. The most complex terms involved in the equations are those describing the recirculation of tracer gases. It can be shown (6) that the contribution of recirculation to measured tracer gas concentrations is negligible for test lengths of less than 20 minutes. Therefore, providing that the measurement technique used is capable of collecting sufficient data within 20 minutes, the tracer gas equations can be simplified to take into account direct connection terms only. Consider the system of four interconnected cells shown in Figure 3. For the case of cell 1, assuming perfect mixing, and that the airspace surrounding the cells under consideration is of infinite volume:

Gas A:

$$C_{A1}(t) = C_{OA1}(1 - An_1) + \frac{F_{21}.C_{OA2} . (e^{-n'_2t} - e^{-n'_1t})}{V_1(n_1 - n_2)}$$

$$+ \frac{F_{31} . C_{OA3} . (e^{n'_3t} - e^{-n'_1t})}{V_1(n_1 - n_3)} \qquad (1)$$

$$+ \frac{F_{41} . C_{oa4} . (e^{n'_4t} - e^{-n'_1t})}{V_1 . (n_1 - n_4)}$$

Gas B:

$$C_{B1}(t) = C_{OB1}(1 - An_1) + \frac{F_{21}\, C_{OB2} . (e^{-n'_2t} - e^{-n'_1t})}{V_1(n'_1 - n'_2)}$$

$$+ \frac{F_{31}.C_{OB3} . (e^{-n'_3t} - e^{-n'_1t})}{V_1.(n'_1 - n'_3)} \qquad (2)$$

$$+ \frac{F_{41}.C_{OB4} . (e^{-n'_4t} - e^{n'_1t})}{V_1(n'_1 - n'_4)}$$

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Gas C:

$$C_{C1}(t) = C_{OC1}(1 - An_1) + \frac{F_{21}\, C_{OC2} \cdot (e^{-n'_2 t} - e^{-n'_1 t})}{V_1(n'_1 - n'_2)}$$

$$+ \frac{F_{31} \cdot C_{OC3} \cdot (e^{-n'_3 t} - e^{-n'_1 t})}{V_1(n'_1 - n'_3)} \qquad (3)$$

$$+ \frac{F_{41} \cdot C_{OC4} \cdot (e^{-n'_4 t} - e^{-n'_1 t})}{V_1\,(n'_1 - n'_4)}$$

Gas D:

$$C_D(t) = C_{OD1}\,(1 - An_1) + \frac{F_{21} . C_{OD2} \cdot (e^{-n'_2 t} - e^{-n'_1 t})}{V_1\,(n'_1 - n'_2)}$$

$$+ \frac{F_{31} C_{OD3} \cdot (e^{-n'_3 t} - e^{-n'_1 t})}{V_1\,(n'_1 - n'_3)} \qquad (4)$$

$$+ \frac{F_{41} C_{OD4} \cdot (e^{-n'_4 t} - e^{-n'_1 t})}{V_1\,(n'_1 - n'_4)}$$

where n'_{1-4} = first order ventilation rate estimates from site data; these are obtained by making a least squares fit to the first six data points of the decay curves of the tracer gases originally injected into each cell. (ie gas A in cell 1, gas B in cell 2, gas C in cell 3, gas D in cell 4)

C_{OYZ} = initial concentration of gas y in cell z at t = 0;

F_{xz} = volume flow rate of air from cell x to cell z (m^3/hr);

V_1 = volume of cell 1 (m^3)

$c_{y1}(t)$ = mean concentration of gas y in cell 1 over the test period Δt;

$$= \int_{t=0}^{t=t} C(t) \Big/ \Delta t \qquad (5)$$

10 site data points is the optimum number; less than this number increases errors due to uncertainty in values of $Cy_1(t)$, whilst more than this number increases errors due to recirculation.

$(1 - A_{n1})$ is a Maclaurin series expansion

$$\text{where } A = -t + \frac{n_1't^2}{2!} - \frac{n_1't^3}{3!} + \frac{n_1't^4}{4!} - \frac{n_1't^5}{5!} \qquad (6)$$

Similar sets of equations exist for cells 2, 3 and 4. For the case of cell 1, initial estimates of airflows are fed into equations (1) to (4) and a computerised version of the Gauss-Seidel iteration process is used to yield more accurate values of n_1 to n_4 and the relevant airflows. The process is repeated for all four cells until the calculated values of airflows and ventilation rates converge: generally this happens within 10 iteration steps. For a much more detailed derivation of this method of analysis, study of reference (7) is recommended.

RESULTS AND DISCUSSION

The test cell arrangement used is shown in Figure 4. The kitchen, dining room, and living room/lobby of a four bedroom house have been taken as cells, whilst the whole upstairs has been taken as one cell. The tracer gases used are as follows: dining room, Freon 12; kitchen, Freon 13B1; living room/lobby, PP1; upstairs, Freon 114. The concentration/time data obtained for a typical test is presented in figures 5 - 8, and the calculated values of ventilation rates and airflows are summarised in Table 2 and in diagrammatic format in Figure 9. Airflows of 10 m^3/hr or less represent the limit of resolution of the technique. Worthy of note are the high flows between lounge and upstairs. The upwards flow is caused by convection, the downward flow by an open window in the lounge. The flow rates between kitchen and dining room are high, despite the door being closed. This is due to the presence of a serving hatch.

The mathematical analysis used has been validated for two [8] and three [9] interconnected cells using environmental chambers with controlled independently measurable air supply and extract rates. The errors in calculated air flow rates are shown to be approximately ±8% for two cell measurements and ±20% for three cell measurements. It should be noted that the test conditions in the latter case were made artificially severe, in order to see if the mathematical analysis would fail. A more likely order of magnitude of error for realistic test

conditions would be between 10% and 20%. At the present time, the authors do not have access to a suitable 4-cell controlled environment system, and so validation of the technique is not possible. However, it is expected that the error in calculated airflow rates will be of the order of ±15%.

The new technique is currently being used to study air movements in dwellings, with particular regard to air movement between upstairs and downstairs. There are a substantial number of tracer gases available which are suitable for use with electron capture detectors (see, for example, reference (10). With careful adjustment of operating conditions, it is felt that the new technique could cope with five or more gases - clearly well beyond what is necessary for studies of domestic properties, but of great interest in the measurement of air movements in large spaces.

CONCLUSIONS

This paper describes the construction and use of a new multiple tracer gas system for the determination of airflows between four interconnected cells. It should be stressed that the piece of equipment used represents a manually operated prototype, and that the next stage of development will involve system automation. The mathematical treatment of concentration/time data used should give values of intercell air movement rates to within ±15%.

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	x			
	1	2	3	4
N_x (ach)	4.33	6.83	3.40	1.63
Nett airflow to/ from outside (m^3/hr)	+40	+45	-5	-80
F_{1x} (m^3/hr)	x	80	20	30
F_{2x} (m^3/hr)	65	x	100	40
F_{3x} (m^3/hr)	15	70	x	150
F_{4x} (m^3/hr)	10	10	120	x

Table 2: Ventilation and airflow rates

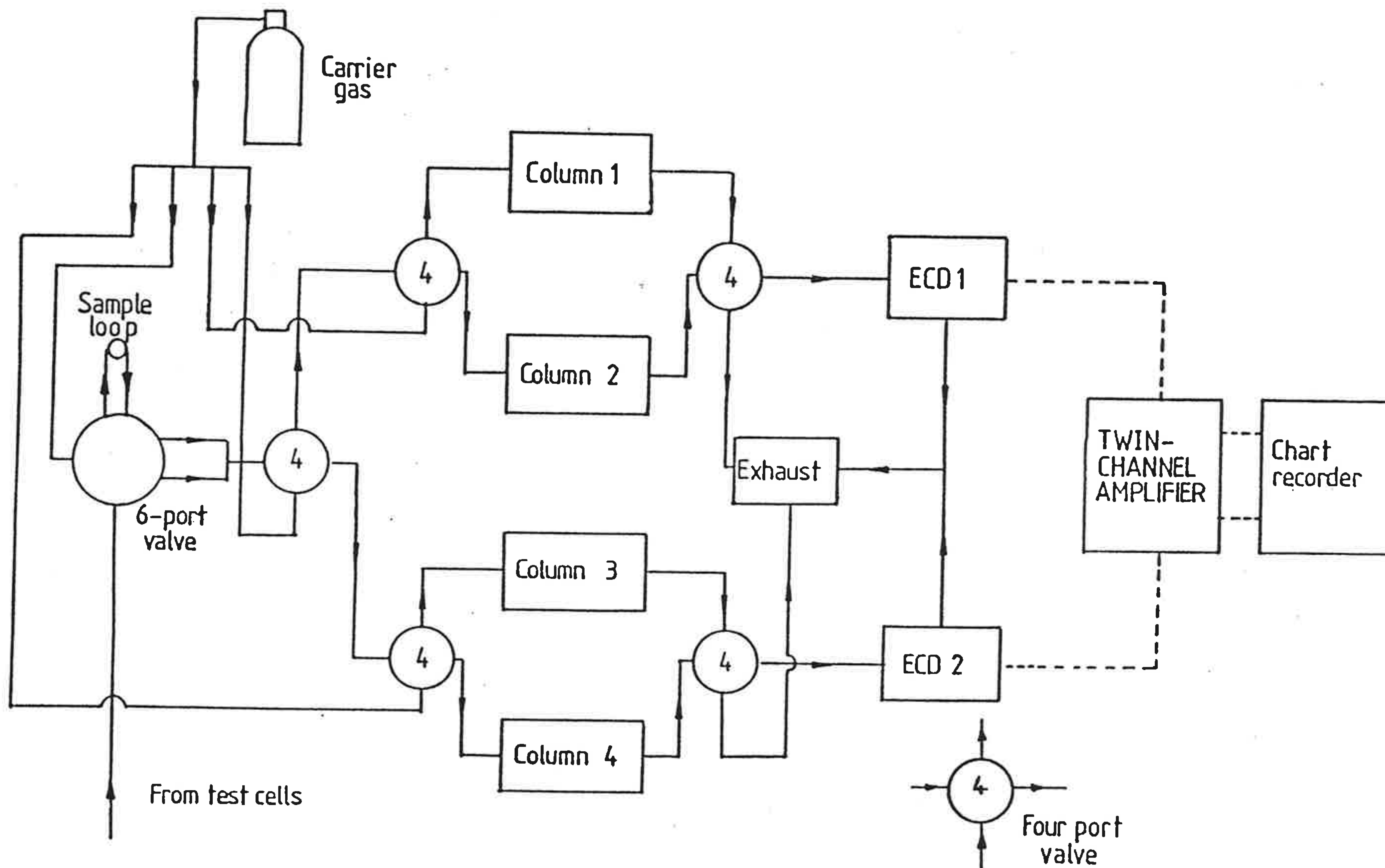


FIGURE 1: Measurement equipment

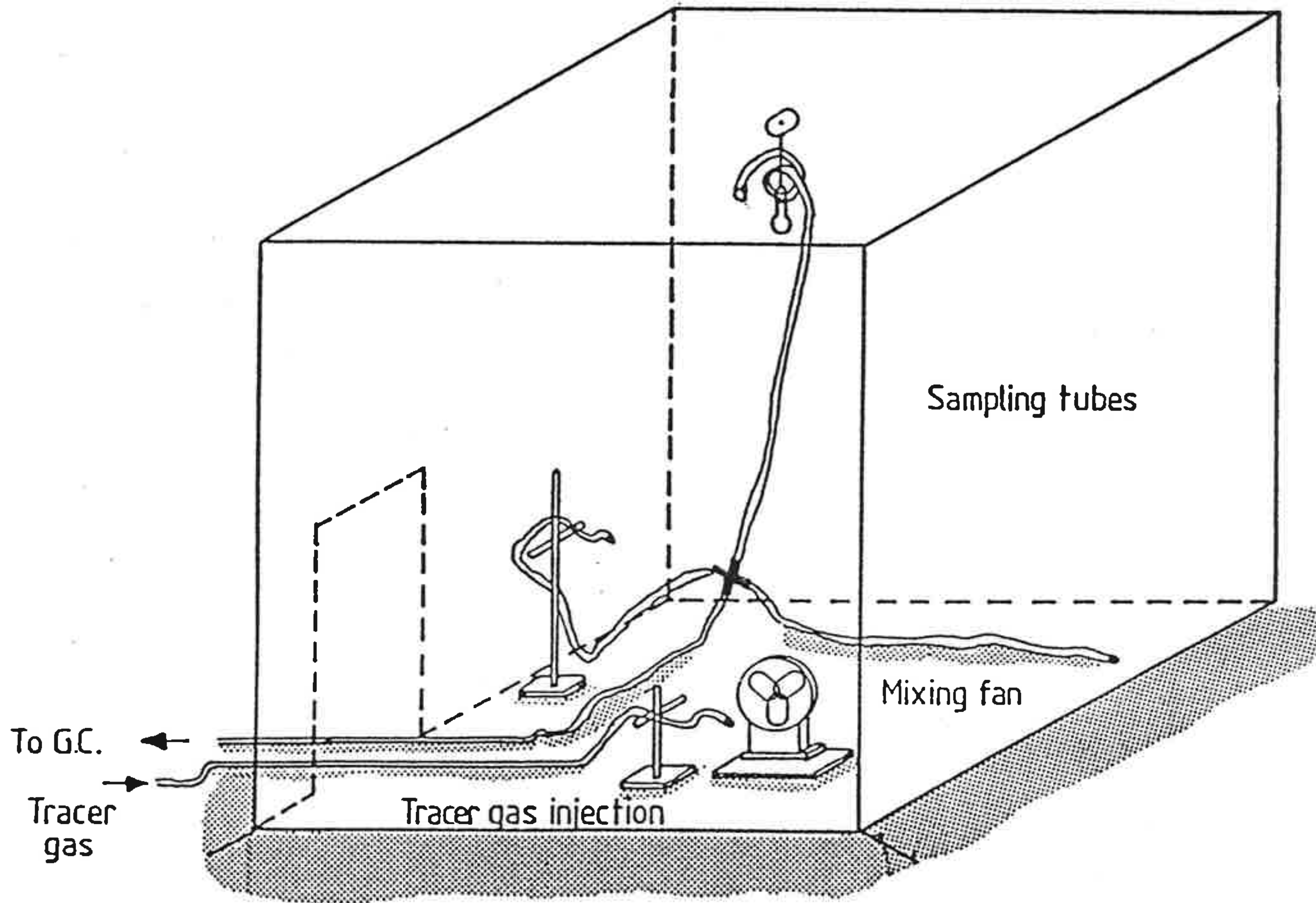


Figure 2: typical test cell

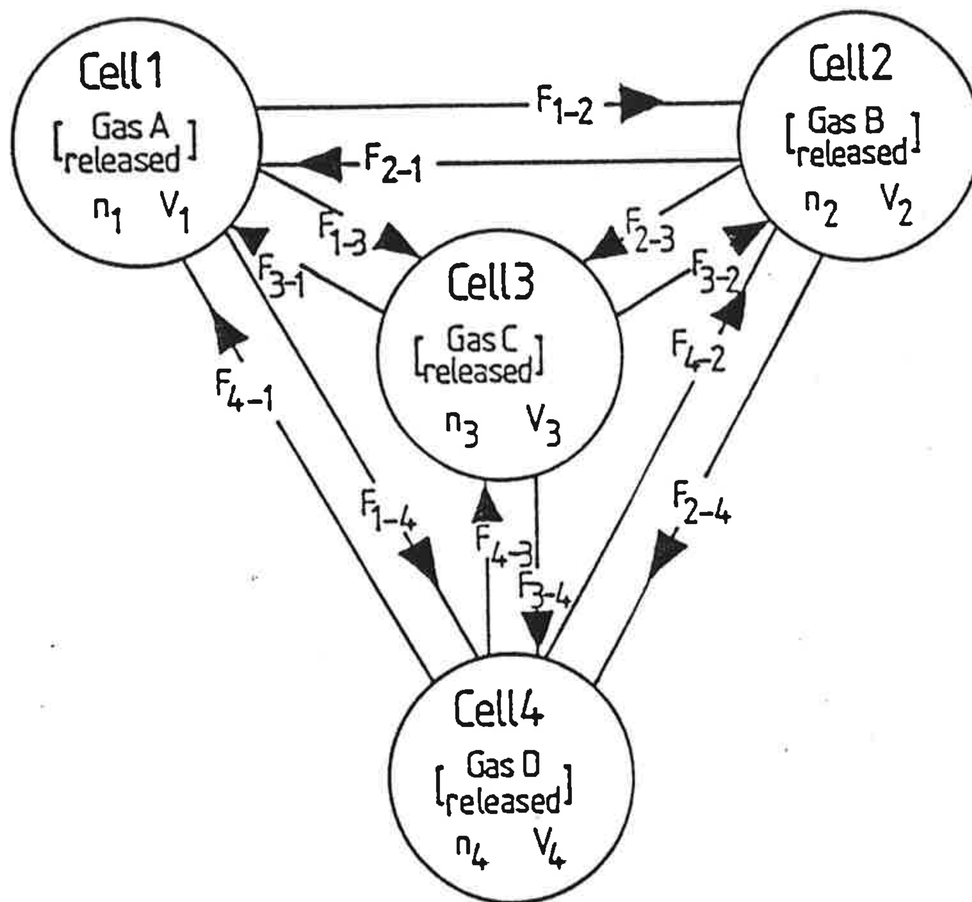
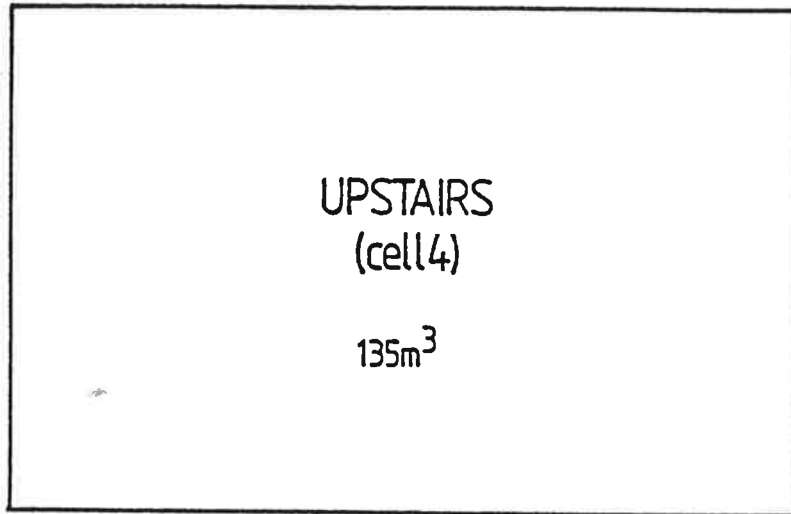


FIGURE 3: flows between 4 interconnected cells



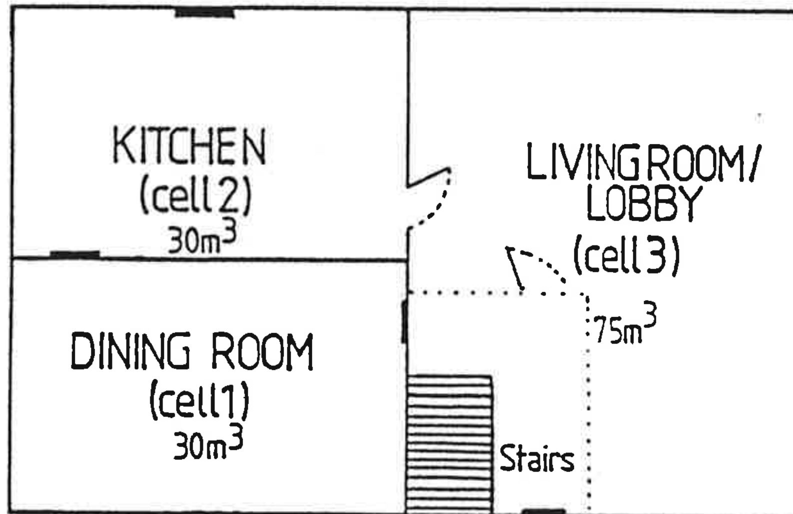


FIGURE 4: Test cell details

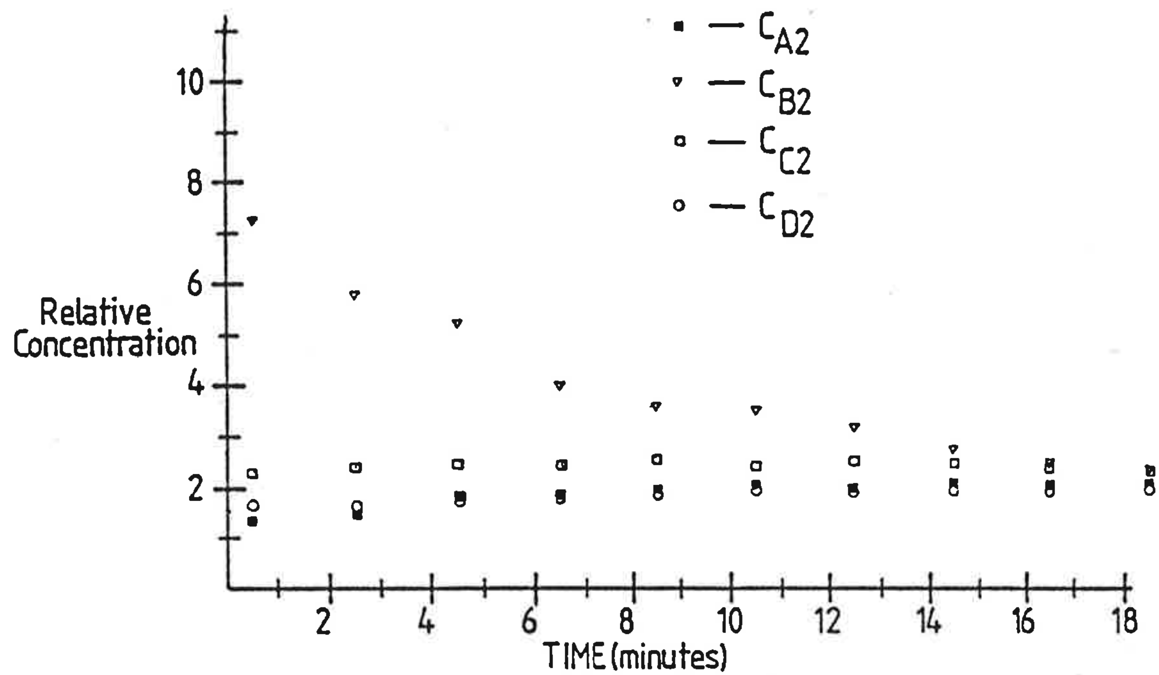


FIGURE 6: Cell 2 concentrations

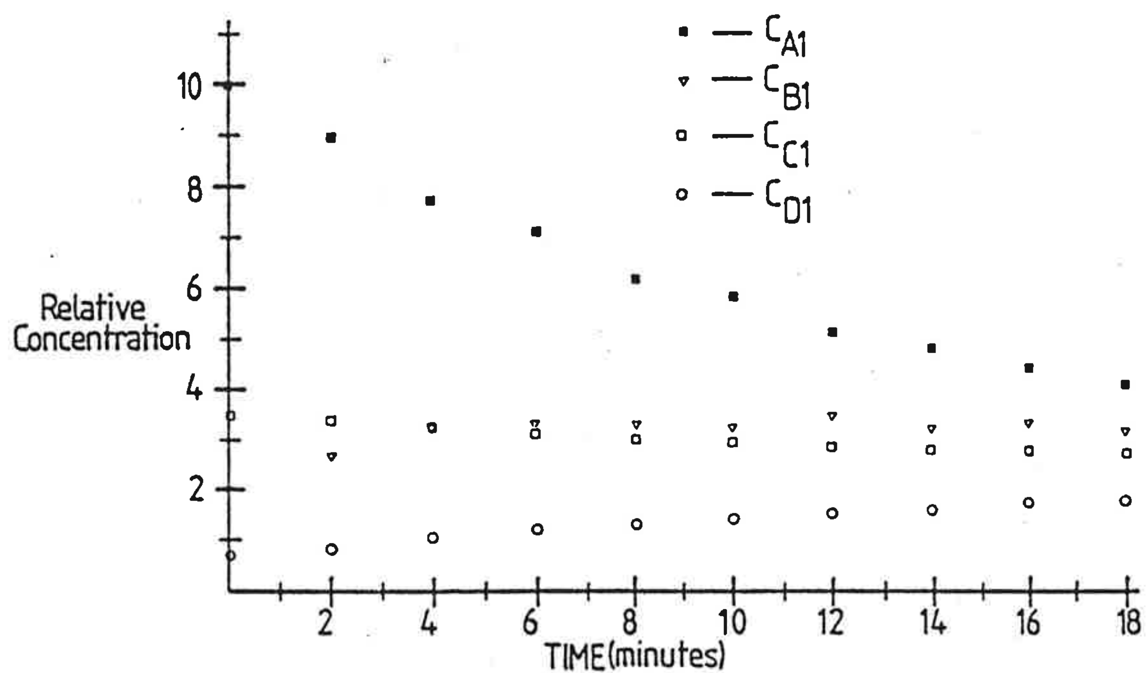


FIGURE 5: Cell 1 concentrations

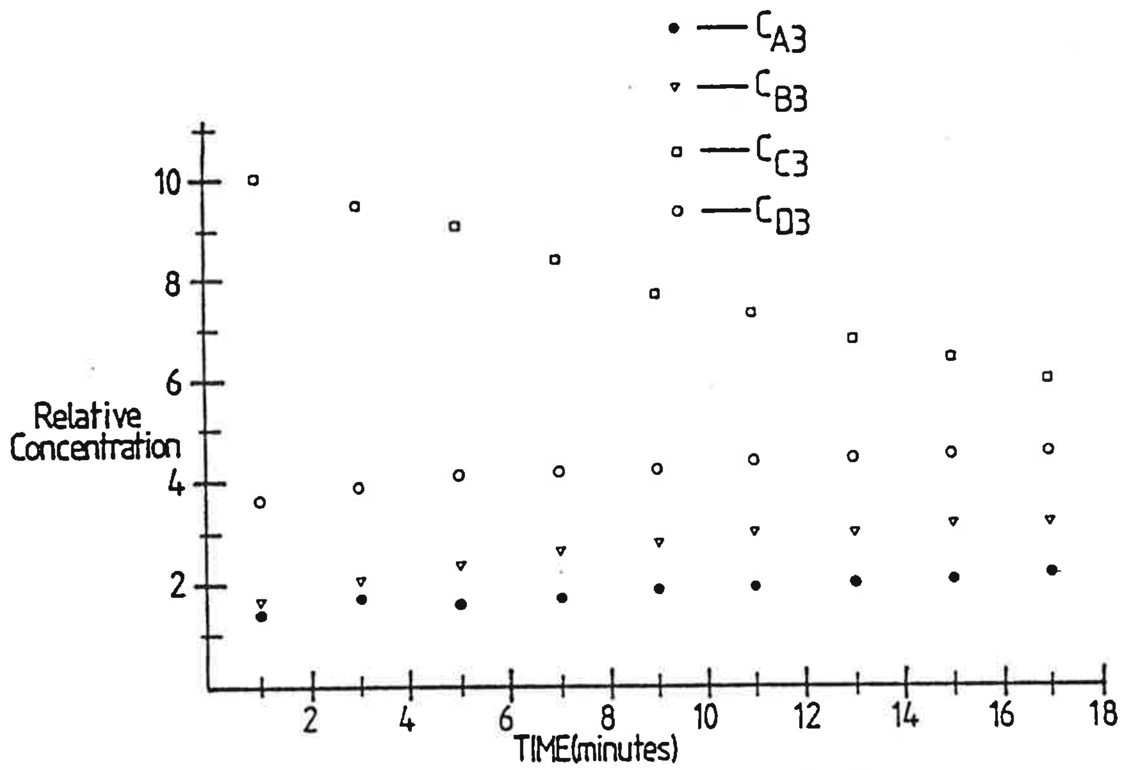


FIGURE 7: Cell 3 concentrations

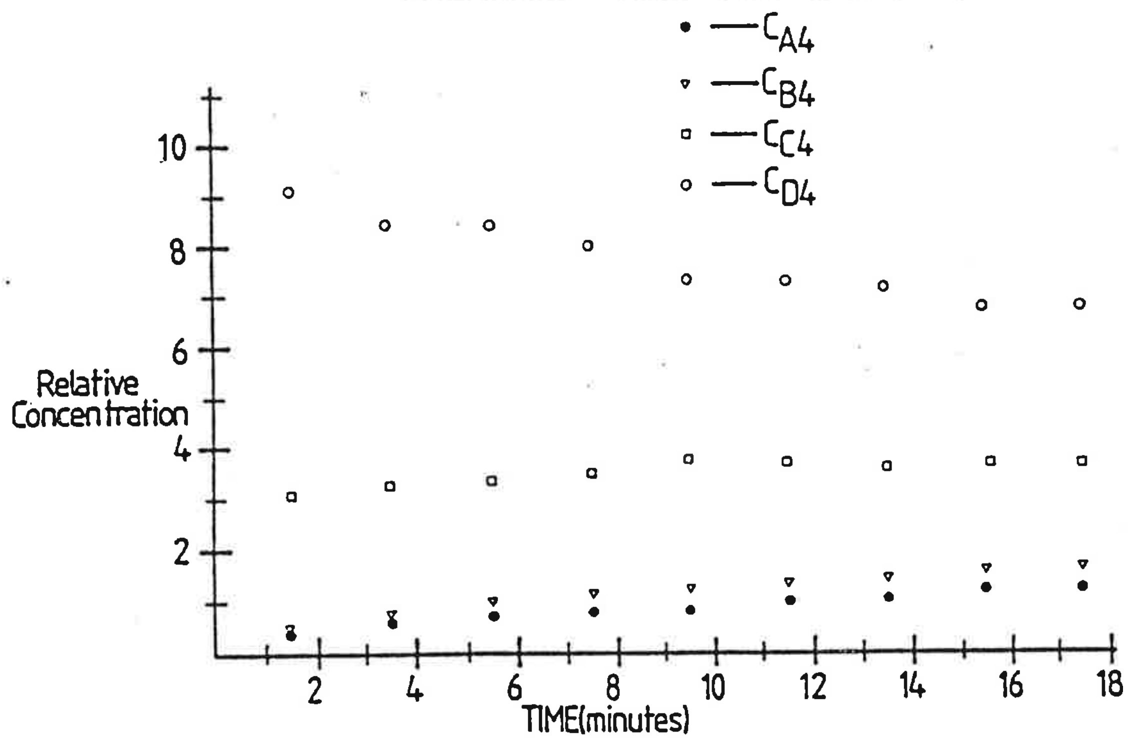


FIGURE8: Cell 4 concentrations

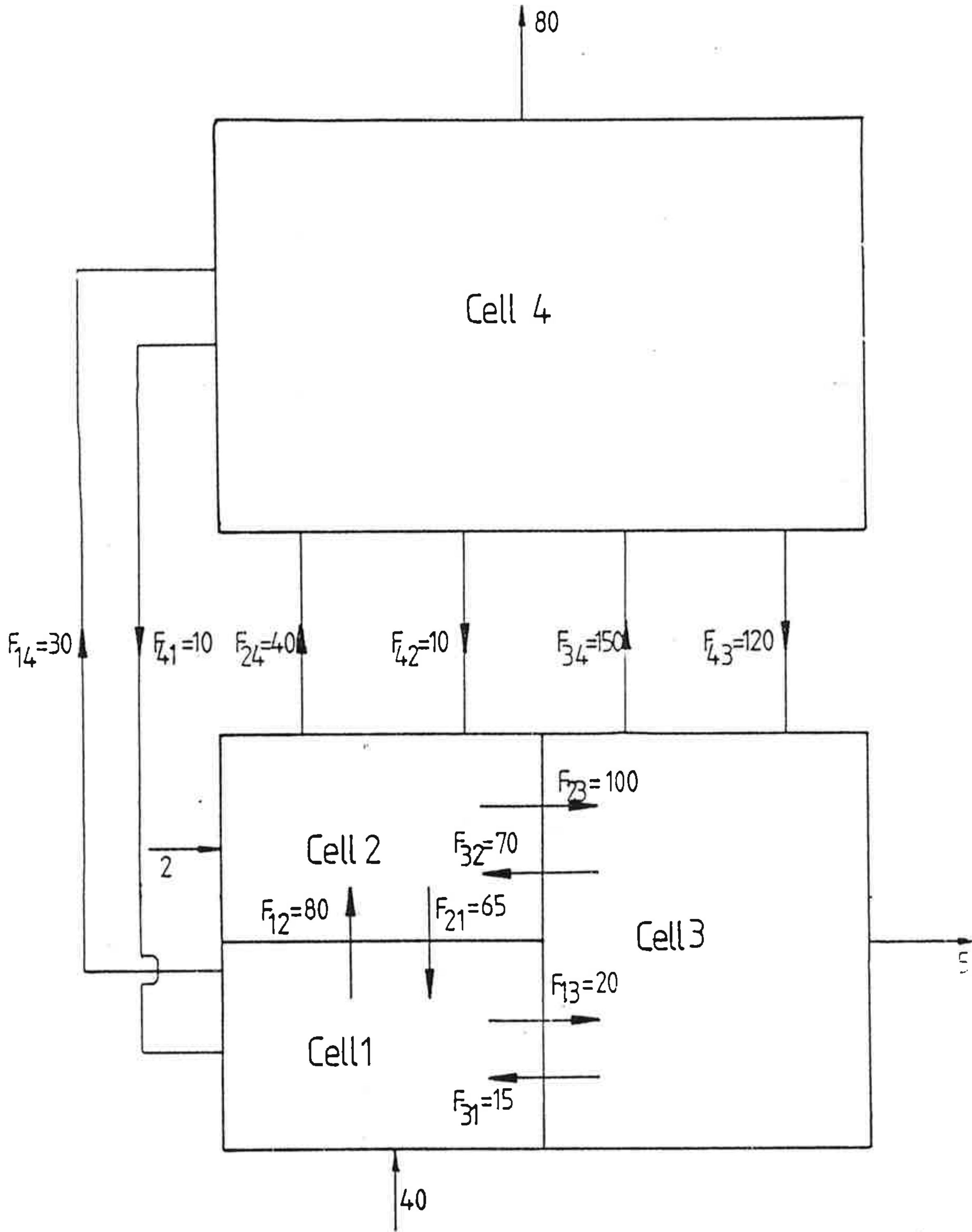


FIGURE 9: Test results