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Use of a single tracer gas for measurement of ventilation rates in a large enclosure

J. Dewsbury

Department of Building
University of Manchester Institute of Science and Technology
Manchester
M60 1QD
England

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SYNOPSIS

This paper describes a preliminary investigation of the validity of a means of calculating the ventilation rate of a large enclosure from experimental data.

It was assumed that the air in the enclosure is not perfectly mixed. The measurement method selected was tracer gas concentration decay. The calculation of ventilation rate was performed by "least squares" fitting of a model to the observed tracer gas concentrations.

Simulations of tracer gas concentration decay measurements were performed with varying initial distribution of tracer gas. The ventilation rate was then calculated from the simulated concentration data.

Conclusions are drawn concerning the accuracy of such calculations and general strategy for meauring ventilation rates using tracer gases.

LIST OF SYMBOLS

C_n	Tracer gas concentration in zone n (zone 0 = outside air)
N	Total number of zones
Q_{mn}	Air flow rate from zone m to zone n
Q^1_{mn}	Air flow rate from zone m to zone n calculated from tracer gas concentration data
t	Time
V_n	Volume of zone n

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1 INTRODUCTION

The measurement of ventilation rates in small enclosures using tracer gas is a well understood and proven technique of ventilation research. The use of tracer gases for measurement of ventilation rates and air movements in large enclosures and multi-cell buildings, typical of factories and office buildings, is not yet at the same stage of development.

A paper presented by the present author at the 4th Air Infiltration Centre Conference[1] described work aimed at measuring ventilation rates in large enclosures for the purpose of estimating ventilation energy loss. The work was not intended to study internal air movements or their implications for air quality.

An instrument system was described which consisted of infra-red gas analysers for the measurement of nitrous oxide concentrations, sampling valves and automatic control and data recording equipment. The fundamentals of a method for calculating ventilation rates from measured data were described and a programme for validation of the measurement and analysis methods proposed.

This paper reports the results of calculating ventilation rates from simulated tracer gas concentration histories and compares the calculated ventilation rates with those assumed for the simulation.

2 SIMULATION AND VENTILATION RATE CALCULATION METHODS

2.1 Simulation Model

The model used for the generation of simulated tracer gas concentration data is shown in figure 1. The model consists of nine zones, which may represent parts of a large enclosure or cells of a multi-cell building. It is assumed that each zone is well mixed. The volumes of the zones and the air flow rates between them are shown in figure 1. These zone volumes and air flow rates were selected so as to give a pattern of tracer gas concentration decay similar to patterns which have been found in practice[4].

The simulation of the tracer gas concentration histories was performed by calculating, for each zone in turn, the net gain or loss of tracer gas over a short period of time assuming that the concentrations in all zones are constant. The new concentrations in the various zones were then calculated from the adjusted quantities of tracer gas.

The initial tracer gas concentrations assumed are given in table 1. The concentration in the outside air is taken to be zero at all times.

The results of the simulations are shown in figures 2, 3 and 4.

2.2 Ventilation Rate Calculation Method

This method is adapted from that described by Penman and Rashid [2] .

The general equation governing the tracer gas concentrations within the space is:

Rate of supply of gas - Rate of removal of gas
= Rate of change of quantity of gas in the space

The easiest ventilation rate measurement method to use is the concentration decay method, in which:

Rate of supply of gas = 0

The rate of removal of gas from the space is simply the sum of the air flow rates from each zone to the outside, each multiplied by its appropriate tracer gas concentration:

$$Q_{10} C_1 + Q_{20} C_2 + \cdots\cdots + Q_{NO} C_N$$

$$= \sum_{n=1}^{N} Q_{no} C_n$$

The rate of change of the quantity of tracer gas in the space is the sum of the volumes of the zones each multiplied by the appropriate rate of change of tracer gas concentration:

$$V_1 \frac{dC_1}{dt} + V_2 \frac{dC_2}{dt} + \cdots\cdots + V_N \frac{dC_N}{dt}$$

$$= \sum_{n=1}^{N} V_n \frac{dC_n}{dt}$$

Thus

$$0 - \sum_{n=1}^{N} Q_{no} C_n = \sum_{n=1}^{N} V_n \frac{dC_n}{dt}$$

If this equation is integrated the effect of random fluctuations in C_n will be reduced without the need for fitting curves to the data. Integrating from time t_o to t_1 the following is obtained:

$$- \sum_{n=1}^{N} Q_{no} \int_{t_o}^{t_1} C_n \, dt = \sum_{n=1}^{N} (V_n (C_{n}, t_1 - C_{n}, t_o)) \qquad (1)$$

In this equation Q_{no} are unknown (assumed constant), C_n are measured and V_n are estimated.

In order to form N different equations which can be solved to find the N unknowns Q_1, Q_2 ..... Q_N, equation (1) can be integrated over N time intervals. If the time intervals are selected to be successive, then in the later stages of a concentration decay measurement independent equations will not be obtained, the (x + 1)th equation being simply a multiple of the xth. This is because the concentration decay in any zone tends to the form

$$C_n = A_n e^{(-B_n t)}$$

where A_n and B_n are constants for zone n. The N equations were therefore formed by integrating equation (1) from the beginning of the experiment to N different values of time.

The N equations can be represented in matrix form as:

$$-[C][q] = [b]$$

where:

$$C_{m,n} = \int_{t=o}^{t_m} C_n \, dt$$

$$q_m = Q_{no}$$

and
$$b_m = \sum_{n=1}^{N} (V_n (C_{n,t_m} - C_{n,o}))$$

Experimental errors will mean that an exact solution of these equations is not possible. The equations can be solved in a least squares sense by minimising the length of the residual vector r , where:

$$[r] = [b] + [C][q]$$

Routines are available in the NAG computer program library to perform this operation without the constraint derived from physical considerations that:

$$Q_{no} \geqslant 0$$

for all n. NAG library routines were used for the calculations for the sake of convenience and in order to see how frequently negative values of Q_{no} were generated. In a practical case the presence of large negative values of Q_{no} might suggest poor accuracy.

3 RESULTS OF CALCULATIONS

Table 1 gives the initial tracer gas concentrations assumed for the calculations. Tables 2, 3 and 4 give the calculated exfiltration rates from each zone compared with the exfiltration rates used in the simulation for experiments 1, 2 and 3 respectively. For each experiment the exfiltration rates were calculated four times, using data from 9, 4.5, 1.8 and 0.9 hours of the experiment respectively. These times should be compared with the reciprocal of the model's ventilation rate i.e. 1.25 hours.

Three errors have been calculated. The percentage error in each zone exfiltration rate was calculated as:

$$\frac{100\ (Q^1_{no} - Q_{no})}{\Sigma Q_{no}}$$

The percentage error in the total exfiltration rate was calculated as:

$$\frac{100\ (\Sigma Q^1_{no} - \Sigma Q_{no})}{\Sigma Q_{no}}$$

The percentage total squared error was calcuated as:

$$\frac{100\ (\Sigma (Q^1_{no} - Q_{no})^2)}{\Sigma (Q_{no})^2}$$

Examination of the tables suggests a number of conclusions.

Firstly, the total exfiltration rate was generally calculated with an accuracy sufficient for practical purposes, only 2 cases out of 12 being worse than ± 25%. As it is the total exfiltration (ventilation) rate which is mainly of interest for energy conservation purposes these results can be regarded as encouraging. It may be thought that these errors are rather large considering that the calculations were performed using simulated data, but it must be remembered that the equations used by the calculations were not fully independent. The two cases of unsatisfactory accuracy occured in the 9-hour calculation in Experiment 1 and the 0.9 hour calculation in Experiment 2. In the former case the loss of accuracy could be expected to result from the combination of uniform initial tracer distrubution and long calculation period leading to the exponential concentration decays mentioned in section 2.2 The latter result is surprising considering the similarity of the plotted tracer concentrations for experiments 2 and 3.

Secondly, the presence of negative calculated flow rates did not indicate poor accuracy either of the total ventilation rate or of the individual flow rates, as quantified by the error terms at the bottom of the tables. There seems therefore to be no advantage in using an unrestrained solution, whereas it has the disadvantage that negative flow rates have no physical meaning.

Thirdly, the individual zone exfiltration rates were generally predicted with rather poor accuracy.

Fourthly, provided unreasonably short measurement periods were avoided (0.9 hour calculation of Experiment 2), uniform initial distribution of the tracer gas did not improve the accuracy of the calculations. This means that in a space where poor mixing exists naturally, the tracer gas can be released at a known site or sites and provided that these partake in the general air circulation in the space then useful experimental data should be obtained. Artificial mixing will not be required.

4 DISCUSSION AND CONCLUSIONS

It is not difficult to produce good mixing in practice in small rooms by the use of oscillating fans, indeed good mixing often occurs naturally. Thus the representation in the model presented here of each zone as well mixed can accord well with reality when the zones represent the rooms of a multi-cell building. In a large enclosure, however, good mixing does not always occur[1,3,4,5]. The division of a large enclosure into a number of well-mixed zones constitutes an approximation to the real situation of a continuously varying concentration field. If a larger number of zones is used in the model better approximation to reality is attained, but the complexity of the analysis increases and the number of measurement points required in an actual experiment also increases if the concentrations in all zones are to be measured. It is this latter, practical, constraint which is the most severe.

If the initial distribution of tracer gas is not uniform then the tracer gas concentrations at the various sampling points vary rapidly both in time and space during the early part of a measurement[1]. The assumption of well-mixed zones may thus introduce considerable inaccuracy into the measurement of the quantity of tracer gas in the space, this being the key variable in the subsequent analysis.

In measuring ventilation rates using tracer gas we can therefore identify two situations. In the first situation, good mixing through the whole building or good mixing of every zone in the building occurs naturally or can be arranged by the investigator. In this case tracer gas experimental techniqes and single or multi-zone calculation methods can be applied with confidence. In the second situation, good mixing does not occur and can not be arranged. It is intended that a future paper will deal with the approximate representation of a continuous tracer gas concentration field.

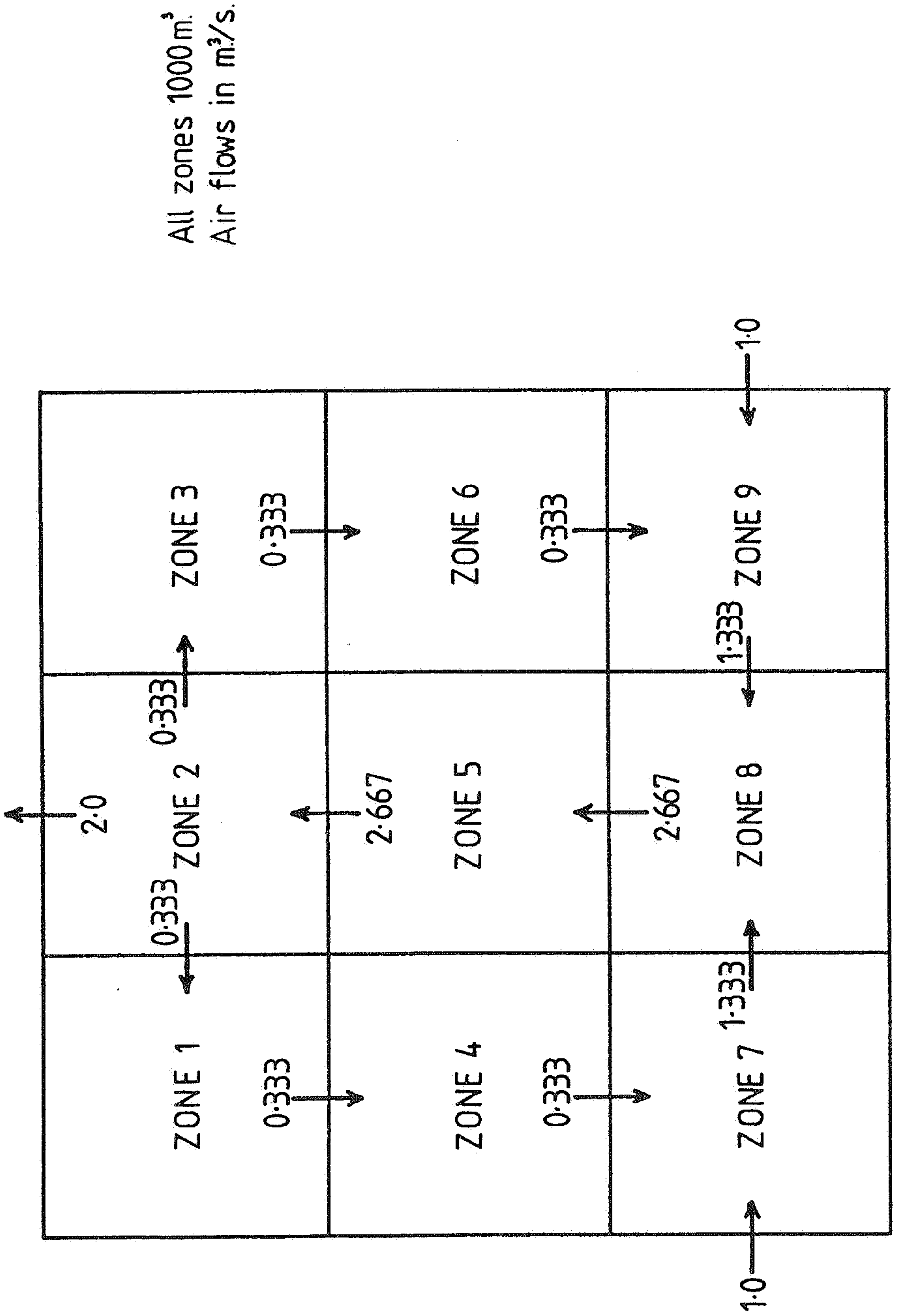
All zones 1000 m³.
Air flows in m³/s.
ZONE 1
ZONE 2
ZONE 3
ZONE 4
ZONE 5
ZONE 6
ZONE 7
ZONE 8
ZONE 9
0·333
0·333
0·333
0·333
0·333
0·333
2·0
2·667
2·667
1·333
1·333
1·0
1·0

Figure 1

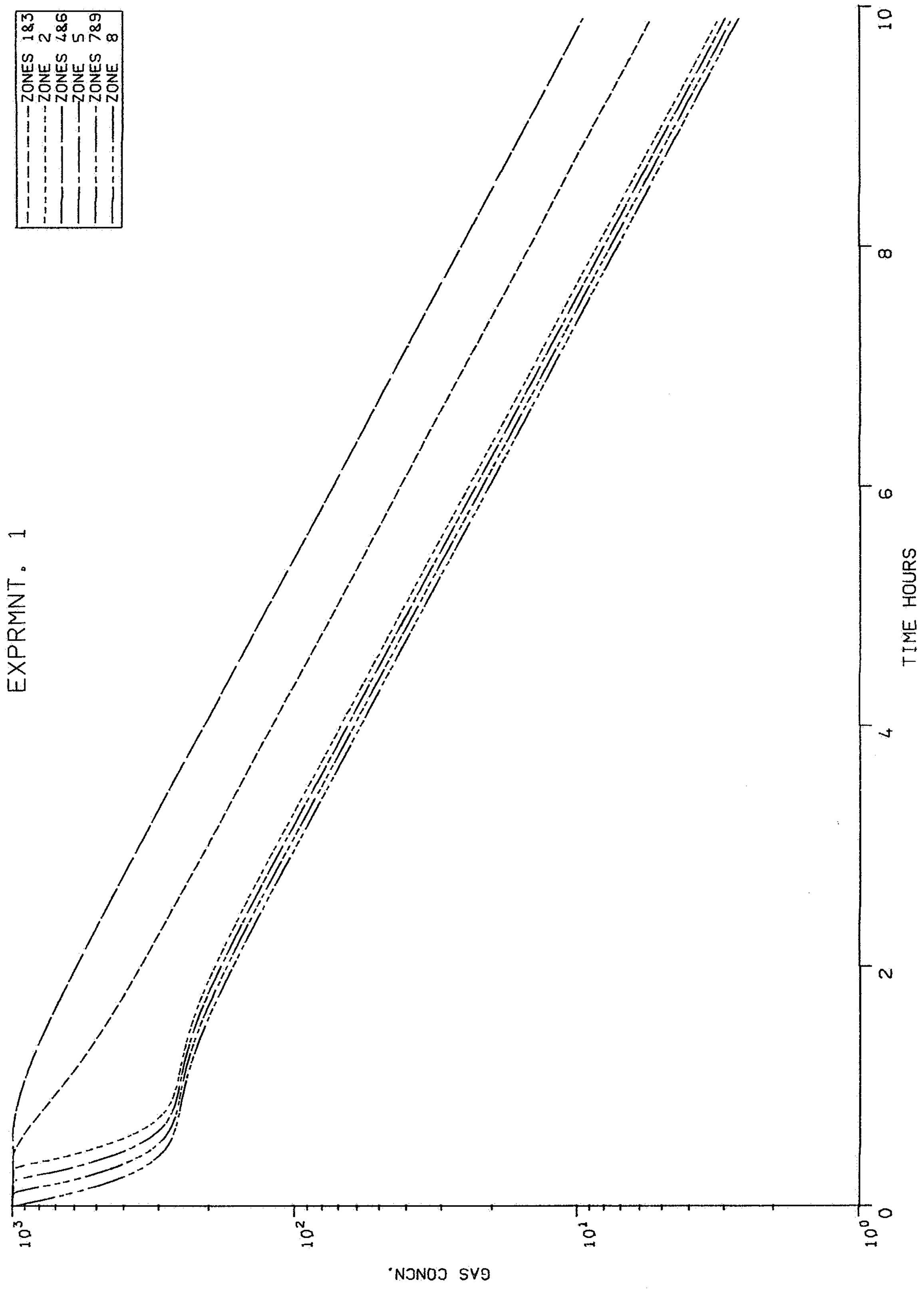
EXPRMNT. 1
ZONES 1&3
ZONE 2
ZONES 4&6
ZONE 5
ZONES 7&9
ZONE 8
GAS CONCN.
10^3
10^2
10^1
10^0
TIME HOURS
0
2
4
6
8
10

Figure 2

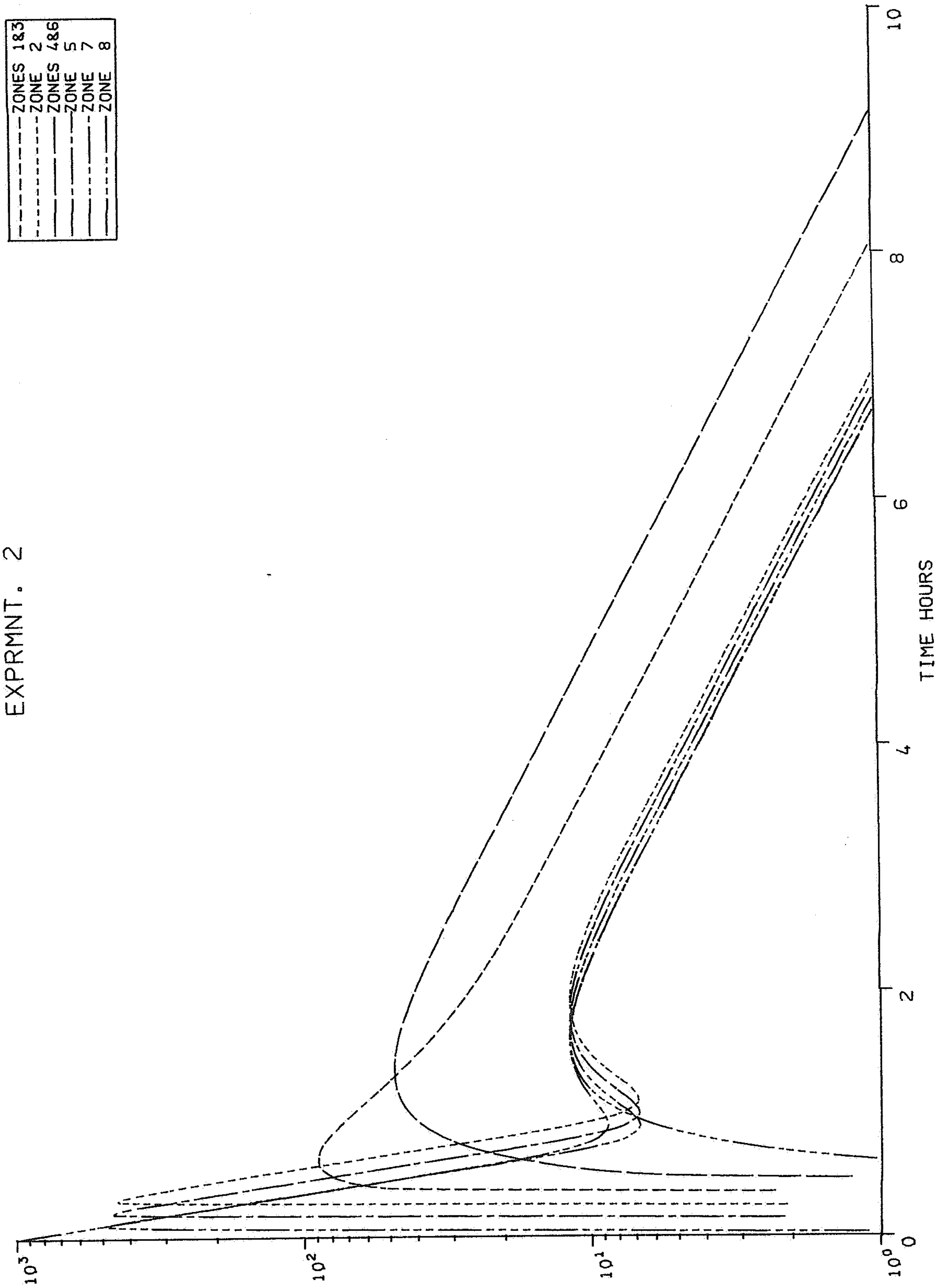
EXPRMNT. 2
ZONES 1&3
ZONE 2
ZONES 4&6
ZONE 5
ZONE 7
ZONE 8
GAS CONCN.
10^3
10^2
10^1
10^0
TIME HOURS
0
2
4
6
8
10

Figure 3

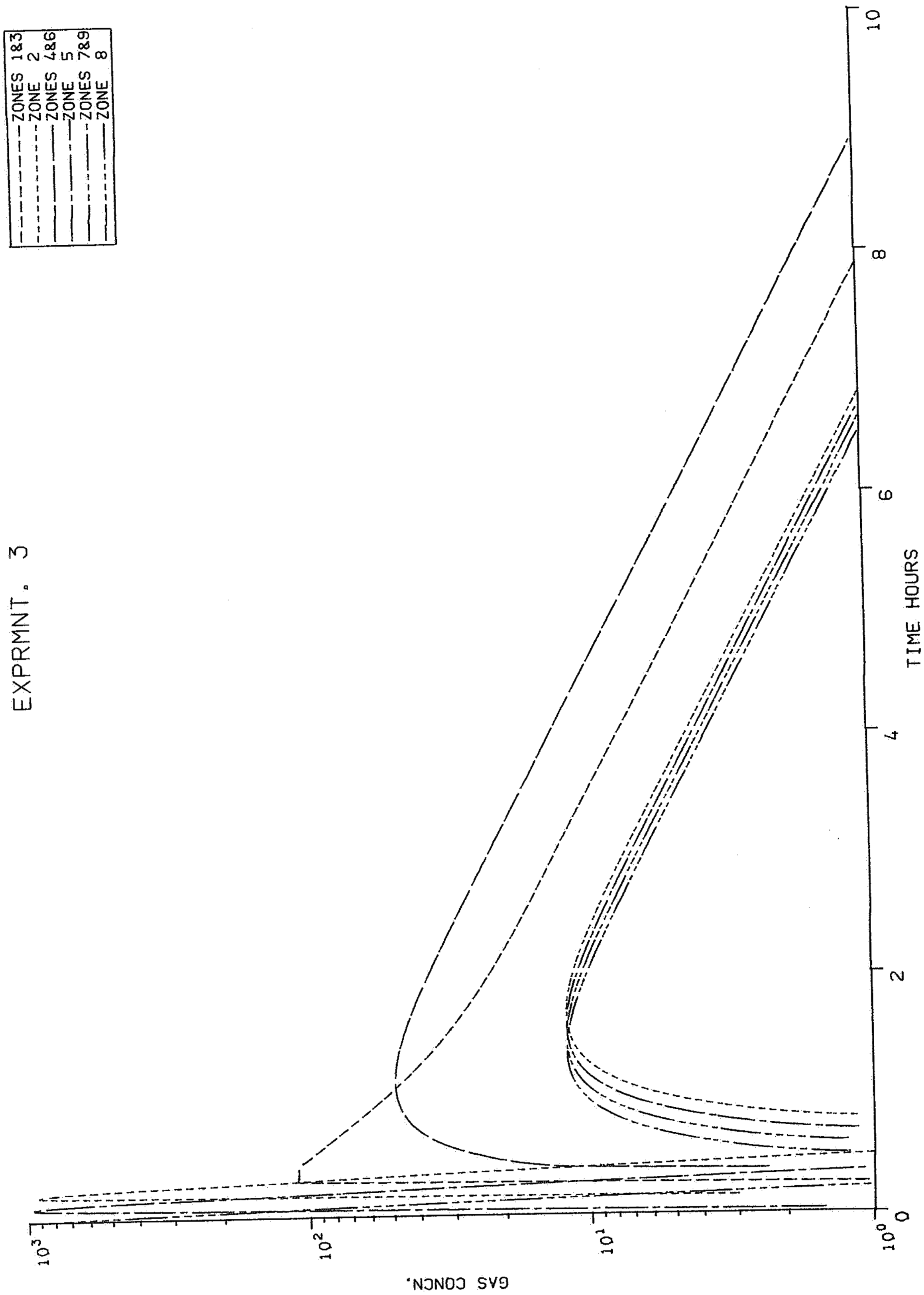
EXPRMNT. 3
ZONES 1&3
ZONE 2
ZONES 4&6
ZONE 5
ZONES 7&9
ZONE 8
GAS CONCN.
10^3
10^2
10^1
10^0
TIME HOURS
0
2
4
6
8
10

Figure 4

TABLE 1

Initial tracer gas distributions for simulations

Zone	Experiment[1]	Experiment[2]	Experiment[3]
1	1000	0	0
2	1000	0	0
3	1000	0	0
4	1000	0	0
5	1000	0	0
6	1000	0	0
7	1000	1000	0
8	1000	0	1000
9	1000	0	0

Units of concentration are arbitrary.

TABLE 2

Assumed and calculated exfiltration rates, Experiment 1

Zone	Actual m^3/h	9 hour calcn		4.5 hour calcn		1.8 hour calcn		0.9 hour calcn	
		Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %
1	0	-79	-1	573	+8	269	+4	1521	+21
2	7200	3889	-46	2551	-65	5222	-27	4334	-40
3	0	-79	-1	573	+8	269	+4	1521	+14
4	0	-471	-7	-515	-7	-55	-1	-1014	-14
5	0	2955	+41	2285	+32	2997	+42	2364	+33
6	0	-471	-7	-515	-7	-55	-1	-1014	-14
7	0	1175	+16	1140	+16	-1136	-16	-562	-8
8	0	2047	+28	1791	+25	342	+5	446	+6
9	0	1175	+16	1140	+16	-1136	-16	-562	-8
Totals	7200	10141	+41	9023	+25	6717	-7	7034	-2
% total squared errors			52		65		30		41

TABLE 3

Assumed and calculated exfiltration rates, Experiment 2

Zone	Actual m^3/h	9 hour calcn Calc m^3/h	9 hour calcn Error %	4.5 hour calcn Calc m^3/h	4.5 hour calcn Error %	1.8 hour calcn Calc m^3/h	1.8 hour calcn Error %	0.9 hour calcn Calc m^3/h	0.9 hour calcn Error %
1	0	-445	-6	174	+2	68	1	761	+11
2	7200	1525	-79	6313	-12	7194	0	6513	-10
3	0	-445	-6	174	+2	68	1	761	+11
4	0	468	+7	-282	-4	-40	-1	-1410	-20
5	0	1477	+21	2979	+41	1042	+14	882	+12
6	0	468	+7	-282	-4	-40	-1	-1410	-20
7	0	1926	+27	-1525	-21	369	+5	83	+1
8	0	1414	+20	486	+7	-1796	-25	-677	-9
9	0	236	+3	121	+2	160	+2	-334	-5
Totals	7200	6624	-8	8158	+13	7025	-2	5169	-28
% total squared errors			79		24		9		13

TABLE 4

Assumed and calculated exfiltration rates, Experiment 3

Zone	Actual m^3/h	9 hour calcn Calc m^3/h	Error %	4.5 hour calcn Calc m^3/h	Error %	1.8 hour calcn Calc m^3/h	Error %	0.9 hour calcn Calc m^3/h	Error %
1	0	-401	-6	106	+1	38	+1	5	0
2	7200	3438	-52	8599	+19	7911	+10	7599	+5
3	0	-401	-6	106	+1	38	+1	5	0
4	0	73	+1	-257	-4	-137	-2	-20	0
5	0	3223	+45	-10	0	-774	11	-378	-5
6	0	73	+1	-257	-4	-137	-2	-20	0
7	0	171	+2	943	+13	430	+6	67	+1
8	0	1730	+24	-1901	-26	54	+1	18	0
9	0	171	+2	943	+13	430	+6	67	+1
Totals	7200	8077	+12	8272	+15	7853	+9	7303	+1
% total squared errors			54		14		3		1

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