4028

THE INFLUENCE OF DOOR SWING AND DOOR VELOCITY ON THE EFFECTIVENESS OF DIRECTIONAL AIRFLOW

E.B. Sansone, Ph.D. **S.D. Keimig, Ph.D.**

ABSTRACT

Directional airflow induced by pressure differentials is used to supplement local exhaust ventilation by controlling the airborne transfer of contaminants. To assess the influence of the direction of door swing (into a room, into a corridor, or along a wall, i.e., a sliding door) and door velocity on the airborne transfer of contamination, the concentration of a tracer gas (ethane) was measured at various locations in a model consisting of four adjacent rooms between two corridors. Ethane concentrations were measured with a hydrocarbon analyzer as a function of pressure differential, direction of door swing, time of door opening and closing, and door velocity. Contamination was transferred in the direction of decreasing static pressure. Opening and closing a door led to exchange of air between the spaces separated by the door regardless of the direction of induced airflow that existed when the door was closed. The extent to which a space was contaminated by opening and closing a door was directly proportional to the time the door was open. Less contamination was transferred when doors opened in the same direction as the airflow induced by the pressure differential than when doors opened against the airflow. Less contamination was transferred when doors were opened slowly; the velocity of door closure had less effect. The protection provided by directional airflow can be increased considerably by making simple alterations in door construction and work practices.

INTRODUCTION

Directional airflow, directing the flow of air by means of differential air pressures from areas of lower contamination to areas of higher contamination, is used to supplement primary containment devices such as local exhaust hoods. The use of directional airflow has been recommended to reduce the risk of personnel exposure to potentially hazardous agents (Jonas 1965; Barkley 1978; NIH 1981; NIH/CDC 1984); its usefulness has been demonstrated in full-scale facilities (Sullivan and Songer 1966; Hambraeus and Sanderson 1972; Foord and Lidwell 1975) and in models (Bouwman 1975; Keene and Sansone 1984; Keimig et al. 1987).

This paper presents the results of experiments designed to determine the effect of the direction of door swing (into or out of a room) and door velocity on the transfer of airborne contaminants.

METHODS

Experiments were performed in a poly(methyl methacrylate) model consisting of four rooms and two corridors (Figure 1). Rooms had spring-loaded doors centered in the short walls of the room. The door frame was gasketed and greased to ensure a good seal. The apparatus corresponded to a scale model of a portion of an existing facility.

E. B. Sansone, Director, Environmental Control and Research Program, and S.D. Keimig, Senior Research Scientist, Environmental Research Section, NCI-Frederick Cancer Research Facility, Frederick, MD.

To allow for ventilation, introduction of tracer, sample collection, and pressure and flow measurement, there were vents in the ceiling and floor of the rooms and corridors and holes in the doors to the rooms. The model was ventilated by drawing air from the laboratory through dust filters into the model and out through external vacuum lines or a hydrocarbon analyzer. Each room and corridor was provided with individual, volumetrically controlled exhaust and supply air. Airflow rates were measured using calibrated rotameters. Pressure differentials were independently established in each room by adjusting supply airflow rate. Directional airflow, induced by the pressure differential, was from the clean corridor to the room and then to the dirty corridor. Magnehelic gauges were used to monitor pressure differential.

Ethane was used as the contaminant because its molecular weight (30.07) is close to that of air (28.96) and it is readily quantitated using a hydrocarbon analyzer. Introduction of the tracer into the model was accomplished by passing the gas through a needle valve that delivered approximately 2.5 ml ethane/min through a fritted glass diffuser within a model room (room 3) at a height corresponding to a spill at bench top level. Samples were collected at a height approximating breathing level.

Contaminant analysis was performed using a flame ionization detector with a 100% hydrogen fuel accessory and a potentiometric recorder. With this system 0.1 ppm ethane could be reliably detected. During an experiment, the ethane concentration in the room under study was monitored continuously. The amount of ethane transferred was measured by integrating the area under the ethane concentration versus time curve. This quantity was used as the denominator of a ratio, the numerator of which was the area under the ethane concentration versus time curve for room 3 obtained contemporaneously. The ratio thus represents the relative effectiveness in preventing contamination transfer, a large ratio indicating better protection than a small one.

Experiments were designed to reveal how the tracer was transported through the model system under various conditions of pressure differentials and door manipulations. In all experiments, after appropriate pressure differentials were established, room 3 was contaminated with ethane. When a steady-state had been reached (i.e., ethane concentration constant), usually 600-800 ppm in the contaminated room, ethane concentrations were measured in other rooms and/or in the corridor. Experiments were performed with air flow from corridor to rooms (clean corridor) or with air flow from rooms to corridor (dirty corridor). The experiments are described in more detail below.

<u>Airflow from Corridor to Rooms (Clean Corridor)</u>

After establishing pressure differentials and with all doors closed, room 3 was contaminated at a constant rate until steady-state concentrations were reached. Samples were taken from the other rooms and the corridor.

After establishing pressure differentials, all doors to the (positive) corridor were opened. Room 3 was contaminated at a constant rate until steadystate concentrations were reached. Samples were taken from the other rooms and the corridor. (This experiment was also performed with air flow from rooms to corridor and under neutral conditions, i.e., with no flow in either direction.)

After establishing pressure differentials and with all doors closed, room 3 was contaminated at a constant rate until a steady-state concentration was reached. The door between the contaminated room and the (positive) corridor was opened and closed after six seconds. The amount of contamination transferred to the other rooms was measured with the door opening inward (into the room) and outward (into the corridor).

After establishing pressure differentials, the doors between rooms 1, 2, and 4 and the clean corridor were opened and room 3 was contaminated at a constant rate until steady-state conditions were reached. The door between the contaminated room and the (positive) corridor was opened and closed after six seconds. The amount of contamination transferred to the other rooms was measured with the doors opening inward and outward.

<u>Airflow from Rooms to Corridor (Dirty Corridor)</u>

After establishing a pressure differential of 0.02 in H_2O and with all doors closed, room 3 was contaminated at a constant rate until steady-state concentrations were reached. (Because the corridor was negative to the rooms, the corridor was also contaminated.) To establish whether room-to-room differences could be observed, a series of experiments were performed in which the doors to rooms 1, 2, and 4 were opened and closed after three and six seconds and the amount of contamination transferred to the room was measured.

After establishing pressure differentials and with all doors closed, room 3 was contaminated at a constant rate until steady-state concentrations were reached. The door of an uncontaminated room (room 2) was opened and closed after three, six, or nine seconds and the amount of contamination transferred into the room was measured as a function of pressure differential between the contaminated room and the corridor, the uncontaminated room and the corridor, and the direction of door swing.

After establishing pressure differentials and with all doors closed, room 3 was contaminated at a constant rate until steady-state concentrations were reached. The door between room 2 and the negative corridor was opened into the room and closed after six seconds. The amount of contamination transferred to room 2 was measured for two door velocities: slow, where opening or closing the door required 3 seconds; and fast, about 3/4 seconds. With the exception of certain door velocity tests, the remaining tests were performed using the fast door velocity.

RESULTS

Air flow from corridor to rooms (clean corridor): As long as the door to the contaminated room remained closed and the pressure in the contaminated room was less than that in the corridor, ethane could not be detected in any of the other rooms or in the corridor. However, when the doors were opened after pressure differentials had been established and one room was contaminated, ethane was transferred from the contaminated room to the corridor and to all the other rooms. Table 1 shows the ratio of the steady-state concentration of ethane in the contaminated room to that in the other rooms and the corridor for corridor-to-room pressure differentials ranging from 0.01 to -0.01 in water. (Note: Larger ratios indicate less contamination transfer.)

If the door to the contaminated room was opened and closed after steady-state conditions had been reached in the room, ethane was transferred from the room to the corridor and to all the other rooms. Table 2 shows the ratio of steady-state ethane concentration in room 3 to the total amount of ethane transferred to each room as a function of pressure differential, direction of door swing, and door position (open or closed).

Air flow from rooms to corridor (dirty corridor): When the doors to rooms 1, 2, or 4 were opened and closed after three and six seconds, the amount of ethane transferred to the rooms varied from 2.7 to 5.5 ppm. These data were subjected to statistical analysis; no significant room-to-room differences were observed.

Table 3 shows the ratios of steady-state ethane concentration in room 3 to total ethane transferred when doors to various rooms were opened and closed after three, six, and nine seconds as a function of the pressure differential between the four rooms and the corridor and the direction of door swing.

The ratios of steady-state ethane concentration in room 3 to the total amount of ethane transferred to room 2 as a function of the velocity of door opening and closing are shown in Table 4.

DISCUSSION

The first series of experiments, with the corridor positive to the rooms, showed that, if the doors remained closed, contamination of the clean corridor and adjacent rooms would not occur. If doors were left open, however, directional air flow did not prevent contamination of the corridor and the adjacent rooms (Table 1). These data also showed the ratio of the steady-state concentration of ethane in the contaminated room to that in each of the other rooms and the corridor was essentially constant for pressure differentials ranging from 0.01 to -0.01 inches of water. The corridor was most contaminated, while the rooms adjacent to the contaminated room were less contaminated but to about the same extent, and the most remote room was least contaminated.

When the door to the contaminated room was opened and closed after six seconds, each room became contaminated (Table 2). These data showed that the direction of door swing was strongly associated with contamination transfer. When the test room doors were closed, the transfer occurring with the door to room 3 opening into the room was significantly (α=0.01) lower than that with the door opening into the corridor. On the average, 38% more contamination was transferred when the door opened into the clean corridor.

Considerably more contamination was transferred to the test rooms when the doors of rooms 1, 2, and 4 were held in the open position (Table 2). Again, significantly increased protection (α=0.01) was obtained with the door to room 3 opening into the room, but in this case, 26% more contamination was transferred when the door opened into the corridor.

Significant differences were also observed between the amount of contaminant transferred to the three test rooms. This phenomenon may be attributed to two factors: the distance of the test room from the source room and the vane effect of the opened source room door. For those tests where doors were opened outward, the open door of room 3 served as a vane to direct contaminated air toward rooms 1 and 2. Consequently, one would expect room 4 to receive less contamination, as was generally observed. In contrast, the experiments conducted with doors opening inward should not be influenced by the vane effect; room-to-room variability should be governed by distance from the source room. Room 1, the farthest from room 3, generally showed the lowest level of contamination. A similar observation concerning the influence of door swing on contamination was made in connection with floor contamination in a double corridor animal facility (Sansone et al. 1977).

When doors were closed, protection showed a linear inverse relationship ($p<10^{-4}$) to pressure differential; no linear relationship was observed in the open door experiments. While the closed door data appear to indicate that increasing the pressure differential decreases protection, this is a result of the way air is exhausted from the corridor of the model. In our experiments, the volume of air exhausted from the corridor was constant; the quantity of supply air was varied to obtain the desired pressure differential. To increase the pressure differential, more air was supplied to the corridor and, therefore, more air passed from the corridor to the rooms through the vent holes in the doors. Assuming that a constant volume of contaminated air was transferred from room 3 to the corridor each time the door to room 3 was opened and closed, as the pressure differential was increased, more contaminated air would be transferred from the corridor to the rooms. When the data of Table 2 are adjusted for this effect, the statistically significant association between protection and pressure differential disappears.

One method of establishing directional airflow is to provide the clean corridor with supply air but no exhaust ventilation. In this case, the total amount of contamination entering the rooms would be independent of pressure differential and the negative association of protection with pressure differential should disappear.

These data indicate that doors should remain closed to reduce contamination and that the rooms at greatest risk of cross-contamination when the corridor is positive to the rooms are the rooms immediately adjacent to the contaminated room.

The second series of experiments was designed to examine the airborne transfer of contaminants when the corridor was negative to the rooms. The first experiments performed with this configuration of pressure differentials showed that there were no significant ($p = 0.33$) room-to-room differences. We believe this was the case because, at steady-state, the entire length of the corridor was contaminated uniformly so it was immaterial which room door was opened. However, this will not be true in the case of a relatively short release, which will not allow steady-state conditions to be reached in the corridor.

The effect of varying the pressure differentials from room 3 to the corridor and from rooms 1, 2, and 4 to the corridor and the time the doors to rooms 1, 2, and 4 were opened was examined (Table 3). Statistical analysis of the data in Table 3 showed that more contamination was transferred the longer a door was left open ($p < 0.001$) and a lower pressure differential from the contaminated room (room 3) to the corridor offered more protection ($p < 0.001$). The observed effect of time of door opening is in accord with one's intuition, and the other finding is consistent with the data obtained when the air flow was from the corridor to the rooms (Table 2). The pressure differential between room 2 and the corridor also had a highly significant effect ($p < 0.001$) on the results when doors were opened outward. In this case, the higher pressure differentials usually resulted in increased protection, presumably because the removal of contaminated air from room 2 was more rapid due to the higher pressure differential. However, no significant linear association of contamination with the pressure differential between the test rooms and the corridor was found for inward door data.

The data of Table 3 show that in most cases greater protection from contamination transfer occurred when test room doors opened into the contaminated corridor. In no case was substantially greater protection provided when doors opened into the room. This observation of greater protection with doors opening into the corridor is not in disagreement with the clean corridor experiments (Table 2), where doors opening into the room provided higher protection. Note that in both cases, contamination transfer was least when the door was opened in the same direction as the airflow induced by the pressure differential.

When a door is opened between two spaces, the pressure behind the door (i.e., the side away from the direction of motion) is reduced by a function related to the density of the fluid and the velocity of the door's motion. The extent to which there is transfer of fluid from one side of the door to the other will be greater or less depending upon the direction and magnitude of the pressure differential across the doorway. If the direction of door motion is with the pressure differential, the amount of fluid exchanged will be less than if the direction of door motion is against the pressure differential.* Therefore, to minimize the transfer of contamination between adjacent spaces, pressure differentials should be established so that contaminated areas are at relatively lower pressure and the direction of door swing should be in the same direction as the flow of air induced by the pressure differentials.

Analyses of variance established that the velocity of opening and of closing a door are significant ($p<10^{-4}$ and $p = 6 \times 10^{-4}$, respectively) predictors of contamination transfer (Table 4). Opening a door slowly transferred only about 40% of the amount of ethane transferred when the door was opened quickly. Closing a door slowly, however, transferred about 90% of the amount of ethane transferred when the door was closed quickly. These trials were conducted with directional airflow from the rooms into the corridor. It is reasonable to suppose that if directional airflow were reversed and/or if the direction of door swing were reversed, the extent of contaminant transfer would still be influenced by the velocity of door motion.

CONCLUSIONS

A scale model of particular geometry was used. With only four rooms, the end walls must have had some effect on the transfer of contamination and the results observed. At the flow rates used, the rooms were ventilated at about 10 air changes per hour; other flow rates would have led to different concentrations. However, we believe the principles illustrated by the results are valid irrespective of these factors.

Contamination will be transferred in the direction of decreasing static pressure and can be influenced by the size of the pressure differential. Optimal protection is afforded when doors remain closed; opening and closing a door will allow air exchange between the spaces separated by the door. The longer a door is open, the greater the contamination that may be transferred. Doors should open in the same direction as the airflow established by the pressure differential. (This may conflict with building and fire codes.) Doors should be opened and closed slowly to decrease turbulence and, thus, reduce transfer of contaminants. Automatic devices should be installed to limit the velocity of the door. Modification of work practices may be used, but this is a less reliable alternative than automatic devices. The pressure differential of a clean area relative to a contaminated area does not need to be large.

Application of these results to full-scale situations should be done with caution. It should be noted in particular that personnel, equipment, and furniture contribute to turbulence and temperature differentials in real facilities. No attempt to account for these factors has been made.

The results of these experiments indicate that even with properly functioning ventilation systems, pressure differentials, and directional airflow, there is potential for transfer of contamination. This should be borne in mind when designing, evaluating, or operating a facility.

*Esmen, N.A., Graduate School of Public Health, University of Pittsburgh, Personal communication, 3 September 1985.

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TABLE 1
Ratios of Steady-State Ethane Concentration in Room 3 to the Other Rooms and the Clean Corridor for Various Pressure Differentials Established before Opening the Doors to All Rooms

Pressure differential, corridor to room (in H_2O)	Room 3 / Room 1	Room 3 / Room 2	Room 3 / Room 4	Room 3 / Corridor
+0.01	8.9 ± 0.3[A]	3.1 ± 0.1	3.3 ± 0.5	2.1 ± 0[C]
0[B]	9.4 ± 1.3	4.1 ± 0.2	3.8 ± 0.1	2.0 ± 0.1
-0.01	8.4 ± 0[C]	3.8 ± 0.1	3.3 ± 0.1	2.0 ± 0.1

[A]Mean ± standard deviation for three trials.
[B]Less than ± 0.002.
[C]Less than 0.05.

TABLE 2
Ratios of the Area under the Concentration Versus Time Curve for Room 3 to the Area under the Concentration Versus Time Curve for Room 1, 2, or 4

Pressure differential, corridor to room (in H_2O)	Room 1, 2 and 4 doors closed					
	Inward			Outward		
	Room 3 / Room 1	Room 3 / Room 2	Room 3 / Room 4	Room 3 / Room 1	Room 3 / Room 2	Room 3 / Room 4
0.005	4010 ± 620[A]	2080 ± 250	3500 ± 780	1140 ± 150	1510 ± 230	3750 ± 740
0.01	2500 ± 420	1350 ± 360	1820 ± 240	770 ± 54	960 ± 130	2800 ± 500
0.02	1390 ± 300	760 ± 150	1300 ± 110	780 ± 35	680 ± 68	1220 ± 160
	Room 1, 2 and 4 doors open					
	Inward			Outward		
	Room 3 / Room 1	Room 3 / Room 2	Room 3 / Room 4	Room 3 / Room 1	Room 3 / Room 2	Room 3 / Room 4
0.005	650 ± 140	420 ± 65	300 ± 44	500 ± 75	340 ± 53	420 ± 71
0.01	550 ± 60	540 ± 120	360 ± 50	390 ± 81	250 ± 40	370 ± 94
0.02	510 ± 28	660 ± 130	310 ± 66	370 ± 60	290 ± 40	480 ± 76

[A]Mean ± standard deviation for two or more trials; larger ratios indicate less contamination transfer.

TABLE 3
Ratios of the Area under the Concentration Versus Time Curve for Room 3 to the Area under the Concentration Versus Time Curve for Room 1, 2, or 4

Pressure differential, room 3 to corridor (in H_2O)	Time of door opening (sec)	Pressure differential, rooms 1, 2, and 4 to corridor (in H_2O)			
		0[A]	0.005	0.01	0.02
0.005	3	2330 ± 990[B]	1930 ± 330	1930 ± 710	1920 ± 180
			(4050 ± 940)[C]	(5520 ± 570)	(4060 ± 250)
	6	1370 ± 400	1540 ± 210	1520 ± 280	1450 ± 120
			(3060 ± 250)	(3770 ± 780)	(3490 ± 600)
	9	1130 ± 350	1320 ± 330	1310 ± 360	1490 ± 180
			(2560 ± 210)	(2270 ± 210)	(2800 ± 370)
0.01	3	1480 ± 590	1770 ± 250	1600 ± 390	1760 ± 280
			(1550 ± 210)	(1740 ± 100)	(1930 ± 90)
	6	1000 ± 210	1440 ± 380	1390 ± 350	1320 ± 200
			(1160 ± 63)	(1430 ± 120)	(1670 ± 230)
	9	800 ± 160	1050 ± 230	1130 ± 270	1270 ± 190
			(1060 ± 55)	(1130 ± 170)	(1360 ± 51)
0.02	3	690 ± 240	910 ± 240	720 ± 260	860 ± 210
			(730 ± 38)	(1140 ± 93)	(890 ± 120)
	6	570 ± 200	750 ± 140	710 ± 210	760 ± 270
			(620 ± 81)	(850 ± 57)	(750 ± 55)
	9	540 ± 200	630 ± 110	620 ± 210	640 ± 150
			(490 ± 30)	(680 ± 39)	(550 ± 30)

[A]Less than ± 0.002 in. H_2O.
[B]Mean ± standard deviation for four or more trials in each room with doors opening into rooms; larger ratios indicate less contamination transfer.
[C]Values in parentheses are the means and standard deviations for trials in room 2 with the door opening into the corridor.

TABLE 4
Ratios of the Area under the Concentration Versus Time Curve for Room 3 to the Area under the Concentration Versus Time Curve for Room 2

Pressure differential, room 3 to corridor (in H_2O)	Pressure differential, room 2 to corridor (in H_2O)	Door closing velocity	Door opening velocity: Slow[A]	Door opening velocity: Fast[A]
0.005	0.005	slow	3610 ± 1060[B]	1210 ± 250
		fast	2340 ± 480	1210 ± 410
0.005	0.01	slow	3440 ± 640	1110 ± 280
		fast	3310 ± 980	980 ± 140
0.005	0.02	slow	4150 ± 2600	1670 ± 860
		fast	3470 ± 1520	1400 ± 580
0.01	0.005	slow	2180 ± 910	800 ± 170
		fast	1850 ± 660	620 ± 130
0.01	0.01	slow	3150 ± 1240	900 ± 150
		fast	2090 ± 450	990 ± 260
0.01	0.02	slow	2190 ± 770	840 ± 150
		fast	1830 ± 490	850 ± 90
0.02	0.005	slow	1120 ± 220	390 ± 60
		fast	1090 ± 100	440 ± 100
0.02	0.01	slow	1150 ± 140	490 ± 70
		fast	1140 ± 320	530 ± 70
0.02	0.02	slow	1250 ± 130	510 ± 80
		fast	1270 ± 290	530 ± 100

[A] Slow door motion required 3 seconds; fast door motion required 3/4 seconds.
[B] Mean ± standard deviation for six trials; larger ratios indicate less contamination transfer.

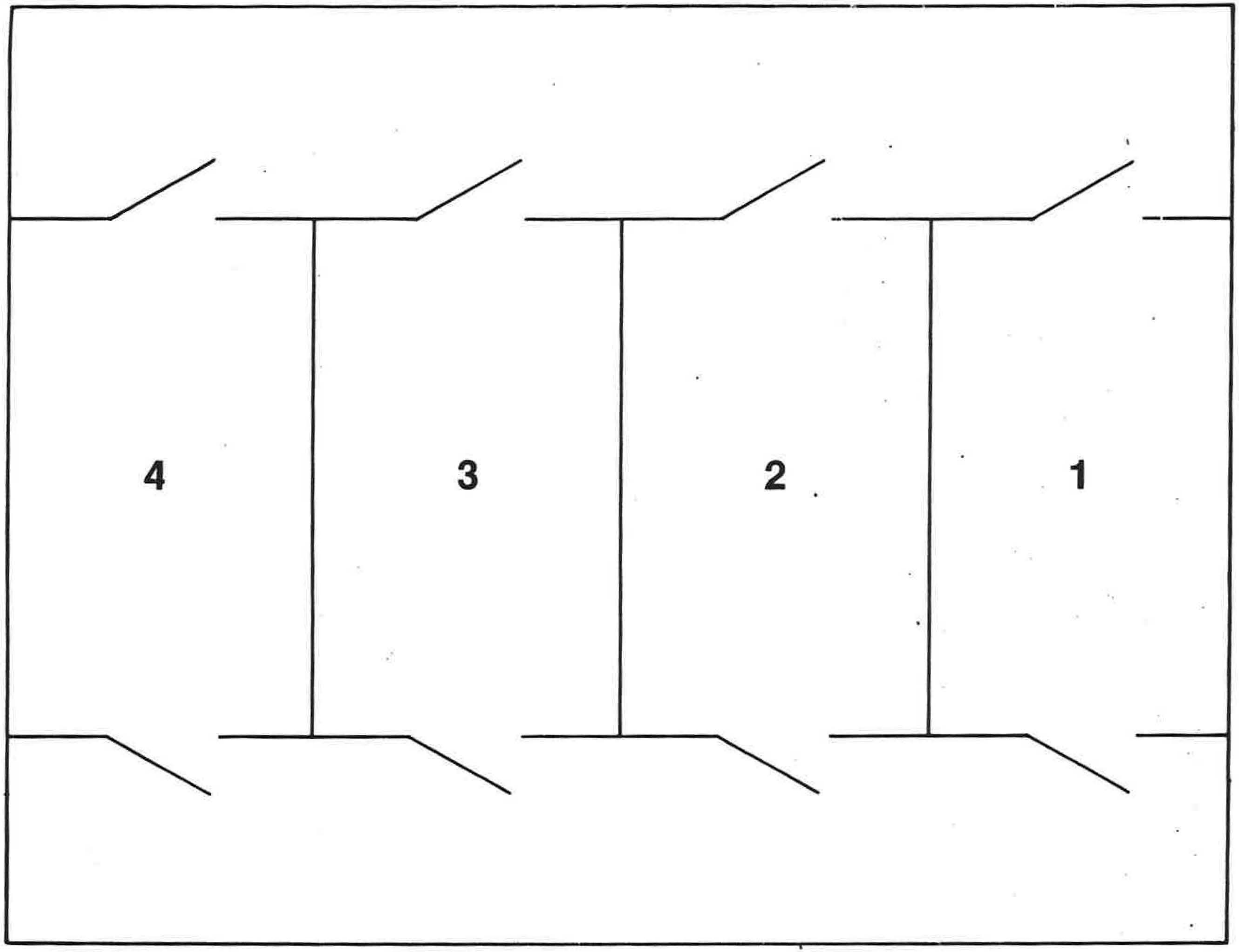

Figure 1. Schematic plan of the model. The numbers identify the rooms referred to in the text. The doors are shown opening into the corridor; for some experiments, the doors opened into the room and were hung from the same side of the jamb.