LBL-10223
EEB-Vent 80-9

THE EFFECTS OF ENERGY-EFFICIENT VENTILATION RATES ON INDOOR AIR QUALITY AT AN OHIO ELEMENTARY SCHOOL

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The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Energy of the U. S. Department of Energy under contract No. W-7405-ENG-48.

TABLE OF CONTENTS

ABSTRACT

The Lawrence Berkeley Laboratory measured the indoor air quality at Fairmoor Elementary School in Columbus, Ohio. A mobile laboratory was used to monitor air outdoors and at three indoor sites (two classrooms and a large multipurpose room); tests were made at three different ventilation rates. The parameters measured were outside air flow rates, odor perception, microbial burden, particulate mass, total aldehydes, carbon dioxide, carbon monoxide, sulfur dioxide, ozone, and nitrogen oxides. This report gives the results of the these measurements and compares them with the existing outdoor air quality standards. Carbon dioxide concentrations increased as the ventilation rate decreased, but still did not exceed current standards. Odor perceptability increased slightly at the lowest ventilation rate. Other pollutants showed very low concentrations, which did not change with reductions in ventilation rate. This study indicates that it would be possible to achieve moderate energy savings at Fairmoor School while maintaining acceptable indoor air quality.

keywords: air pollution, airborne microbes, carbon dioxide, carbon monoxide, energy conservation, indoor air quality, nitrogen oxides,odors, particulate mass, schools, sulfur dioxide, ventilation.

INTRODUCTION

Institutional and commercial buildings together use approximately 15% of the primary energy consumed in the United States. Schools alone account for 3% of energy consumption (about 1.77 x 10^{15} Btu/year). More than half of this energy is used to maintain the comfort of building occupants through heating, cooling, and ventilation (see Figure 1). Since heating or cooling outside air as it enters a building requires a significant amount of energy, considerable energy savings can usually be effected by minimizing the use of outdoor air for ventilation.

Because of their high energy use, much of it for the heating and cooling of outdoor ventilation air, schools have received considerable attention for special energy conservation studies. The U.S. National Energy Act is providing support for energy-conserving retrofits in schools, and the American Association of School Administrators (AASA) initiated a project, "Saving Schoolhouse Energy" which has analyzed energy conservation opportunities in ten elementary schools.[1] Fairmoor Elementary School in Columbus, Ohio, was one of the schools selected by the AASA for this project. The present report discusses the study of the impact of energy-efficient ventilation rates on indoor air quality at that school.

In assessing the effect of reducing the ventilation rate in order to save energy, we must consider both the particular needs for ventilation and the existing codes for building ventilation. In general, ventilation is needed to:

1) Establish a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) in the occupied environment.

2) Remove moisture from internal sources.

3) Dilute human and nonhuman odors to a level below the olfactory threshold.

4) Remove contaminants produced by human activity, construction materials, etc., within tne ventilated space.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has developed a ventilation standard giving recommended and minimum ventilation rates for several types of building spaces. This standard, ASHRAE 62-73, entitled <u>Standards for Natural and Mechanical Ventilation</u>,[2] has been adopted by many states and local governments, and is widely accepted in the United States. Table 1 illustrates the section of ASHRAE Standard 62-73 that applies to schools. Under certain circumstances*, the proportion of outdoor air required to keep the indoor air up to an acceptable standard may be reduced to 15% of the average recommended quantity, but in no case may

(*) Particulate filtering equipment and high-efficiency adsorption or other odor and gas removal equipment must be employed so that air entering the space is purified to meet specified air-quality requirements.

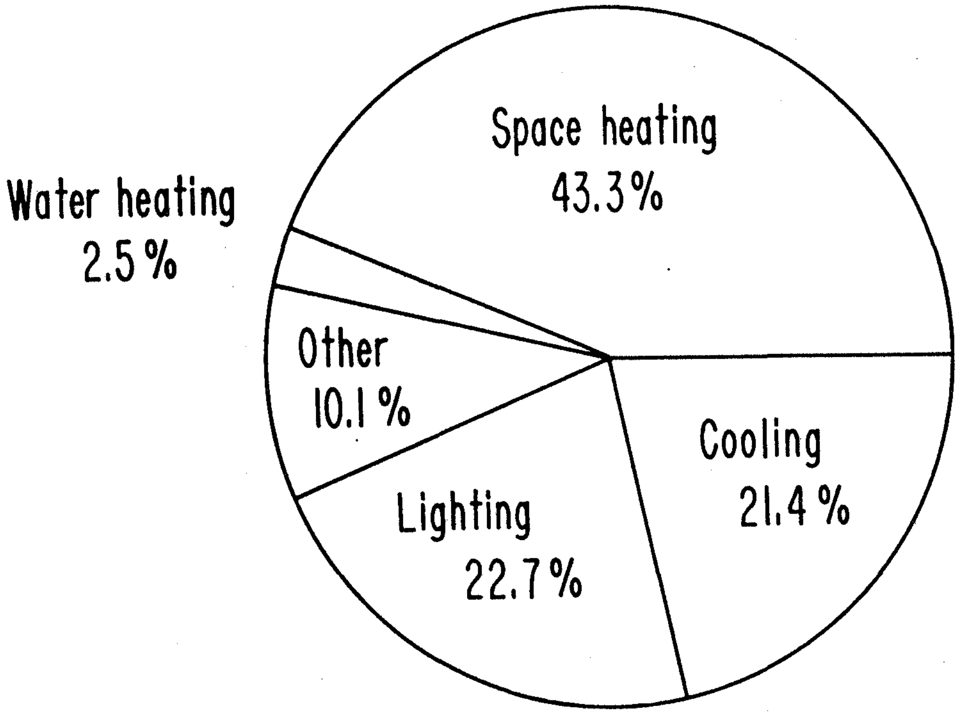

Figure 1. Primary energy use for all non-residential buildings divided into four main functional uses (from Oak Ridge National Laboratory, Commerical Energy Use: A Disagregation by Fuel, Building Type and End Use, ORNL/ ON-14).

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Table 1. Ventilation standards for schools from ASHRAE 62-73.

	Estimated persons/ 1000 sq ft floor area. Use only when design occupancy is not known	Required ventilation air, cubic feet per minute per human occupant, (when the number is bracketed, refer to the notes).		Comments
		Minimum	Recommended	
<u>Schools</u>				
Classrooms	50	10	10-15	
Multiple Use Rooms	70	10	10-15	
Laboratories	30	10	10-15	*
Craft Shops, Vocational Training Shops	30	10	10-15	*
Music, Rehearsal Rooms	70	10	15-20	
Auditoriums	150	5	5-7½	
Gymnasiums	70	20	25-30	
Libraries	20	7	10-12	
Common Rooms, Lounges	70	10	10-15	
Offices	10	7	10-15	
Lavatories	100	15	20-25	
Locker Rooms	20	(30)	(40)-(50)	**
Lunchrooms, Dining Halls	100	10	15-20	
Corridors	50	15	20-25	
Utility Rooms	3	5	7-10	
Dormitory Bedrooms	20	7	10-15	

*Special contaminant control systems may be required
**cfm/locker

the quantity of outdoor air be less than 8.5 m^3/h (5 cfm) per occupant. It appears that the recommended outside air ventilation rates in ASHRAE Standard 62-73 are based largely on the odor research performed over forty years ago by C.P. Yaglou et al.[3] at the Harvard School of Public Health. More recently, a new standard, ASHRAE 90-75R, Energy Conservation in New Building Design,[4] has stipulated that the minimum ventilation rate for each type of occupancy given in ASHRAE 62-73 must be used in designing new buildings. At present, the ASHRAE standard for ventilation air for classrooms in new schools is 16.9 m^3/h (10 cfm) per occupant. A reduction to 8.4 m^3/h (5 cfm) per occupant is permitted if certain air purification equipment is installed so that the incoming air meets specific air-quality levels.

Rising energy costs have generated interest in new ventilation standards for buildings. The Ventilation Group at Lawrence Berkeley Laboratory (LBL) has constructed a mobile laboratory and undertaken a series of field studies at schools. The Fairmoor Elementary School in Columbus, Ohio, was the second school at which field monitoring was conducted to determine the effects of energy-efficient ventilation rates on indoor air quality and on the health and comfort of the occupants. Subcontracts were awarded to The Research Corporation of New England (TRC) for odor studies, and to the Naval Biosciences Laboratory (NBL) for studies on microbial content.

EXPERIMENTAL FACILITIES AND METHODS

The School Building and Mechanical Ventilation System

Fairmoor Elementary School consists of a three-story building constructed in 1949 and a single-story addition built in 1955. The original building contains twelve classrooms, administrative offices, a kitchen, and a lunchroom. The addition has twelve classrooms and a large multipurpose room that functions as both an auditorium and gymnasium. A corridor connects the two buildings.

Heat for the entire school is generated by two identical gas-fired boilers positioned side by side in the basement of the original building. The heat is distributed through the school by circulating steam (in the original building) and hot water (in the addition) to unit ventilators in each room. This system is shown schematically in Figure 2. The single-unit ventilators (Exhibits 1a and 1b) are affixed to external walls. They heat the rooms by passing air around the heating coils; a fraction of the air is drawn from the outside, and the rest is drawn from within the classroom. In each unit ventilator, a pneumatically operated damper regulates the amount of outdoor air entering the classroom. The dampers are controlled by thermostat and temperature sensors, which measure indoor and outdoor temperatures, and by a centrally located timer that controls the daily heating cycle.

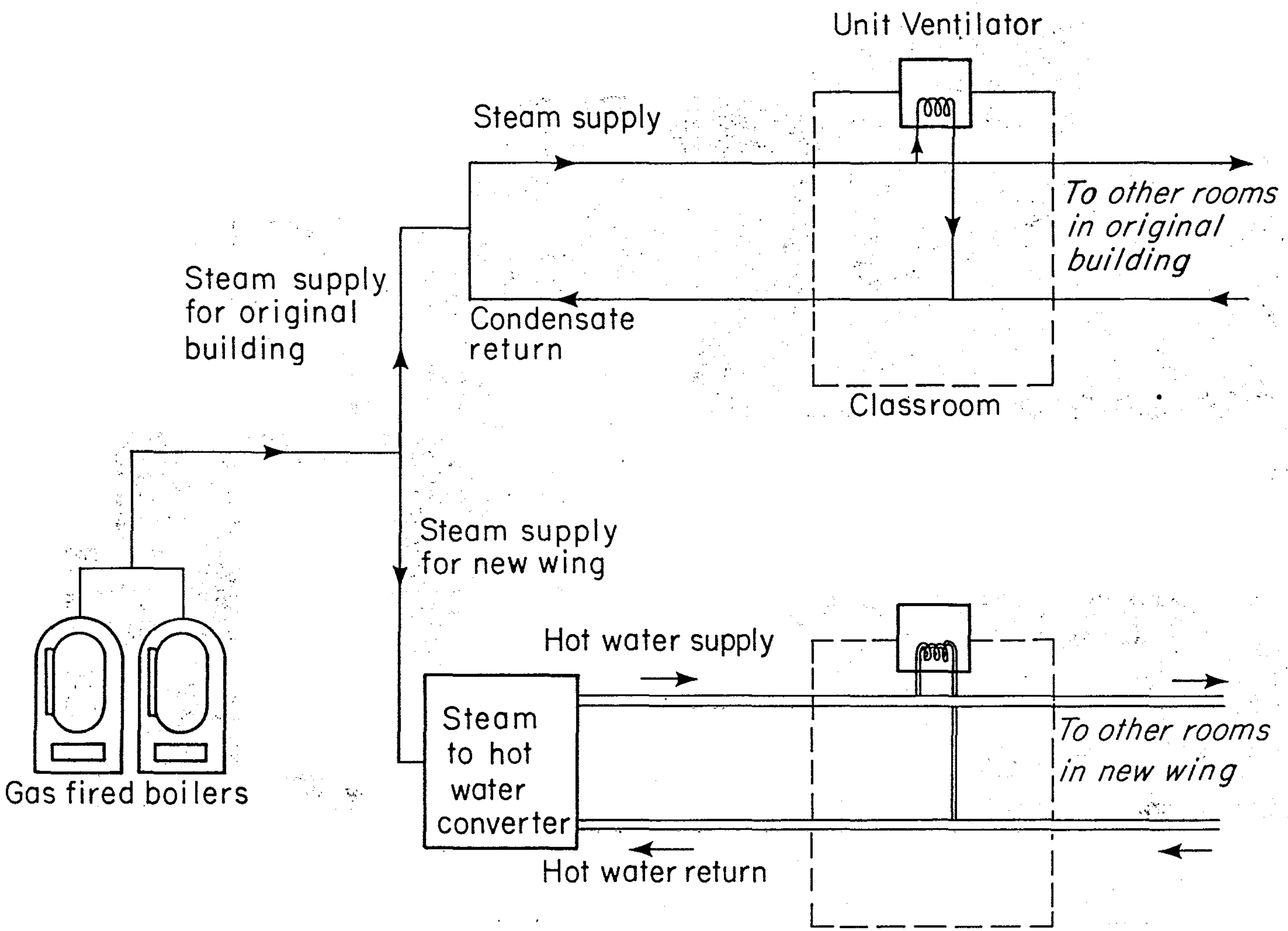

Figure 2. Schematic of the heating system at Fairmoor Elementary School.

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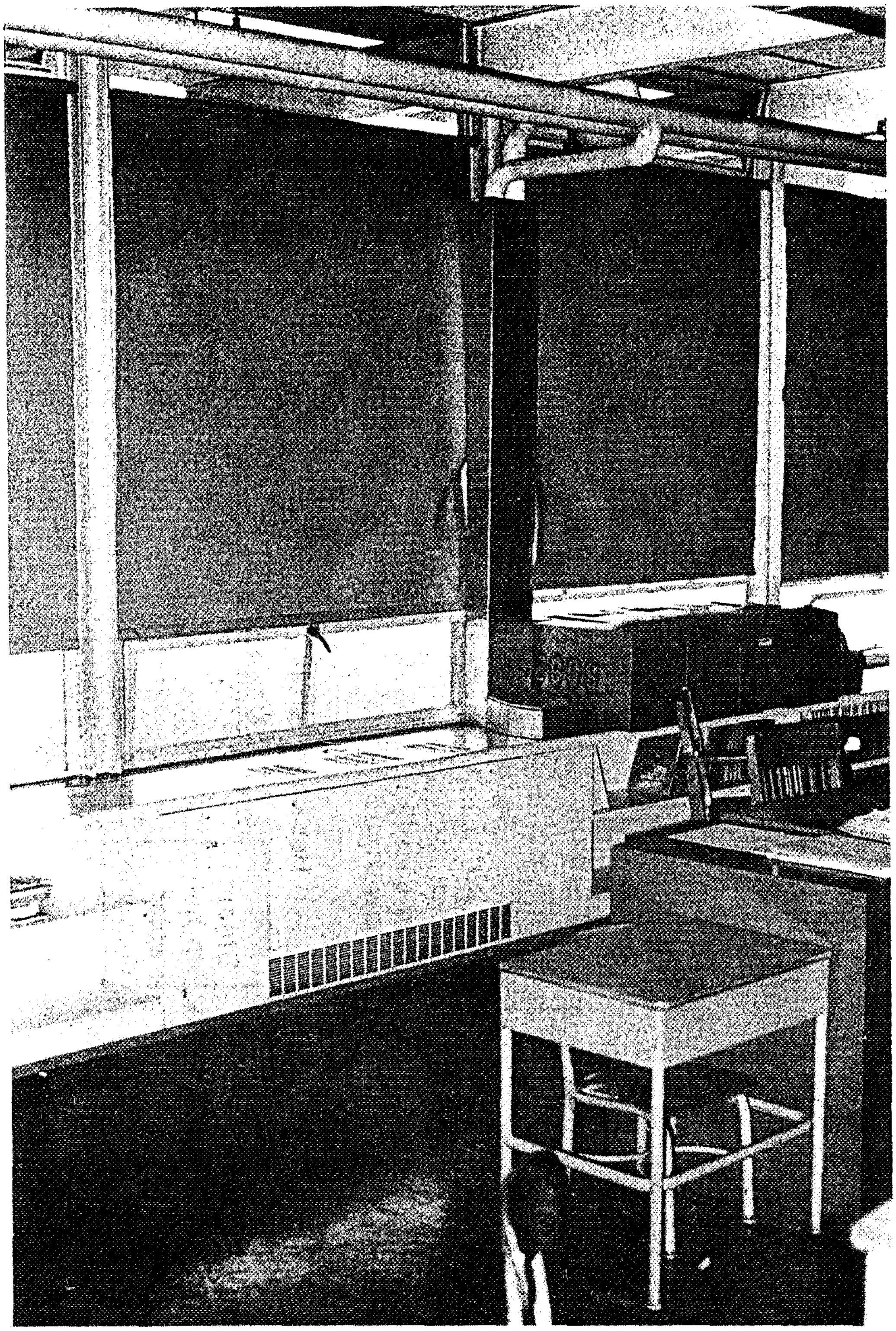

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Exhibit 1a. The unit ventilator in a room in the new addition.

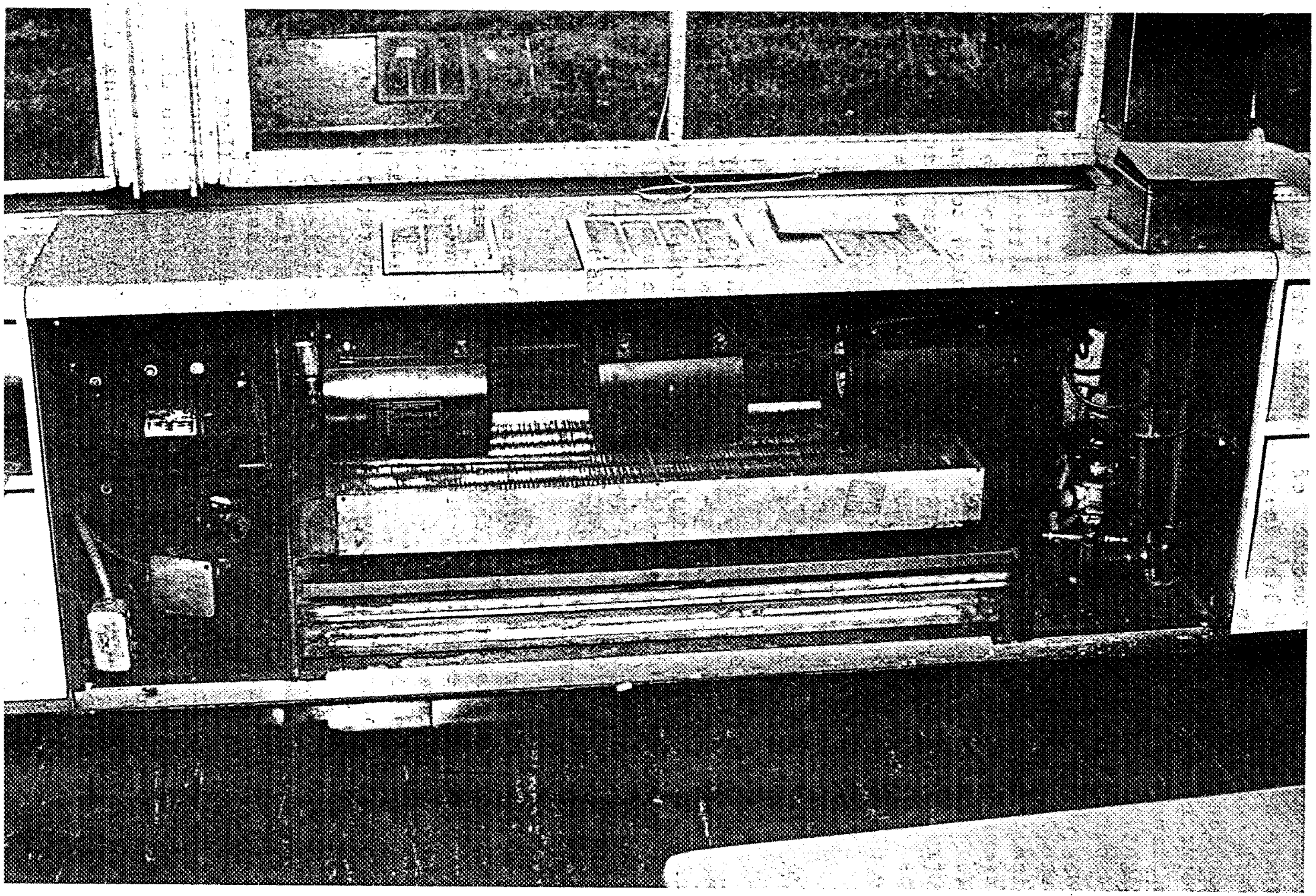

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Exhibit 1b. View of the unit ventilator without the front panel.

Figure 3 is a schematic representation of the unit ventilator in various modes of operation. Figure 3(a) represents normal occupancy conditions. In this mode the damper is positioned to provide not less than the required amount of outside air, as established by local or state codes. Figure 3(b) depicts the warm-up cycle prior to occupancy each day. In this mode the damper is positioned so that the flow of outside air is restricted as much as possible while the room air is recirculated through the heating coils; this setting is meant to produce maximum heating. (However, we found that because the dampers were not tight, outside air was able to leak into the classroom, as shown.) The dampers remain in this closed position during nights and weekends, during which time the room is maintained at a low "night setback" temperature. Figure 3(c) shows an economizer mode that is used when the outside temperature exceeds the thermostat setting. In this mode the intent is to allow a free flow of outside air into the building. Figure 3(d) shows the outside supply register sealed to completely block the entry of outside air in order to obtain a low ventilation rate. This was not a normal operating mode and will be discussed later with the results of the ventilation measurements.

The EEB Mobile Laboratory

The central research facility used by LBL to study the indoor air quality at Fairmoor Elementary School was the Energy Efficient Buildings (EEB) Mobile Laboratory designed and fabricated by LBL in early 1978.[5] The laboratory contains sampling, calibration and monitoring systems for field studies of indoor air quality and energy utilization in buildings. Table 2 lists the instrumentation in the EEB Mobile laboratory and the parameters monitored.

Air from four sites is drawn through teflon sampling lines into the laboratory for analysis of the common inorganic gaseous pollutants. The four sites are sequentially sampled for ten minute intervals; thus, each site is monitored every forty minutes. A microprocessor controls the sampling and calibration sequences; data from the analyzers and other instruments under microprocessor control are stored on floppy disks.

The EEB Mobile Lab was positioned outside Fairmoor Elementary School in early January, 1979 (see Exhibit 2). Sampling points were selected at one outdoor site and three indoor sites: a classroom in the original building (Room 20), a classroom in the new addition (Room 12), and the multipurpose room. Air-flow rates were measured by a tracer-gas system developed at LBL,[6] in which nitrous oxide is injected into the rooms and monitored continuously. Every five minutes the system calculated the rate at which indoor air was entering the room by observing changes in the indoor concentrations produced by injections of nitrous oxide.

Particulates, total aldehydes, and microbial content were measured on a time-integrated basis. Particulate matter was measured by automated dichotomous air samplers (DAS) developed at LBL.[7] The DAS use a flow-controlled virtual impaction system to separate the aerosol into fine and coarse fractions (below 2.5 microns and from 2.5 to 15 microns, respectively). The particulate matter was collected for twenty-four

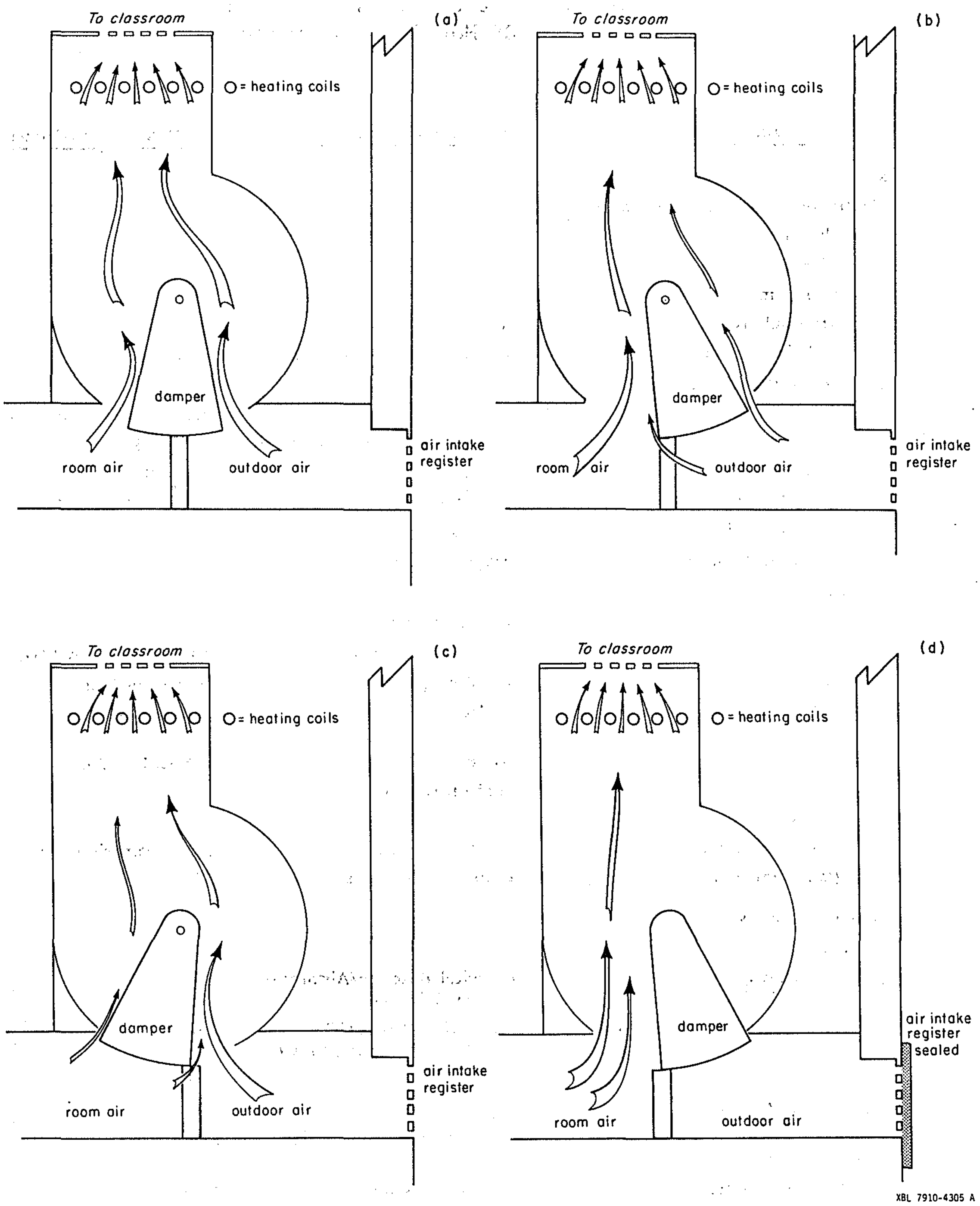

Figure 3. Damper position and air flow in various modes of operation of the unit ventilators:

3a. Normal occupancy mode
3b. Warm-up mode
3c. Economizer mode
3d. Zero percent outdoor air mode

Table 2. Instrumentation in the EEB Mobile Laboratory.

Parameter	Principle of Operation	Manufacturer/Model
Field		
Continuous Monitoring Instruments:		
Infiltration		
N_2O or C_2H_6 (Tracer gas)	IR	LBL
Indoor Temperature and Moisture		
Dry-Bulb Temperature	Thermistor	Yellow Springs 701
Relative Humidity	Lithium Chloride Hygrometer	Yellow Springs 91 HC
Outdoor Meteorology		
Dry-Bulb Temperature	Thermistor	Meteorology Research 915-2
Relative Humidity	Lithium Chloride Hygrometer	MRI 915-2
Wind Speed	Generator	MRI 1074-2
Wind Direction	Potentiometer	MRI 1074-2
Solar Radiation	Spectral Pyranometer	Eppley PSP
Metric Rain Gauge	Tipping Bucket	MRI 382
Gases		
SO_2	UV Fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV Absorption	Dasibi 1003-AH
CO	NDIR	Bendix 8501-5CA
CO_2	NDIR	M.S.A. Lira 303
Radon	Alpha Dosimetry	LBL
Particulate Matter		
Size Distribution	Optical Scattering	Royco Particle Counter 225
Radon Progeny	Under Development	LBL
Sample Collectors		
Gases		
Formaldehyde Total Aldehydes	Chemical Reaction/Absorption (Gas Bubblers)	LBL
Selected Organic Compounds	Adsorption (Tenax GC Adsorption Tubes) for GC Analysis	LBL
Particulate Matter		
Aerosols (Respirable/ Non-respirable)	Virtual Impaction/Filtration	LBL
Bacterial Content	Inertial Impaction	Modified Anderson Sampler
Data Acquisition System		
Microprocessor		Intel System 80/20-4
Multiplexer A/D Converter		Burr Brown Micromux Receiver MM6016 AA Remote MM6401
Floppy Disk Drive		ICOM FD3712-56/20-19
Modem		Vadic VA-317S

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Exhibit 2. The EEB Mobile Lab at the Fairmoor Elementary School.

hours on teflon filters. The samples were then analyzed at LBL using beta-ray attenuation to measure mass concentration, and X-ray fluorescence to determine chemical composition for twenty-eight elements. To measure total aldehydes, air was bubbled through solutions of 3-methyl-2-benzothiazolinone hydrazone (MBTH), which reacts stoichiometrically with water-soluble aliphatic aldehydes. Samples were taken for twenty-four hours and subsequently analyzed at LBL using a standard colorimetric procedure.[8] The microbial burden was measured by means of a modified Anderson sampler. Twenty minute samples were taken four times a day and analyzed by NBL personnel at the school.

Odor Measurements

TRC measured odor perception in a mobile odors laboratory brought to Fairmoor Elementary School. Odor panelists were recruited from people in the area who were not regular occupants of the school building. Air samples from the building were collected in 100-liter Tedlar bags and brought to the odors laboratory.

Odor measurements were carried out under normal and reduced ventilation conditions. At all sites, the sensory perception of odors was measured in two ways: The first method employed a forced-choice triangle olfactometer (Exhibit 3) to determine the number of dilutions necessary to bring an odorous air sample to a level at which 50% of the members of the odor panel could no longer detect it; this neutral level is expressed as ED_{50}.[9] The olfactometer is equipped with five stations; the first four present dilution ratios of 81, 27, 9, and 3, and the fifth presents the undiluted odor. There are three glass sniffing ports at each station; two supply filtered outside air and the other supplies the air from within the building in one of the five concentrations, progressing from weakest to strongest (undiluted). For each of the five concentrations, the odor panelist indicates which of the three ports he or she believes delivers odorous air. The second method for testing odor intensity, used immediately after the first, employed a device called a butanol olfactometer (Exhibit 4). The panelists are presented with the undiluted odor and asked to compare it with progressively increasing concentrations of butanol until they perceive a match between the intensity of the butanol and the intensity of the undiluted sample.[10]

In addition to the procedures described above, both the odor panelists and the building occupants filled out questionnaires (Exhibit 5) twice daily, giving their reaction to various aspects of the room environment, including the presence of odors, and rating each on a nine-point scale. Each aspect was also rated for acceptability.

TRC also collected air samples for laboratory analysis of the odorant composition. Two liters of room air were passed through tubes packed with porous polymer Tenax, which adsorbed the organics and odorants present in the air. The odorants adsorbed were then identified by gas chromatographic and mass spectroscopic (GC/MS) techniques and their character and intensity were determined by a GC/odorogram and sensory judge.

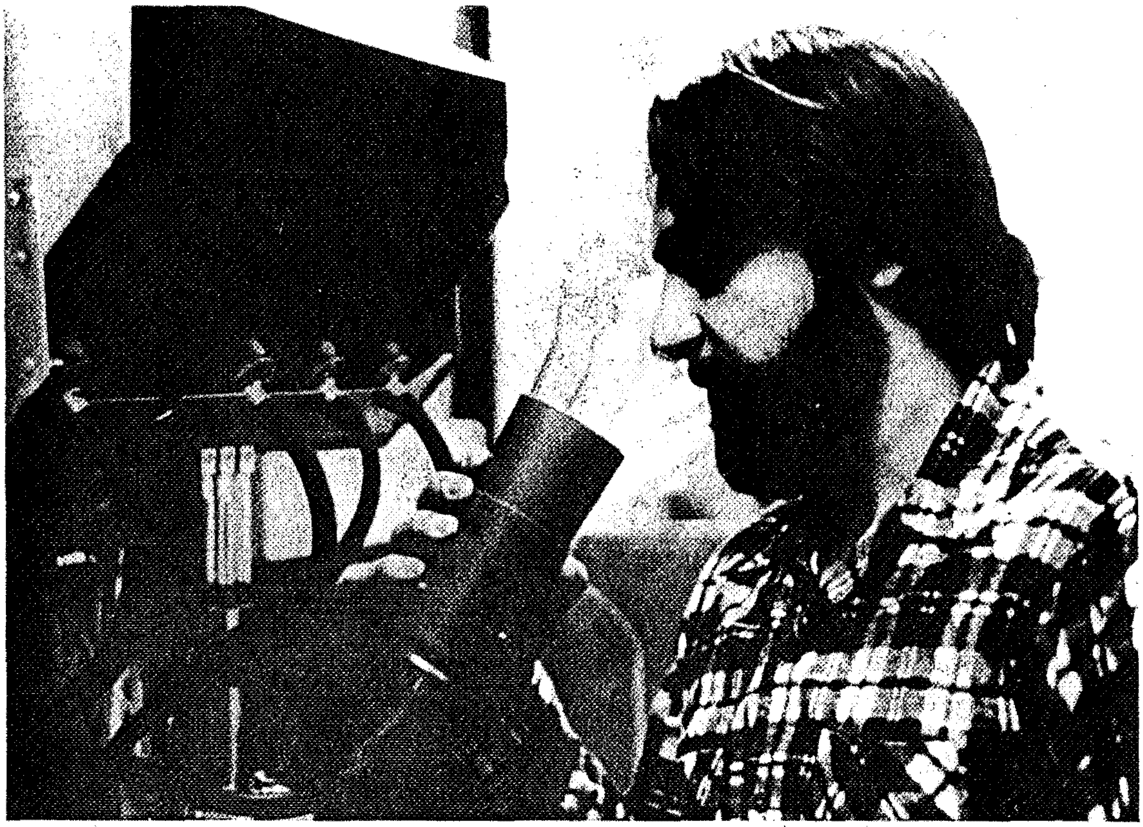

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Exhibit 3. Forced-choice triangle olfactometer. The subject chooses, by smell, which of the three nozzles emits odorous air.

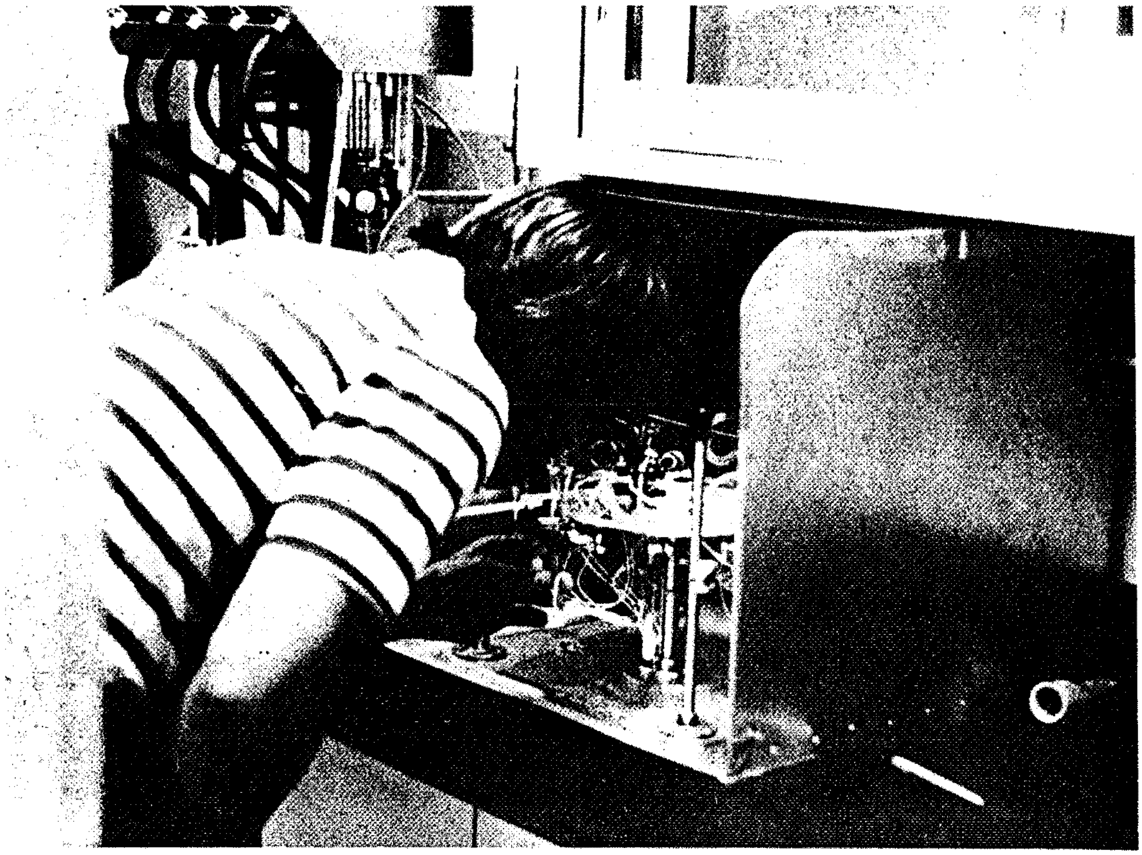

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Exhibit 4. Subject using the butanol binary dilution olfactometer to find a level of butanol intensity that matches the percent intensity of the "occupancy odor."

Day Number ____________ Date ____________ Time ____________ Room Number ____________

EVALUATION SHEET

Rating of Individual Elements of the Room Environment			Acceptable	Unacceptable
Cold	____:____:____:____:____:____:____:____:____	Hot	☐	☐
Humid	____:____:____:____:____:____:____:____:____	Dry	☐	☐
Drafty	____:____:____:____:____:____:____:____:____	Stuffy	☐	☐
Stale	____:____:____:____:____:____:____:____:____	Fresh	☐	☐
No odor	____:____:____:____:____:____:____:____:____	Strong odor	☐	☐
Loud noise	____:____:____:____:____:____:____:____:____	No noise	☐	☐

Overall Rating of the Room Environment

Acceptable ____:____:____:____:____:____:____:____:____ Unacceptable

1. Do you have a cold today?

   Yes ☐ No ☐

2a. If you are a smoker, about how many hours ago today did you have your last smoke?

   _____ hours ago

2b. If you are not a smoker or if you did not smoke today, check this box . . . . ☐

Exhibit 5. Questionnaire filled out by students and odor panelists.

Ventilation Modes

The objective of the study was to monitor indoor air quality at normal and reduced ventilation rates. We intended to change the flow of outside air through the unit ventilators by changing the damper position. Therefore, we installed manual override switches and pneumatic pressure controls on the unit ventilators in the three rooms so that we could adjust the damper position. We then proceeded to monitor the air quality inside the two classrooms and the multipurpose room under the normal operating mode of the school and two modes which produced lower ventilation rates.

In the normal operating mode, i.e., under daytime occupancy conditions with the dampers controlled by the room thermostat, the damper opening to the outside was approximately two inches. This opening was supposed to satisfy the minimum outside air requirement of 25.3 m^3/h (15 cfm) per occupant. Since the rate at which outside air flowed through the unit ventilator could not be measured directly, we used the continuous tracer-gas infiltration system, described earlier, for measurements of the ventilation rate. These measurements showed that the outside air flow in the normal operating mode was much lower than expected, approximately 11 m^3/h (6.5 cfm) per occupant, based on twenty-five students in the classroom.

Initially, we had expected that reducing the damper opening by one-third would decrease the outside air flow by roughly a factor of three. However, measurements by the continuous infiltration system indicated that this partial closing of the damper had essentially no effect on the outside air flow. We then manually set the dampers in a closed position in order to greatly reduce the amount of air entering the classroom through the supply register. But because of leaks around the closed dampers, outside air continued to enter and only a moderate reduction in the outside air flow rates was achieved. In Room 12 the rates were reduced from 10.8 to 9.1 m^3/h (6.4 to 5.3 cfm) per occupant and in Room 20 from 11.2 to 7.4 m^3/h (6.6 to 4.4 cfm) per occupant.

To bring about a more significant reduction in the outside air flow, we had to seal the outside supply register when the damper was closed (see Figure 3d). In this mode, which we shall call the "reduced" mode, the outdoor air flow was cut from approximately 11.0 to 2.5 m^3/h (6.5 to 1.5 cfm) per occupant in the two classrooms. The same change was made in the multipurpose room with similar results.

Figures 4, 5, and 6 show the frequency distributions of the air flow rates in Room 20, Room 12, and the multipurpose room in the three modes of operation. As shown, the flow of outdoor air decreased significantly when the dampers were effectively sealed by taping the outside supply register. The average air flow rates for the three indoor sites in the different operating modes are given in Table 3.

The measurements by the continuous tracer-gas infiltration system could be performed only on weekends, when the classrooms were not occupied, because of the possibility of adverse health effects from breathing nitrous oxide. A manual override was put on the timer system during

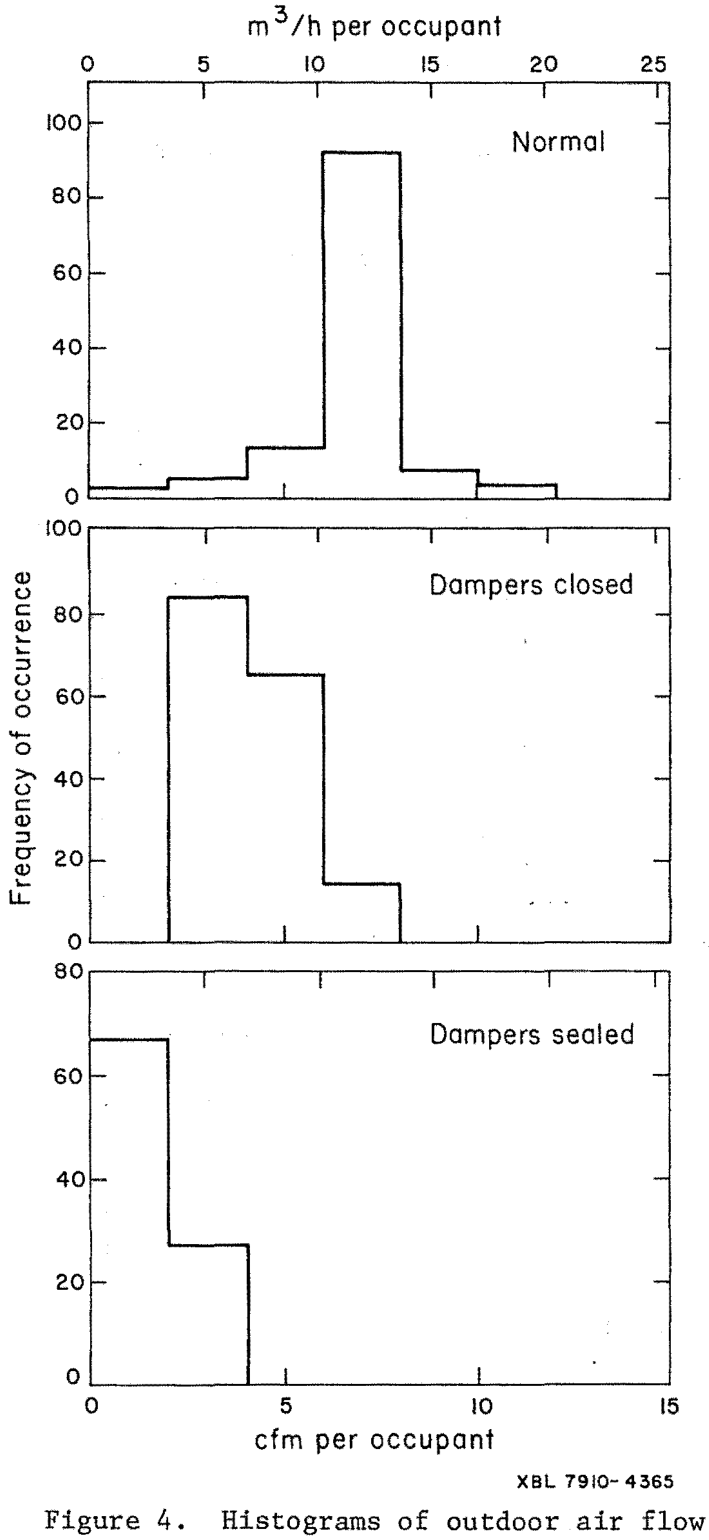

Figure 4. Histograms of outdoor air flow rates in Room 20 during the three modes of operation.

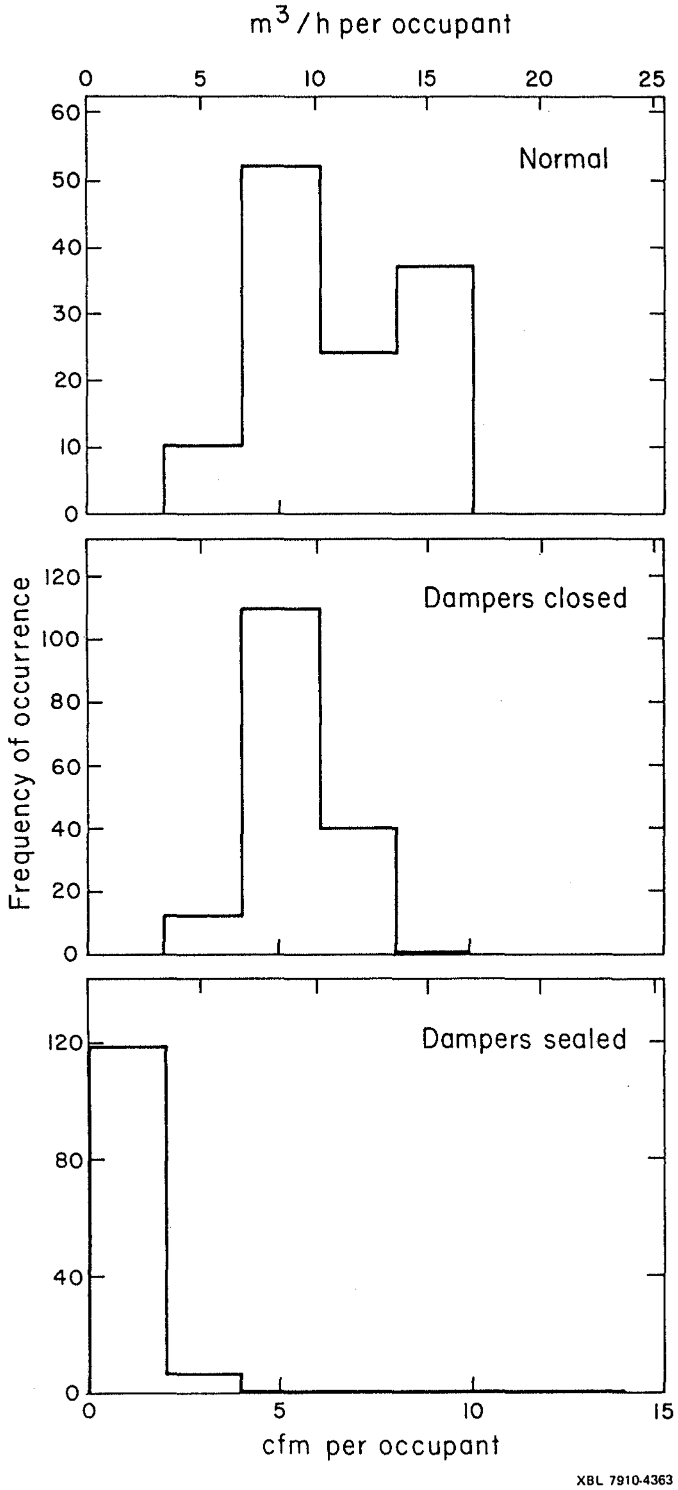

Figure 5. Histograms of outdoor air flow rates in Room 12 during the three modes of operation.

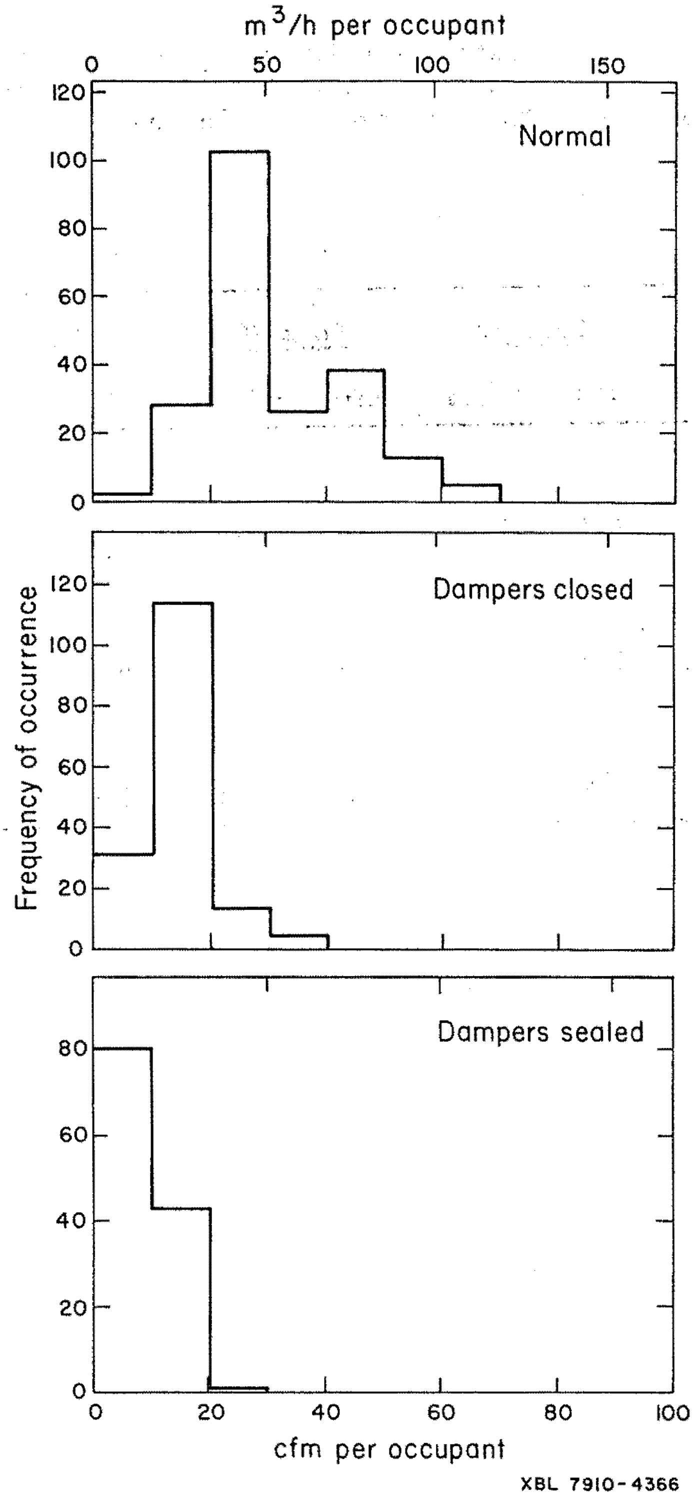

Figure 6. Histograms of outdoor air flow rates in the multipurpose room during the three modes of operation.

Table 3. Outdoor air flow rates at Fairmoor Elementary School measured by the continuous infiltration system and based on twenty-five occupants in the room.

	Room 12		Room 20		Multipurpose room	
Mode of operation	cfm	m3/hr	cfm	m3/hr	cfm	m3/hr
Normal	6.4	10.8	6.6	11.2	30.5	51.8
Dampers closed	5.3	9.1	4.4	7.4	14.8	25.1
Reduced	1.3	2.2	1.8	3.1	9.3	15.7

the weekends so that the school was in the normal heating mode when the air flow rates were measured. TRC used sulfur hexafluoride decay measurements to obtain air flow rates during the school day when the students were in the classrooms. The TRC results showed air flow rates of approximately 16.9 m^3/h (10 cfm) per occupant in both classrooms with the ventilation system operating in the normal mode. These results were significantly higher than those obtained on the weekends using the continuous nitrous oxide infiltration system. The discrepancy was probably due to the different conditions prevailing when students were present; for example, when the students left the room, they usually left the door open until they returned, and this would have increased the room ventilation. We can therefore assume that ventilation rates during student occupancy were somewhat higher than those listed in Table 3.

RESULTS AND DISCUSSION

Odor Perception

Fairmoor Elementary School was the first site visited by TRC as part of its field monitoring program to determine ventilation requirements for controlling odors in buildings. The sensory perception of odors, odor acceptability, and the chemical (organic) composition of indoor air were studied for a two-week period with the ventilation system in the normal and reduced operating mode. Odors were not measured while the system was operating with the dampers closed but unsealed.

Table 4 summarizes the results of the measurements of average odor dilution, odor intensity, and acceptability in the three test rooms for other odor panelists only. Under normal ventilation conditions the dilution ratio (ED_{50}) was close to the ED_{50} for outside air. In the reduced mode, the ED_{50} doubled in the two classrooms and increased slightly in the multipurpose room. The odor intensity exhibited no statistically significant change when the ventilation rate was reduced. The occupants of the three rooms found the odor level acceptable at all times. However, the visitors on the odor panel perceived a small decrease in acceptability in Room 12 when the ventilation rates were reduced and a smaller decrease in acceptability in Room 20 (where the ventilation rate was reduced somewhat less than in Room 12). According to the section of ASHRAE Standard 62-73 pertaining to the odor acceptability of outdoor air, at least 60% of a panel of no fewer than ten untrained observers must agree that the air is free of objectionable odors. If this standard were applied to indoor air, the odor levels in the two classrooms, when the ventilation rate was reduced, would have to be classified as unacceptable. However, it should be noted that when the tests at the reduced ventilation rate were being made, the outside air ventilation rate was quite low -- only 2.5 m^3/h (1.5 cfm) per occupant, much less than the present ASHRAE minimum. Criteria for indoor air quality with respect to odor levels are now being developed by ASHRAE for Standard 62-73R, <u>Standards for Ventilation Required for Minimum Acceptable Indoor Air Quality</u>.[11] One of the proposed changes in

Table 4. Summary of odor and ventilation data of the odor panelists from Fairmoor Elementary School.

	Odor dilution ratio (ED_{50})		Odor intensity Butanol scale (ppm)		Average acceptability (%)	
	Normal vent.	Reduced vent.	Normal vent.	Reduced vent.	Normal vent.	Reduced vent.
Room 12						
a.m.	4	13	57	42		
p.m.	8	9	30	43		
Average	6	11	43	43	76.5	55
Room 20						
a.m.	6	14	50	46		
p.m.	6	10	43	55		
Average	6	12	47	50	67.6	56.3
Multipurpose Room						
a.m.	9	9	44	32		
p.m.	6	9	40	35		
Average	7	9	42	33	94	92

the revised standard is that at least 80% of a panel of no fewer than 20 untrained obseervers must agree on the acceptability of the air quality.

The GC/MS results indicated that the odorants collected in the classrooms originated from cleaning compounds, polishes, and possibly automotive exhaust, but not body odor; however, odorant concentrations were too low to allow positive identification by gas chromatographic odorogram analysis.

In summary, odorant concentrations were low at both normal and reduced ventilation rates; the occupants of the building found the odor level acceptable under both ventilation conditions. Visitors to the classroom sometimes found the odor level unacceptable at the reduced ventilation rate (if acceptability is based on the present odor criteria for outdoor air.)

Microbial Burden

NBL provided scientific and technical support to the LBL Ventilation Group on sampling, assay, and data analysis of airborne bacterial content at Fairmoor School. NBL was contracted to determine whether energy-conserving changes in ventilation practices would lead to unacceptable concentrations of airborne microbes; to this end, microbial burden was measured at different ventilation rates.

Instruments[12] to measure airborne microbes in six sizes were placed at the three indoor monitoring sites. Samples of airborne microbes were taken at 8:00 a.m., 10:00 a.m., 1:00 p.m., and 3:00 p.m. Table 5 gives the average number of colony-forming particles (CFP) per cubic meter of air for all samples. A computerized analysis of the raw data was made to determine whether any parameters showed a significant difference in any room; it was found that reduced ventilation caused a significant increase in microbes in one instance only -- in Room 12 at 1:00 p.m., for the sample of respirable colony-forming particles (less than 5 μm diameter). When a similar analysis was done for total particles, no statistical difference was found at the different ventilation rates; hence, the effect was not a general one and may have been incidental to ventilation conditions within the particular room. The data collected from the multipurpose room did not reveal any correlations of statistical significance.

Table 6 shows that the mean values of CFP/m^3 vary with sampling time and follow a repetitive daily pattern according to the activity in the rooms.

Table 7 lists mean values of CFP/m^3 found in a number of locations, averaged over a two-year period. These values are representative of the general level of bioburden at these sites. If we compare Fairmoor Elementary School in Columbus, Ohio, and Carondelet High School in Concord, California, under normal conditions, we find that the number of CFP/m^3 at Fairmoor was double the number measured at Carondelet.[13] At Fairmoor, the CFP/m^3 increased from 269 to 360 when ventilation was changed from a normal to a reduced operating mode. That a microbial burden in this

Table 5. Mean values of CPF/m^3 in classrooms at Fairmoor Elementary School, calculated as a function of time.

Time	Normal	Damper Closed	Reduced
8:00 a.m.	13	32	19
10:00 a.m.	243	148	305
1:00 p.m.	256*	323	403*
3:00 p.m.	291	280	370

* Note the difference between these two starred values. Since the vents were sealed, we could not have been observing an infiltration of air containing numerous CFP; the explanation could be that rather clean, infiltrating air was acting as a diluent under the normal condition in the rooms.

Table 6. Mean numbers of CFP/m^3 in two classrooms at Fairmoor Elementary School, excluding the 8:00 a.m. sample.

Mode of ventilation	Total particles		Respirable particles		Non-Respirable particles	
	Mean	Stand. dev.	Mean	Stand. dev.	Mean	Stand. dev.
Normal	269	166	104	68	165	110
Damper closed	253	188	116	74	141	126
Reduced	360	206	182	118	177	99

Note: Because of the large standard deviations, there are no significant differences between any of these means. However, in each case, a consistent increase is evident when the operating mode was changed from normal to reduced.

Table 7. Mean values (no. per cubic meter) of number of airborne colony-forming particles at various sites.

Fairmoor Elementary School			
Ventilation:	Automatic	Dampers Closed	Sealed
	269	283	360
(Auditorium - Gymnasium had Peak Value of 1200)			
Carondelet High School (Class in session)			
Ventilation Rate (cfm/occupant)		Room 1	Room 2
13.5		160	107
2.5		115	75
Peralta Hospital (Eye Operatory)			40
Sports Arena			200
NBL Conference Room			180
NBL Men's Rest Room			132
Veterans' Administration Hospital (Martinez)			
Cast Room			333
Research House, Walnut Creek			
Sealed and Vacant			17
Blower On and Vacant			550
Long Beach Naval Hospital			
Cast Room			523
Patient Room			900
Proctology			62
Obstetrics			125
Pediatrics			183

range is not unusual is supported by the data on other buildings given in Table 7.

The number of airborne CFP in the multipurpose room varied more than in the classrooms. This variability, from as low as $12/m^3$ to as high as $1,200/m^3$, is not unexpected since occupants use the area for many different activities and at irregular times. This factor prevented an analysis of the data in that room with respect to ventilation changes.

NBL made the following observations based on the data amassed: It seems that humans can live in air with "bioburdens" of from 20 CFP/m^3 to over 700 CFP/m^3 without apparent adverse health effects. There is no evidence that any retrofitting situation examined caused an increase in airborne microflora above that present in other common situations. Hence, the probability of infection from aerosols of human origin under normal conditions (excluding the presence of "carriers" or "shedders," which is not really a part of the ventilation evaluation problem) seems low. If that very small probability were increased ten-fold as a result of a ten-fold increase in bioburden, then a very low probability of infection would still remain.

Gasesous Contaminants

As the ventilation rate in the three rooms was reduced, the air quality in the three schoolrooms and outdoors was continuously monitored by the EEB Mobile Laboratory. Only the data collected during regular school hours, 8:30 a.m to 3:30 p.m., have been presented here. These data have been grouped by ventilation rate for each room and displayed in histograms of the concentrations observed. Data points were recorded every minute, and averages for the ten-minute intervals were calculated. In the histograms given in this section and in the Appendix, the data points, sorted into bins along the horizontal axis, represent the ten-minute averages for the particular site. Since the data for the three rooms tended to be similar, only one graph is included in the text to illustrate a particular point. The Appendix contains the histograms for each room of all the data on the common inorganic pollutants (carbon dioxide, carbon monoxide, ozone, sulfur dioxide, and the nitrogen oxides).

Carbon dioxide was the only pollutant found in significant concentrations inside the school, its primary sources being the occupants themselves. Figure 7 shows a profile of the carbon dioxide concentrations in Room 12 during a typical school day. The level of carbon dioxide rose when the students entered the room for the morning and afternoon sessions; it fell at noon and at 3:00 p.m., when the students left the classroom. Because of variations in classroom occupancy and activity, the profiles in the three rooms differed slightly from day to day. This was especially true of the multipurpose room, which was not used on a regular basis.

Figure 8 presents a frequency distribution for each ventilation mode of the carbon dioxide concentrations in Room 12. As shown, the carbon dioxide levels increased as the ventilation rates were reduced. Under

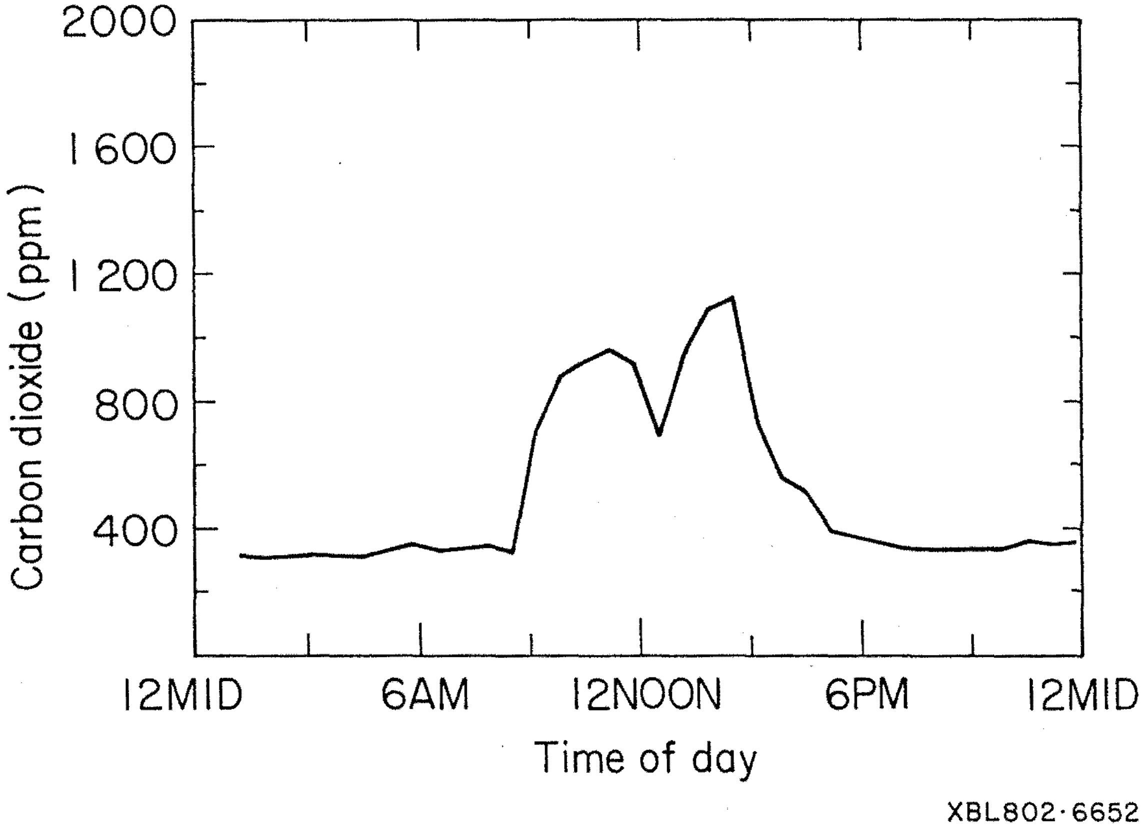

Figure 7. Variation of CO_2 during a 24-hour period in Room 12.

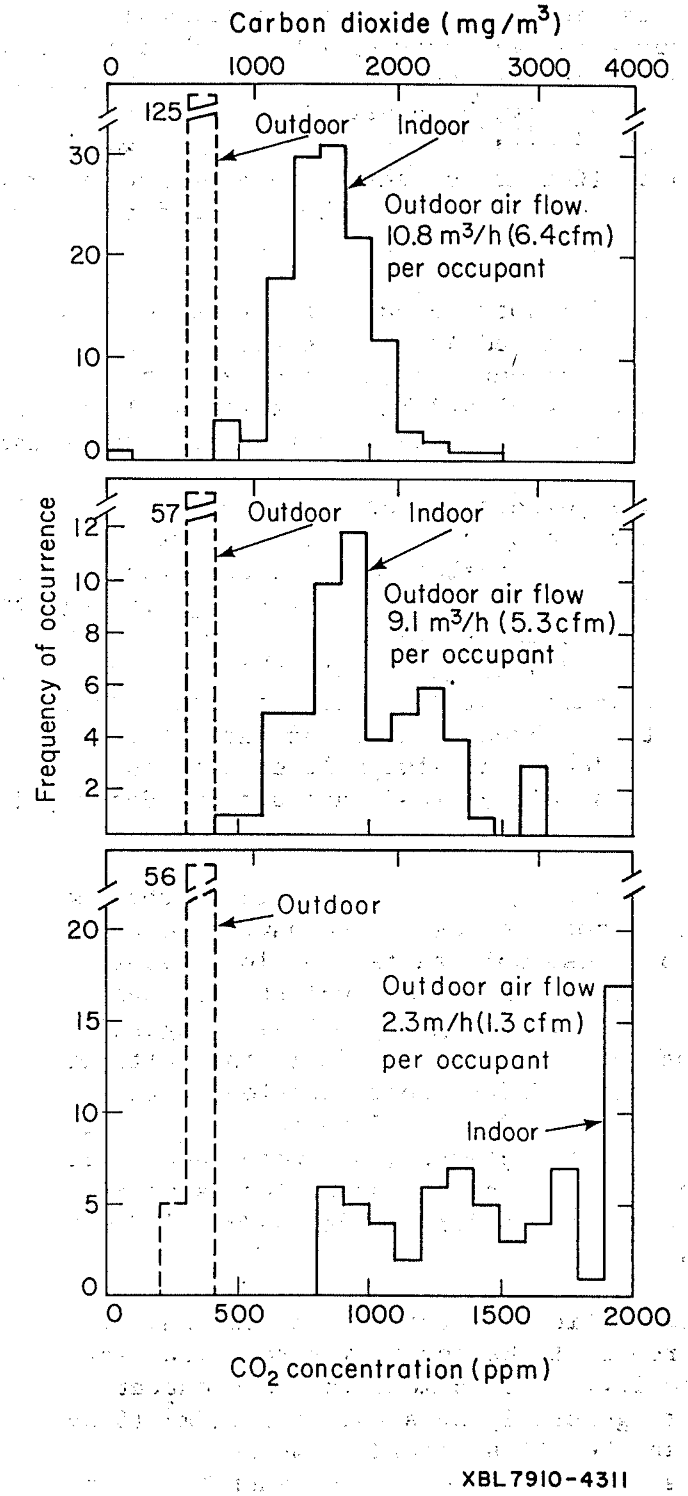

Figure 8. Histograms of the indoor and outdoor CO_2 concentrations in Room 12 at the three ventilation rates.

the normal mode of operation, the carbon dioxide levels never exceeded 3600 mg/m^3 (2,000 ppm). Under the reduced mode of operation, the carbon dioxide levels did rise, occasionally exceeding 5400 mg/m^3 (3,000 ppm); but they never exceeded 7200 mg/m^3 (4,000 ppm) in any of the three rooms, These figures are well within the occupational standards for carbon dioxide, which have been set at 9000 mg/m^3 and 18,000 mg/m^3 (5,000 and 10,000 ppm)[14,15,16] and refer to time-weighted average concentrations for up to 10-hour workshifts in a 40-hour work week; studies have indicated that workers could be exposed to these concentrations day after day without adverse health effects.

The ratios of indoor to outdoor carbon dioxide concentrations for Room 12 were calculated and the results are summarized in Figure 9. As shown, the indoor to outdoor carbon dioxide ratios are slightly higher when the dampers are closed but not sealed. There is a more significant increase in the ratios at the most reduced ventilation rate.

For reactive pollutants that have primarily outdoor sources, the indoor concentrations are generally lower than those found outdoors because the building envelope acts as an effective barrier to these pollutants. Ozone showed this pattern. Although the concentration of ozone outdoors reached as high as 98 μg/m^3 (50 ppb), the indoor ozone levels never exceeded 19 μg/m^3 (10 ppb) in Room 12. Figure 10 shows the frequency distribution of the ratios of the indoor to outdoor ozone concentrations at the three ventilation rates for Room 12. Since the ozone concentration indoors was always lower than the concentration outdoors, their ratio was always less than one and decreased as the ventilation rate decreased.

The other common gaseous pollutants (carbon monoxide, sulfur dioxide, and the nitrogen oxides) also have outdoor sources. The indoor concentrations of these pollutants were low, generally lower than outdoor levels, and never exceeded ambient air quality standards set by the Environmental Protection Agency (EPA).[17] Figure 11 shows the frequency distributions of sulfur dioxide in the multipurpose room at the three ventilation rates. Indoor concentrations were generally less than 108 μg/m^3 (40 ppb) and decreased in the reduced ventilation mode. Outdoor concentrations varied greatly, but were usually less than 150 μg/m^3 (60 ppb). Both indoor and outdoor levels of SO_2 were far below the EPA ambient air quality standard of 365 μg/m^3 (140 ppb) for a twenty-four hour period.

The concentrations of carbon monoxide and nitrogen oxides were very low for all rooms at the three different ventilation rates; outdoor levels were also low. Carbon monoxide concentrations, both indoors and outdoors, were generally less than 5.7 mg/m^3 (5 ppm). These levels were much less than the EPA standard of 40 mg/m^3 (35 ppm) for a one-hour period. The average indoor concentration of nitrogen dioxide was approximately 38 μg/m^3 (20 ppb). The concentrations indoors or outdoors were rarely higher than 113 μg/m^3 (60 ppb), -- levels much lower than the EPA standard of 100 μg/m^3 (50 ppb) for a one-year period. Table 8 lists relevant ambient air quality standards for most pollutants set by the EPA and other agencies. The data on the indoor and outdoor concentrations of carbon monoxide, nitrogen dioxide, as well as on the other

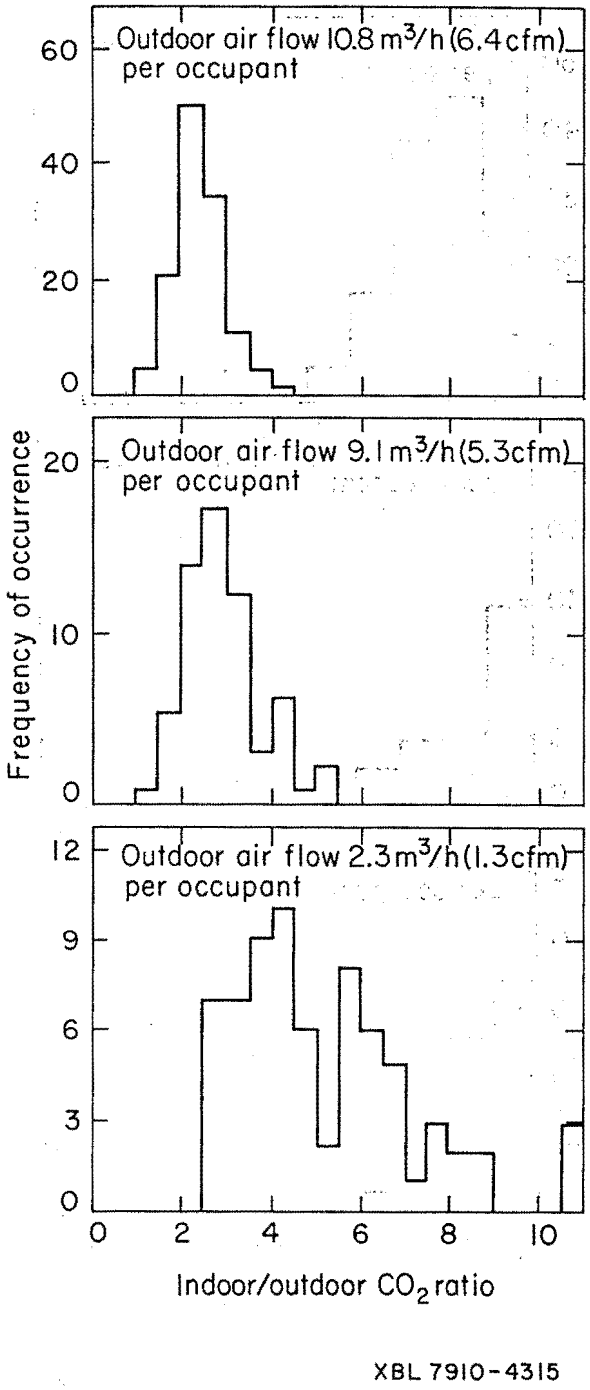

Figure 9. Histograms of the ratio of indoor to outdoor CO_2 concentrations in Room 12 at the three ventilation rates.

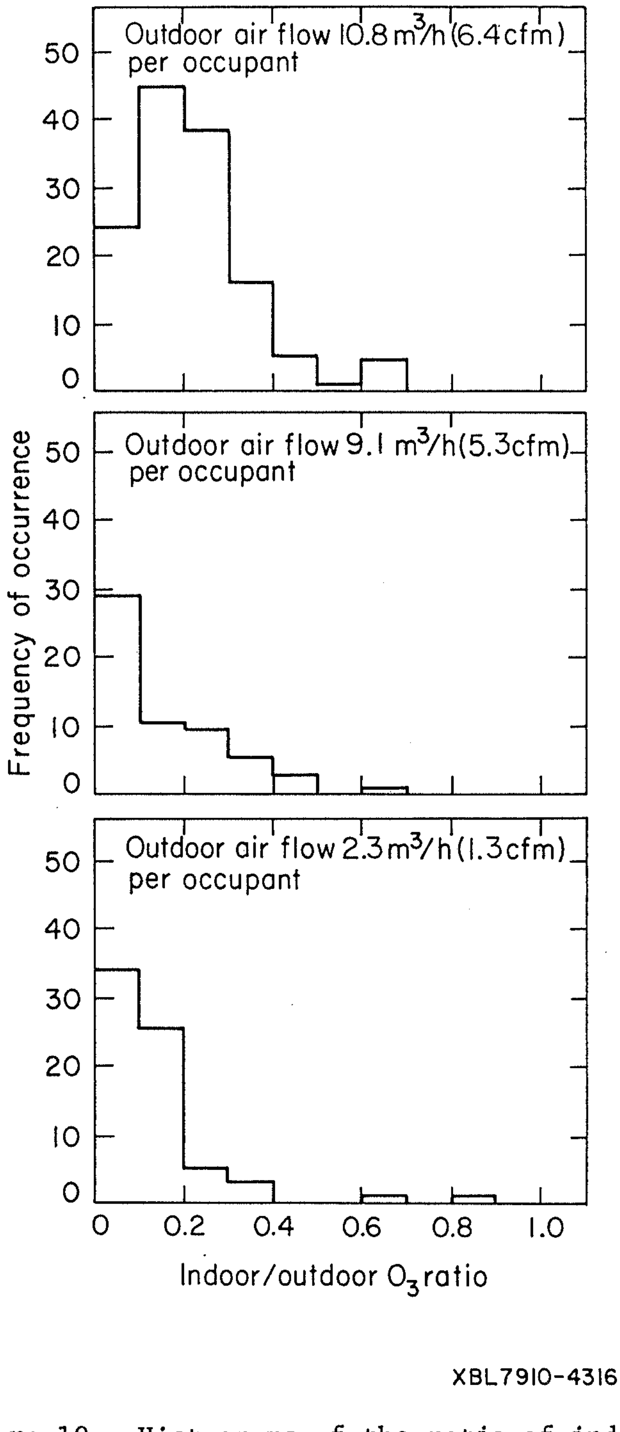

Figure 10. Histograms of the ratio of indoor to outdoor ozone concentrations in Room 12 at the three ventilation rates.

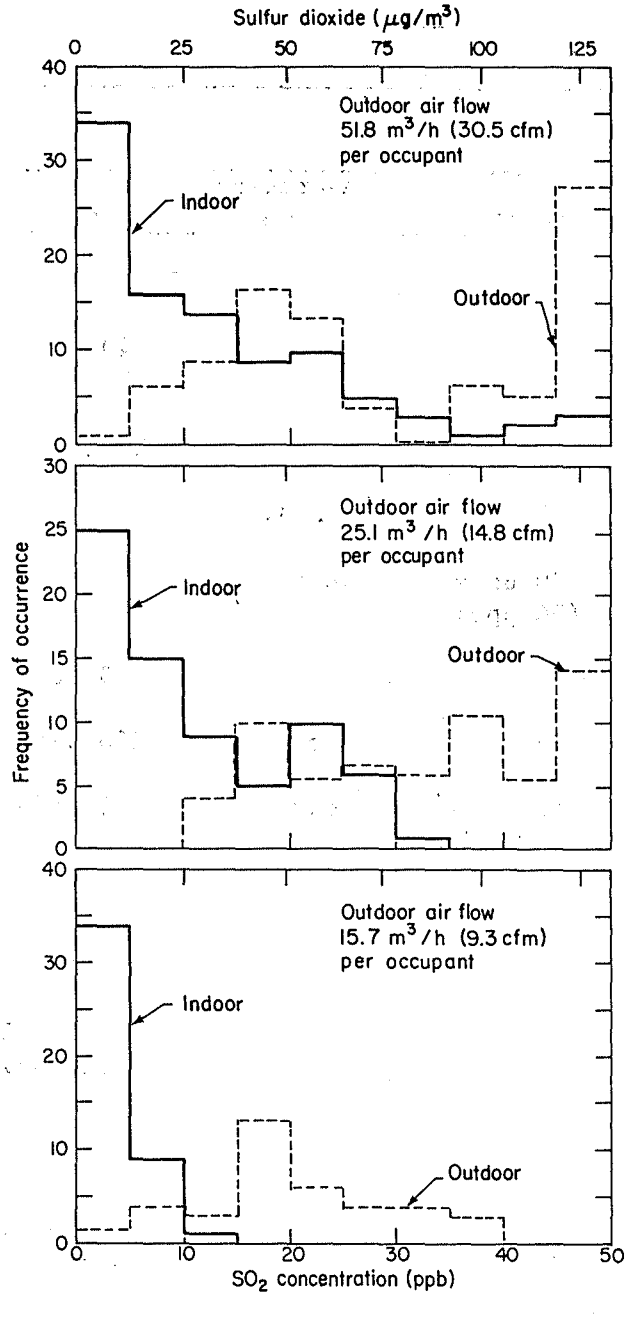

Figure 11. Histograms of indoor and outdoor SO_2 concentrations in the multi-purpose room at the three ventilation rates.

Table 8. Ambient Air Quality Standards

Contaminant	Long Term Level	Long Term Averaging Time	Short Term Level	Short Term Averaging Time
EPA				
Carbon monoxide (CO)			40 mg/m^3 (35 ppm) 10 mg/m^3 (9 ppm)	1 hr. 8 hrs.
Hydrocarbons			160 μg/m^3 (250 ppb)	3 hrs. (6-9 a.m.)
Lead (Pb)	1.5 μg/m^3	3 mos.		
Nitrogen dioxide (NO_2)	100 μg/m^3 (50 ppb)	year		
Ozone (O_3)			240 μg/m^3 (120 ppb)	1 hr.
Particulates	75 μg/m^3	year	260 μg/m^3	24 hrs.
Sulfur dioxide (SO_2)	80 μg/m^3 (30 ppb)	year	365 μg/m^3 (140 ppb)	24 hrs.
Other				
Carbon dioxide (CO_2)			9000-18,000 mg/m^3 (5000-10,000 ppm)	8-10 hrs.
Formaldehyde (HCHO) (Europe)			120 μg/m^3 (100 ppb)	Maximum
Radon (EPA and Canada)			0.02 working levels (∿4 nCi/m^3 in buildings)	

inorganic gaseous contaminants, are given in the Appendix.

The MBTH measurements indicated that the concentration of total aldehydes was very low, usually less than 10 ppb and never exceeding 20 ppb. This is well within the 100 ppb range that is being considered as a standard for total aldehydes.

In summary, of the common inorganic gaseous pollutants, only carbon dioxide was seen in significant concentrations inside the school, even at a reduced ventiltion rate of 2.6 m^3/h (1.5 cfm) per occupant. As the ventilation rate decreased, the carbon dioxide concentrations increased, but the levels remained low, never exceeding 7,200 mg/m^3 (4,000 ppm). The indoor concentrations of carbon monoxide, sulfur dioxide, ozone, and the nitrogen oxides were very low, almost always lower than the outdoor levels. The indoor concentrations of all the gases were lower than the occupational or EPA ambient air quality standards.

Particulates

In order to measure the particulate mass, automated dichotomous air samplers[7] were placed at each of the three indoor sites as well as outdoors. Figure 12 summarizes the data for Room 12, which were typical for the other two rooms as well. Each bar represents a twenty-four hour average. Gaps in the data represent days when the instruments malfunctioned. As shown, the concentration of the particulate mass outdoors, both fine and total, is usually higher than the indoor level. The fine particulate mass indoors ranged from 3 to 27 $\mu g/m^3$ and constituted approximately 75-80% of the total mass. The fine particulate mass outdoors was slightly higher, ranging from 10 to 48 $\mu g/m^3$, and was approximately 65-70% of the total mass.

Table 9 lists the concentrations of the particulate mass observed at each ventilation rate. The averages for the fine particulate fraction indoors and outdoors at the normal ventilation mode were 20 and 26 $\mu g/m^3$ respectively, the average of the daily indoor/outdoor ratio being 0.73. When the dampers were closed but not sealed, the indoor/outdoor ratio was approximately the same as during the normal mode. The lower particulate mass observed both indoors and outdoors indicates that the cleanest outdoor conditions prevailed during the sampling period when the dampers were closed. In the reduced ventilation mode, the indoor fine and coarse particulate mass and indoor/outdoor ratio were slightly lower than during the normal mode of operation. However, the small number of samples collected (four to five days at each ventilation rate) and the large standard deviations observed make it difficult to draw any conclusions from these data other than that the indoor particulate levels did not increase when the ventilation rate was decreased.

The elemental analysis of the particulates by X-ray fluorescence revealed only trace amounts of most of the twenty-eight elements measured. All elements were found to have higher outdoor than indoor concentrations. Lead (presumably from automobile exhaust) was present in concentrations of approximately 100-400 ng/m^3 indoors, with outdoor levels usually at least twice the indoor level. Sulfur (most likely from

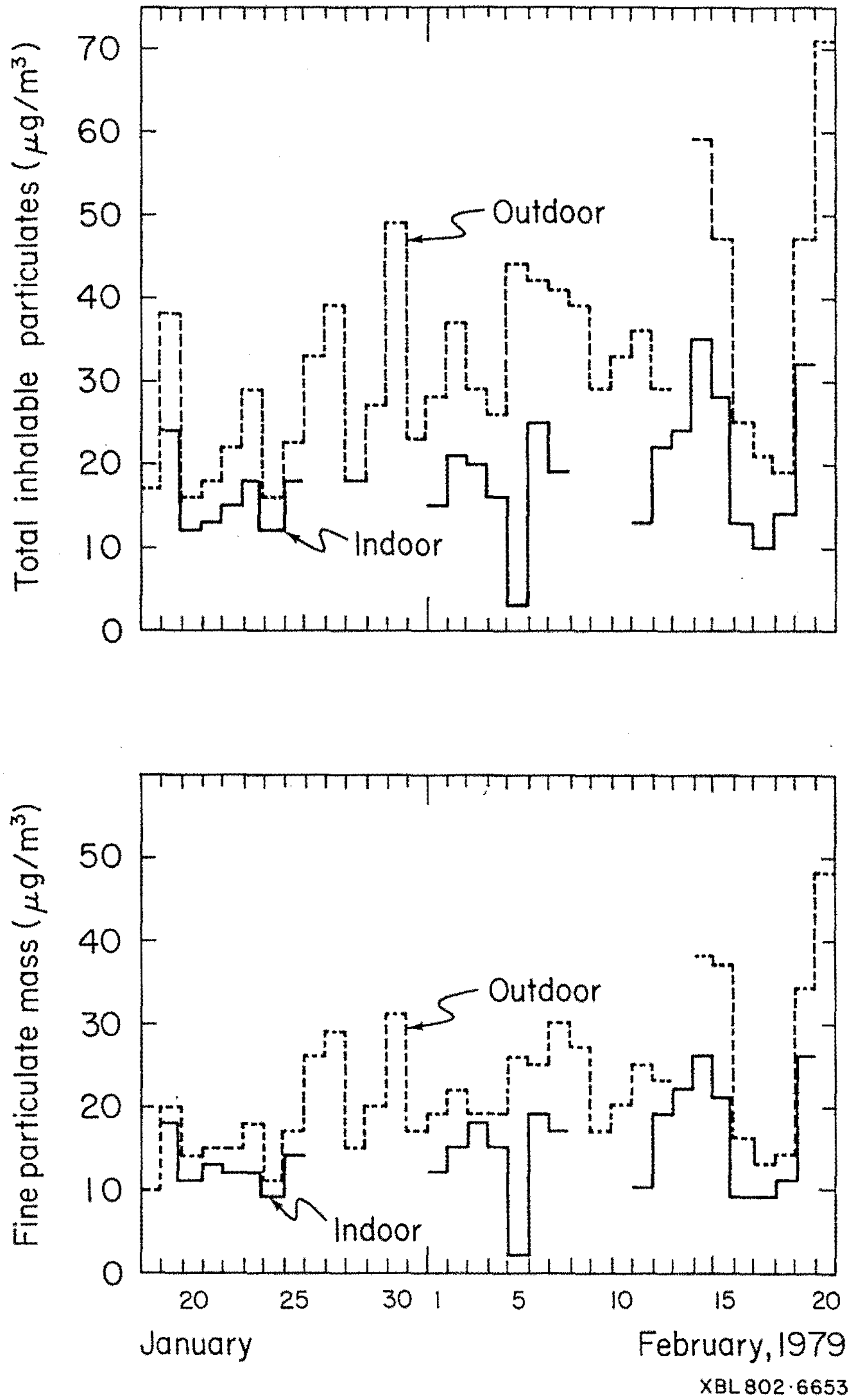

Figure 12. Comparison of particulate mass in Room 12 and outdoors during January and February, 1979.

Table 9. Results of measurements of particulate mass in Room 12, Fairmoor Elementary School.

Ventilation Mode	Fine Particulate Fraction		
	Room 12 ($\mu g/m^3$)	Outdoors ($\mu g/m^3$)	Ratio*
Normal	19.0 ± 5.7	26.3 ± 7.6	0.73 ± .09
Dampers closed	11.7 ± 2.5	15.3 ± 3.8	0.77 ± .09
Reduced	15.5 ± 5.0	26.3 ± 9.2	0.59 ± .06

Ventilation Mode	Total Inhalable Particulates		
	Room 12 ($\mu g/m^3$)	Outdoors ($\mu g/m^3$)	Ratio*
Normal	24.3 ± 8.3	39.5 ± 14.2	0.62 ± .10
Dampers closed	16.0 ± 3.5	23.3 ± 6.7	0.70 ± .07
Reduced	20.3 ± 6.2	37.5 ± 9.3	0.54 ± .06

*The Room 12/outdoors ratios were calculated for each day. The numbers are averages of the ratios obtained.

emissions from automobiles and the school boilers) was the only element present in any significant amount. Concentrations of 2 $\mu g/m^3$ (approximately 6 $\mu g/m^3$ as sulfate ion, $SO_4^{=}$) were typical indoors; the highest indoor level was 4 $\mu g/m^3$ (see Figure 13). Outdoor levels were as high as 8 $\mu g/m^3$.

The present standards for total suspended particulates for outdoor air are 75 $\mu g/m^3$ for a one year average and 260 $\mu g/m^3$ for a twenty-four hour average. The averages for twenty-four hours measured at the Fairmoor School at all three ventilation modes were well within these standards.

In summary, the indoor concentrations of both fine and coarse particulates were usually less than the outdoor levels and were considerably lower than the present standards for outdoor air for a twenty-four hour period. When the ventilation rate was reduced, there was no increase in the level of indoor particulates.

ENERGY SAVINGS

Fairmoor Elementary School occupies approximately 3995 m^2 (43,000 ft^2) of floor space and is located in a 2778 degree-day, base 18.3° C (5,000 degree-day, base 65°F) climate. The energy content of the natural gas consumed during the 1973-1976 time period averaged 6850 gigajoules/yr (6,500 x 10^6 Btu/yr). Natural gas is used for water and space heating, and minimally for warming precooked lunches.

If the amount of outside air entering the school is reduced, less natural gas will be needed for space heating. In estimating the potential energy savings at Fairmoor, we assumed a reduction in ventilation rate of 16.9 m^3/h (10 cfm) per person in the classrooms. This assumption was based on data obtained from various sources, as found in Arnold and O'Sheridan,[18] which have indicated that most schools have ventilation rates in the range of 16.9 to 25.3 m^3/h (10 to 15 cfm) per person, giving a mean of 21.1 m^3/h (12.5 cfm) per person, and on the the results of indoor air-quality studies at Fairmoor School and Carondelet High School,[13] which have confirmed that the ventilation rate could be lowered to 4.2 m^3/h (2.5 cfm) per person without adversely affecting classroom occupants.

To determine the yearly ventilation-heating load for the 2778 degree-day climate of Fairmoor School, we used previous calculations of yearly ventilation-heating load[19] in various locations of the United States to arrive at a figure of about 5.275 x 10^{-2} gigajoules/m^3/h (50,000 Btu/cfm) for the 9:00 a.m. to 5:00 p.m. period. That is, over a full heating season 5.275 x 10^{-2} gigajoules (50,000 Btu) is required to heat each m^3/h (cfm) of outside air to an indoor temperature of 21°C (70°F).

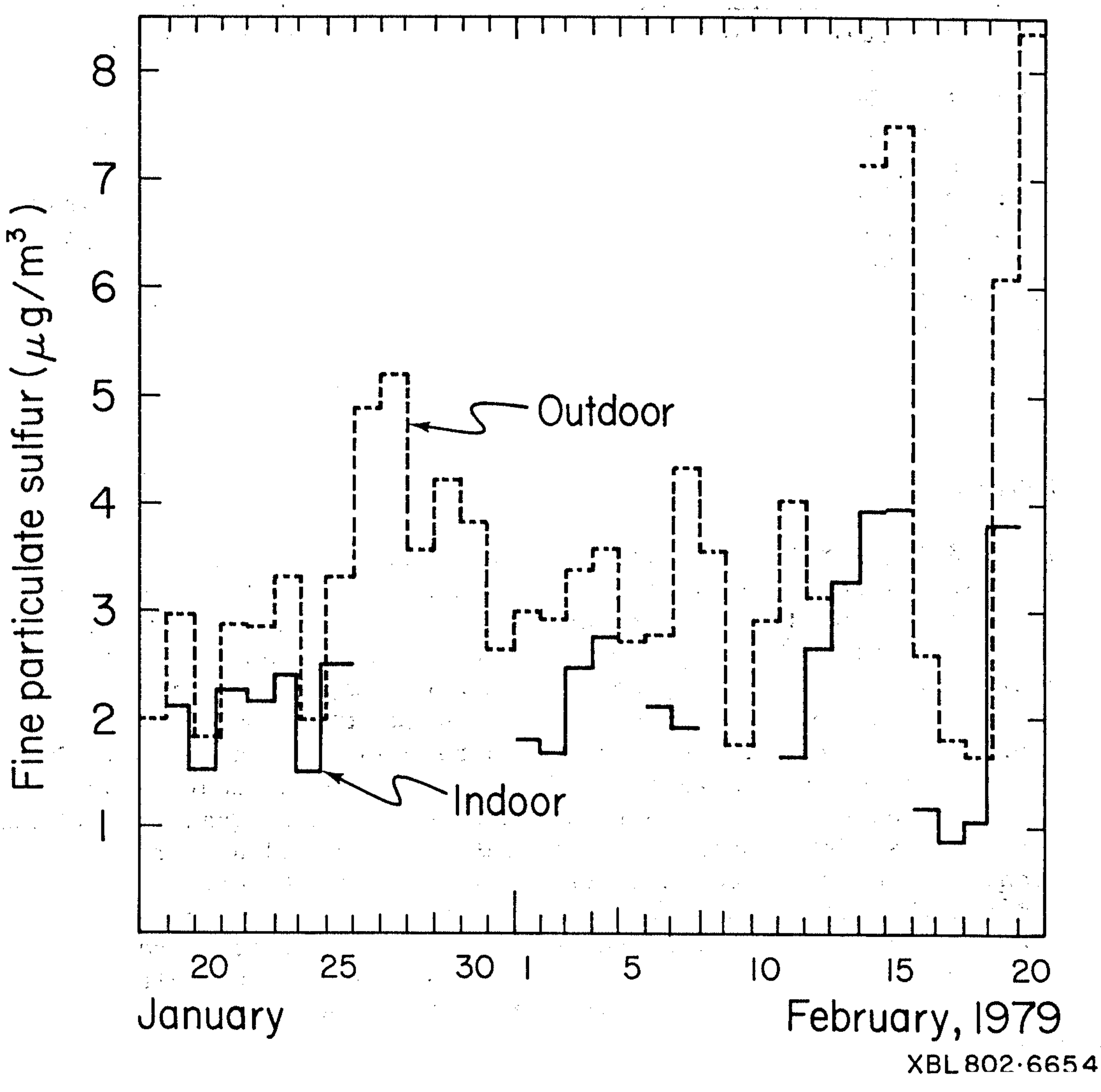

Figure 13. Fine particulate fraction of sulfur in Room 12 and outdoors during January and February, 1979.

If the ventilation rate is reduced from 21.1 to 4.2 m^3/h (12.5 to 2.5 cfm) per person in all twenty-four classrooms and from 50.6 to 33.8 m^3/h (30 to 20 cfm) per person in the multipurpose room, the energy saved is equal to

$$\frac{3.125 \times 10^{-2} \frac{GJ}{m^3/h} \times 11{,}816\ m^3/h}{0.6} = 615\ GJ\ (583 \times 10^6\ Btu)$$

where 0.6 is the efficiency of the heating system and 11,816 m^3/h (7,000 cfm) is the total amount by which the ventilation rate is reduced. For the Fairmoor School, this represents an energy savings of about 10% relative to the yearly energy used for space heating during the 1973-1976 period -- which at 1980 prices, would save over $2,000. This percentage energy savings is lower than it might be in most other schools since the heating system was operated at night in a number of classrooms at Fairmoor School during the 1973-1976 period when the natural gas consumption data were compiled. A more typical energy savings for space heating should be about 20% for schools located in northeastern or northern climates in the U.S.

CONCLUSIONS

In studying various environmental aspects at Fairmoor Elementary School under different ventilation conditions, we found that most pollutant concentrations did not increase even at ventilation rates below generally accepted standards. Of the air pollutants measured, only carbon dioxide increased significantly at lower ventilation rates. However, concentrations never exceeded 7,200 mg/m^3 (4,000 ppm), and thus remained well below levels considered to be hazardous to health. On the whole, the indoor concentrations of gaseous and other contaminants were very low. Reduced ventilation rates improved the air quality slightly in terms of sulfur dioxide and particulates, and did not affect microbial content. Odorant concentrations were low at both normal and reduced ventilation rates, although visitors to the test rooms found the odor levels somewhat less acceptable at reduced ventilation rates. The survey of subjective impressions of indoor air quality revealed a slight deterioration in student comfort when the ventilation rates were reduced.

These results support the feasibility of decreasing the amount of outside air entering the school so that less energy will be needed for heating. In fact, it appears that the outside air ventilation rate could safely be reduced to 4.2 m^3/h (2.5 cfm) per occupant, or half the ASHRAE minimum of 8.4 m^3/h (5 cfm) per occupant.* This conclusion is

---

* When certain conditions concerning filtration and recirculation are satisfied, 8.4 m^3/h (5 cfm) per occupant is the absolute minimum allowed by ASHRAE.

supported by the findings of the field monitoring project at Carondelet High School in California. The result of such a reduction in ventilation rates at Fairmoor Elementary School would be a moderate energy savings, without adverse effects for the health, safety, or comfort of the occupants.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the many people who assisted us in this project. We wish to thank the principal, Nettie McAllister, the staff, and students of Fairmoor Elementary School for their cooperation. Special thanks to Howard Whaley, the custodian, for his invaluable help in the school, and to the students of Rooms 12 and 20 and their teachers, Miss Sammett and Mrs. Lewis, for their patience and cooperation during the study. Bob Fuller and his staff at Ohio State University also assisted us in various aspects of the project.

The LBL Ventilation staff also helped immeasurably in completing this study. Specifically, we would like to thank Steve Brown for his help in the data reduction, James Koonce for the coordination and set up of the experiment, and Pamela Bostelmann and Jeana McCreary for preparing this report.

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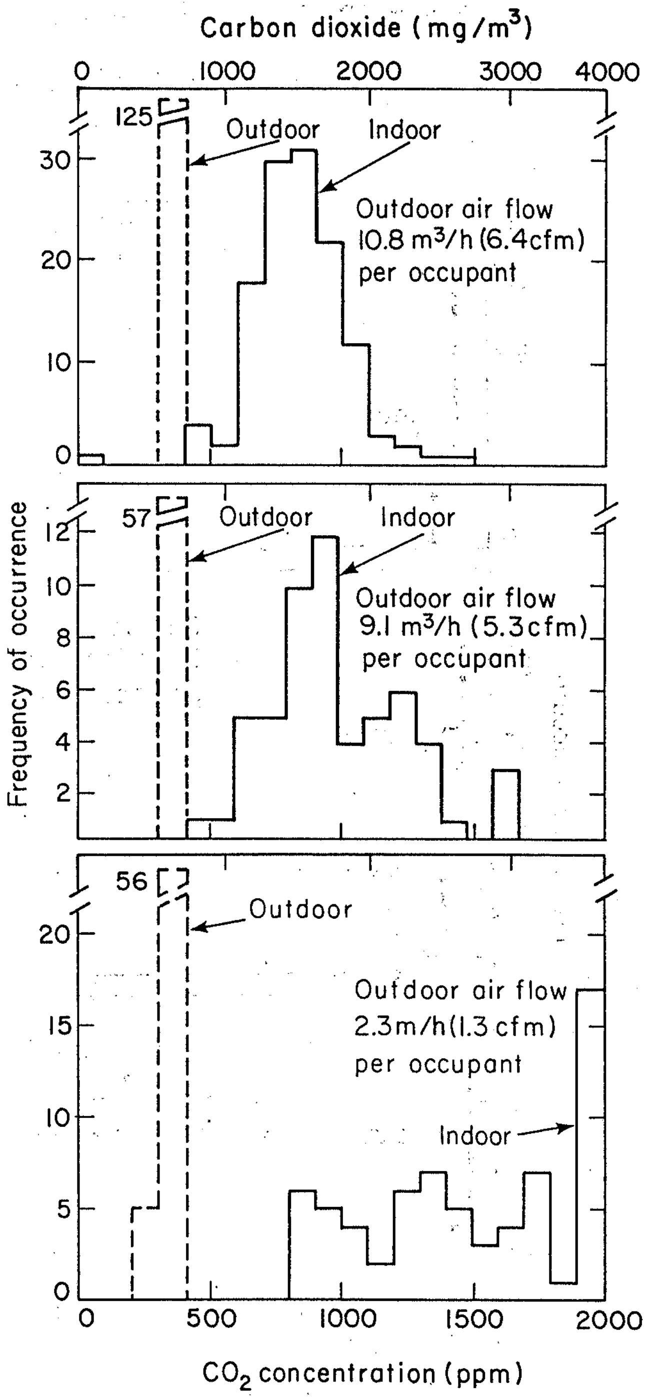
APPENDIX

The Appendix contains histograms of the concentrations of the common inorganic pollutants: carbon dioxide, carbon monoxide, ozone, sulfur dioxide, nitric oxide, and nitrogen monoxide. Only the data collected during the regular school hours, 8:30 a.m. to 3:30 p.m., has been included. For each room, the data on a particular pollutant has been grouped by ventilation rate.

CO$_2$ CONCENTRATIONS AT VARIOUS VENTILATION RATES

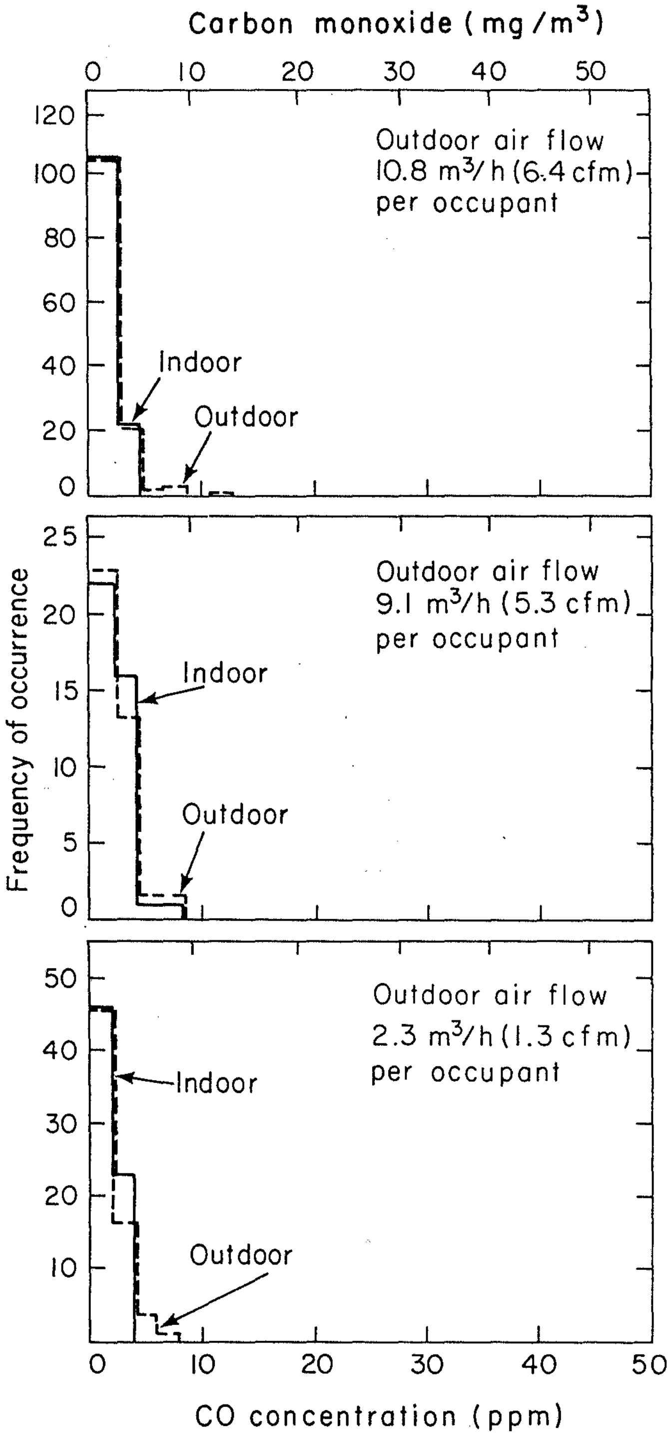
Room 12- Fairmoor Elementary School



XBL 7910-4311

CO CONCENTRATIONS AT VARIOUS VENTILATION RATES

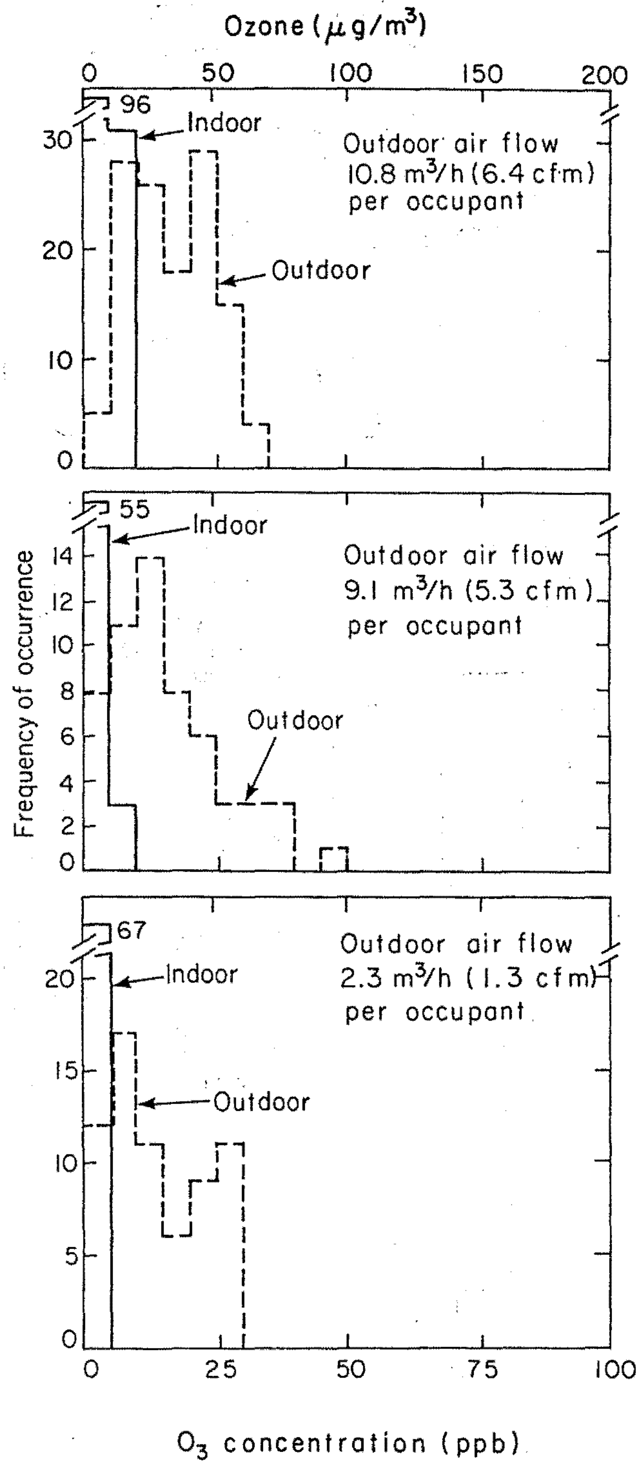
Room 12- Fairmoor Elementary School



XBL 7910-4310

O$_3$ CONCENTRATIONS AT VARIOUS VENTILATION RATES

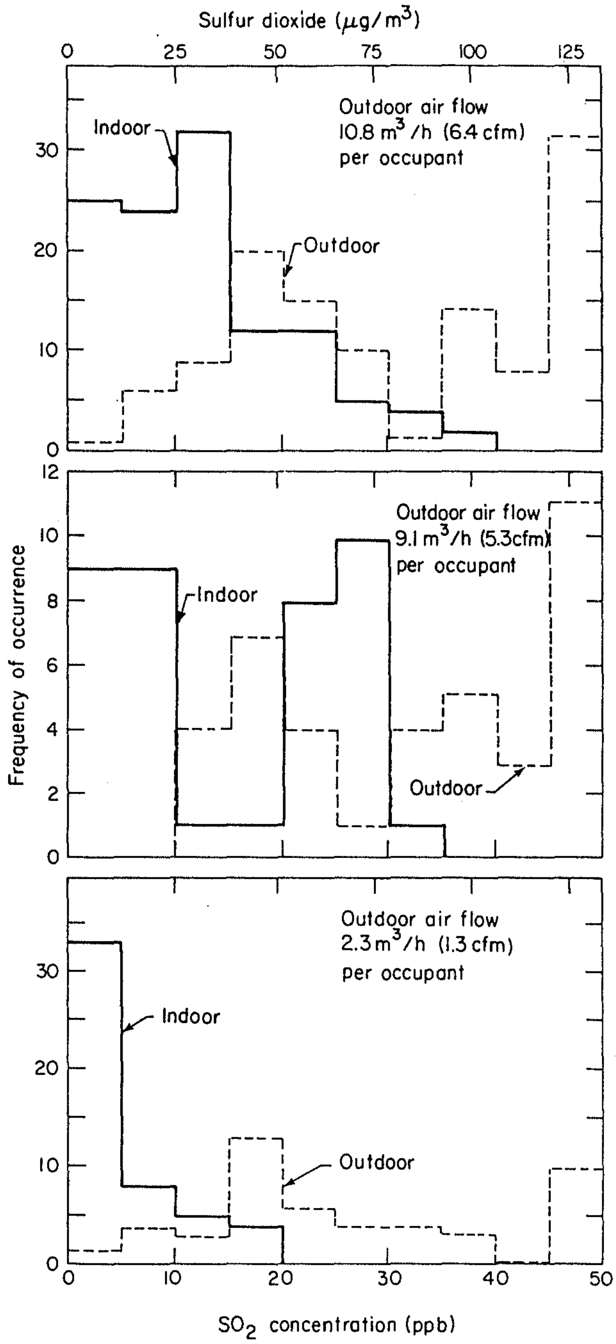
Room 12 - Fairmoor Elementary School



XBL 7910-4309

SO_2 CONCENTRATIONS AT VARIOUS VENTILATION RATES

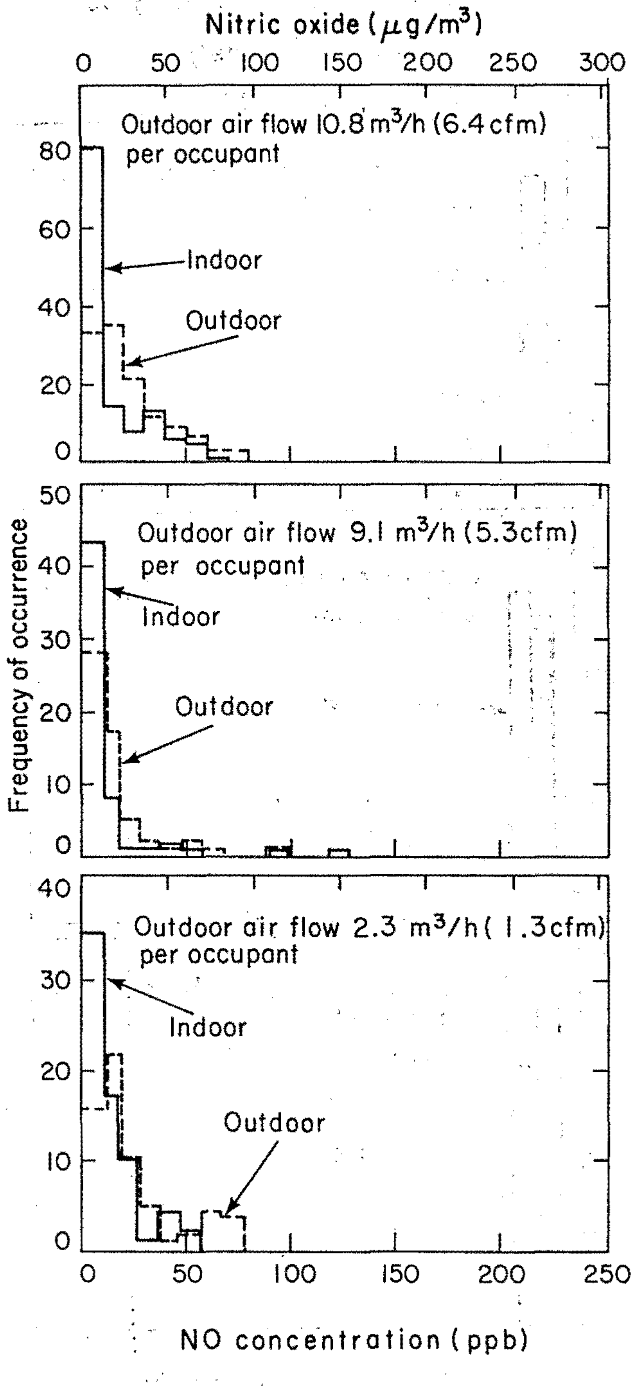
Room 12 - Fairmoor Elementary School



XBL 804-610

NO CONCENTRATIONS AT VARIOUS VENTILATION RATES

Room 12- Fairmoor Elementary School



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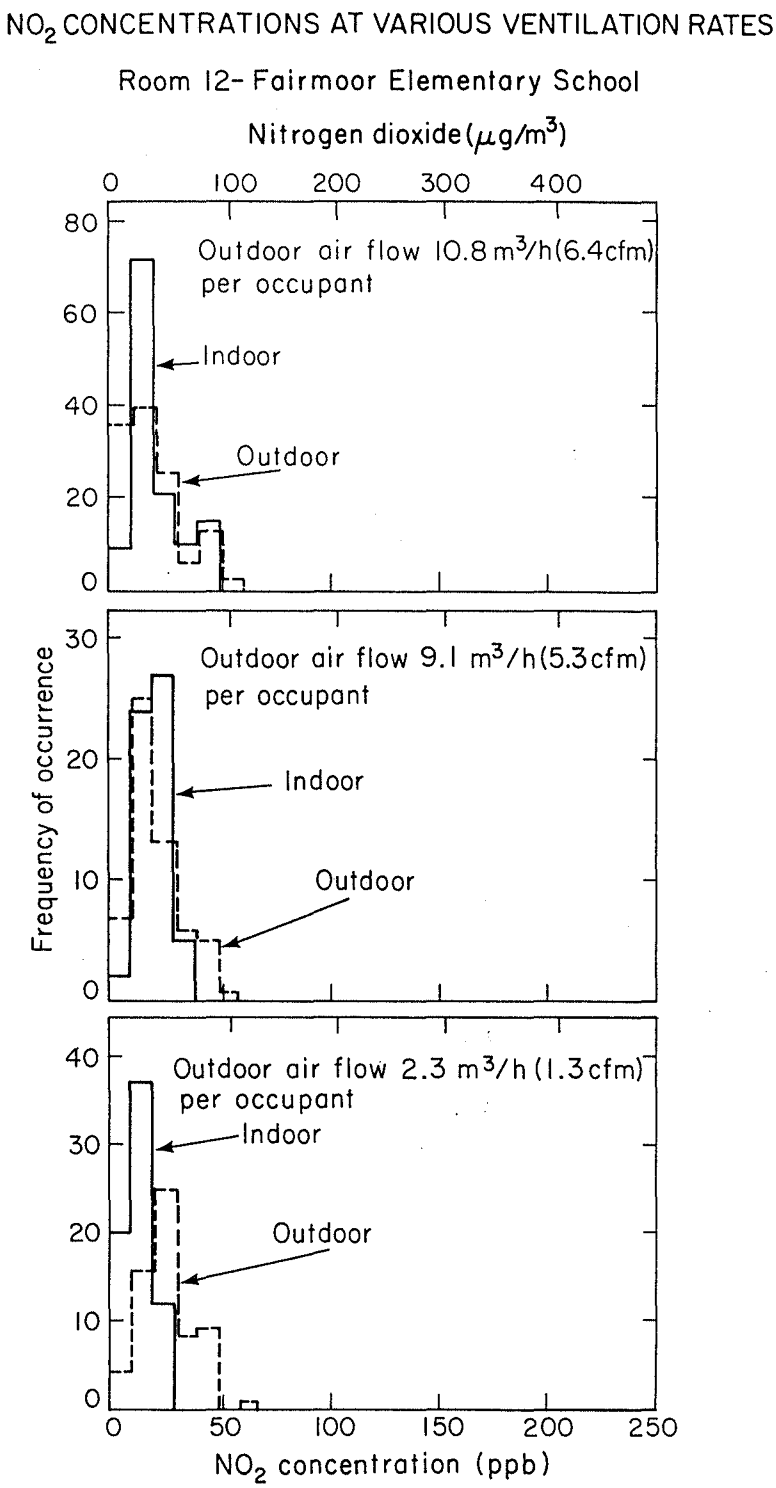

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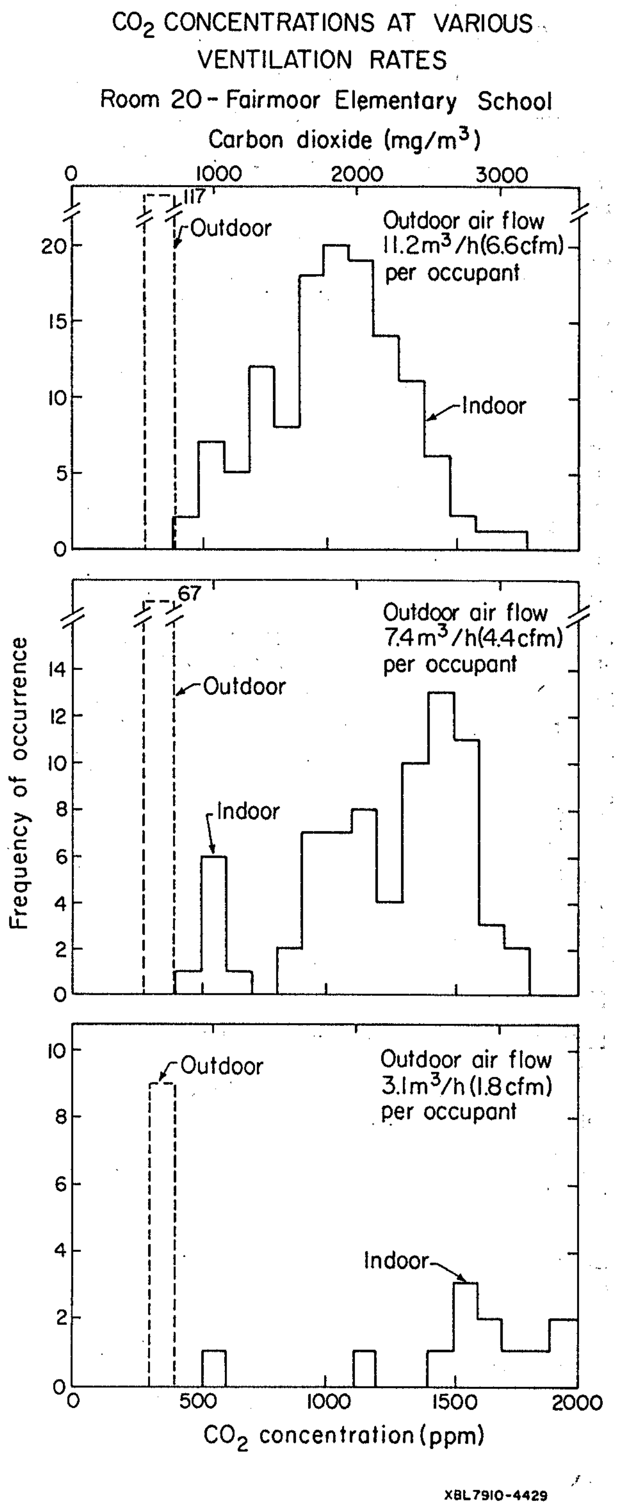
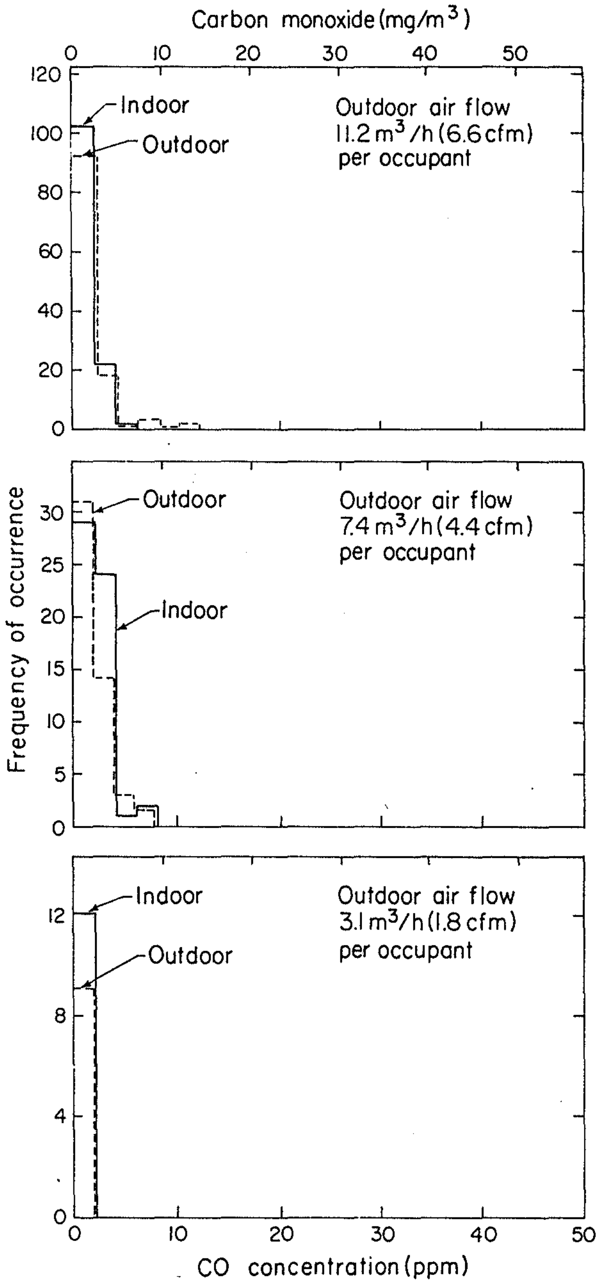


CO2 CONCENTRATIONS AT VARIOUS VENTILATION RATES
Room 20 - Fairmoor Elementary School
Carbon dioxide (mg/m3)
0
1000
2000
3000
117
Outdoor
Outdoor air flow 11.2m3/h(6.6cfm) per occupant
Indoor
67
Outdoor air flow 7.4m3/h(4.4cfm) per occupant
Outdoor
Indoor
Frequency of occurrence
Outdoor
Outdoor air flow 3.1m3/h (1.8cfm) per occupant
Indoor
0
500
1000
1500
2000
CO2 concentration (ppm)
XBL 7910-4429

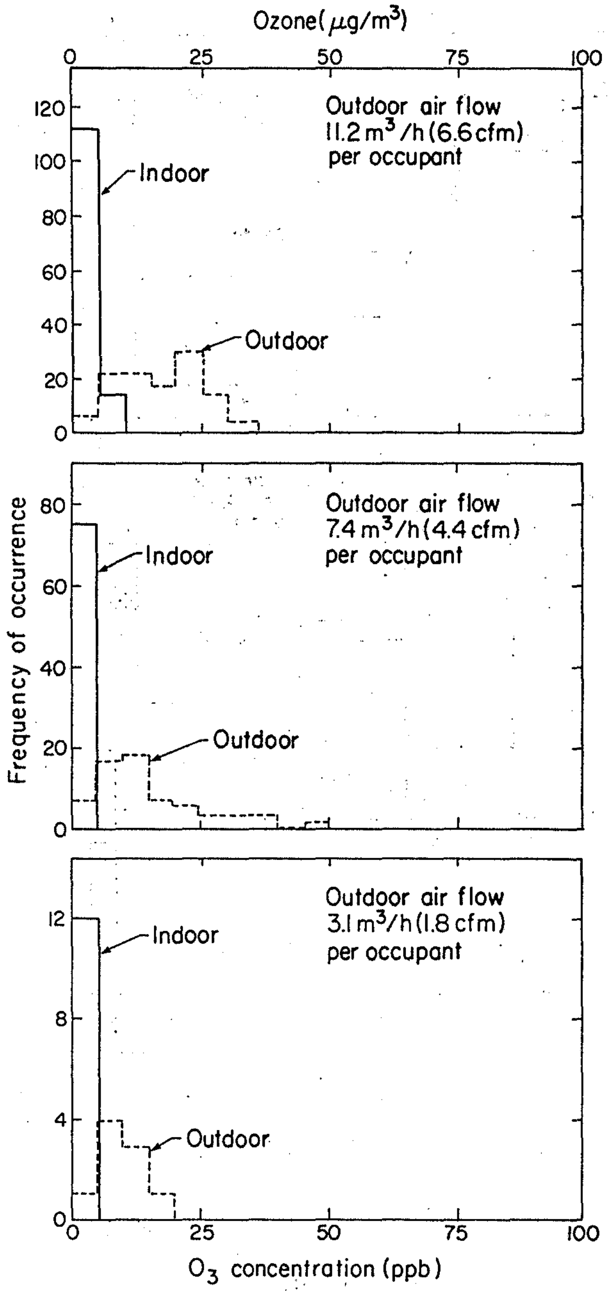
CO CONCENTRATIONS AT VARIOUS VENTILATION RATES
Room 20 - Fairmoor Elementary School



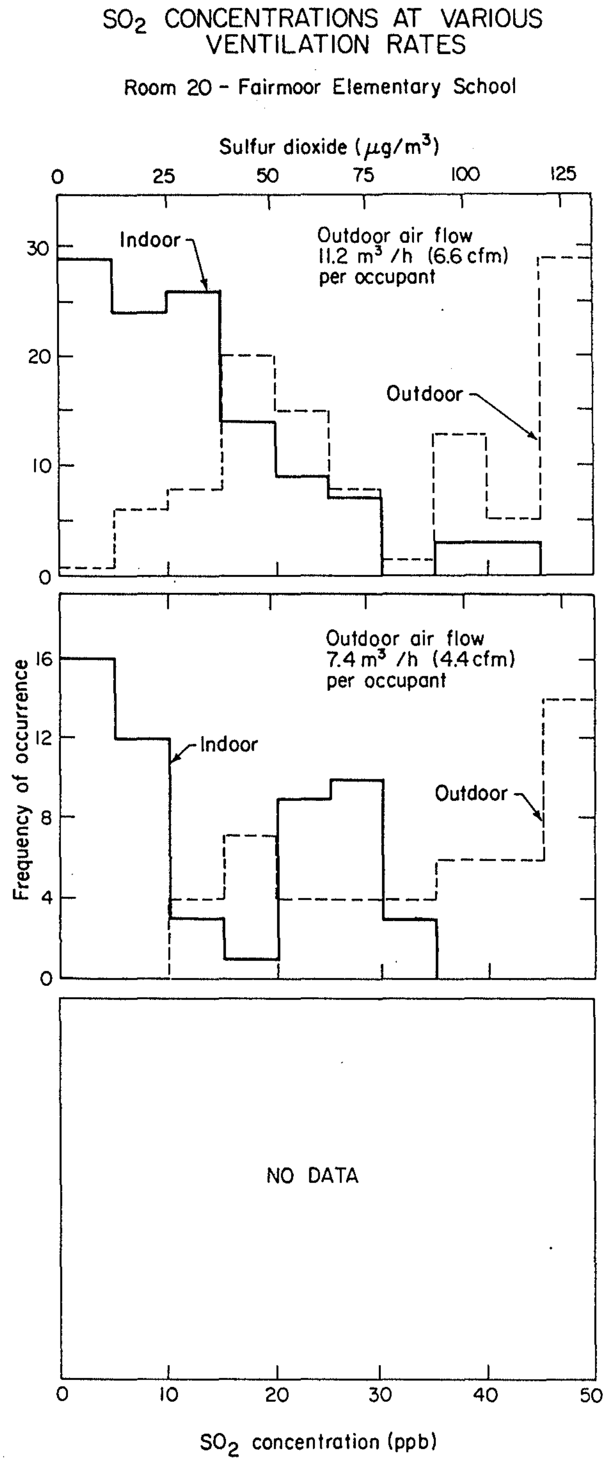
XBL 7910-4436

O_3 CONCENTRATIONS AT VARIOUS VENTILATION RATES

Room 20 - Fairmoor Elementary School

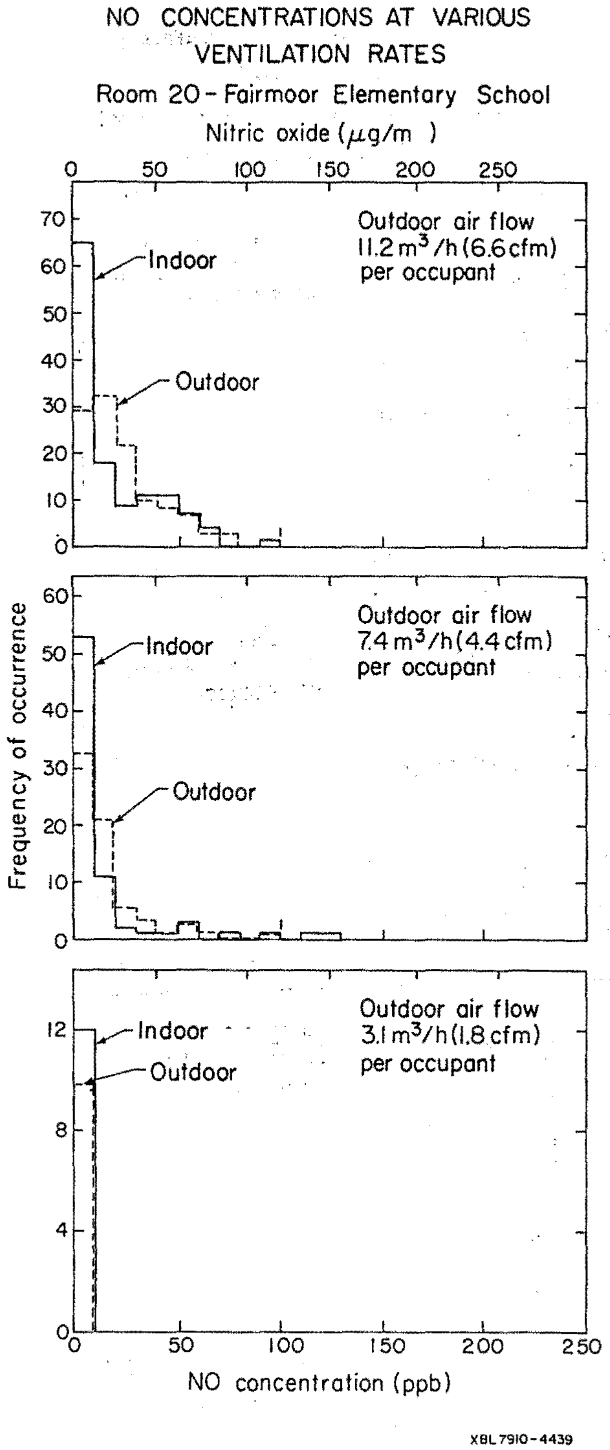


XBL 7910-4437



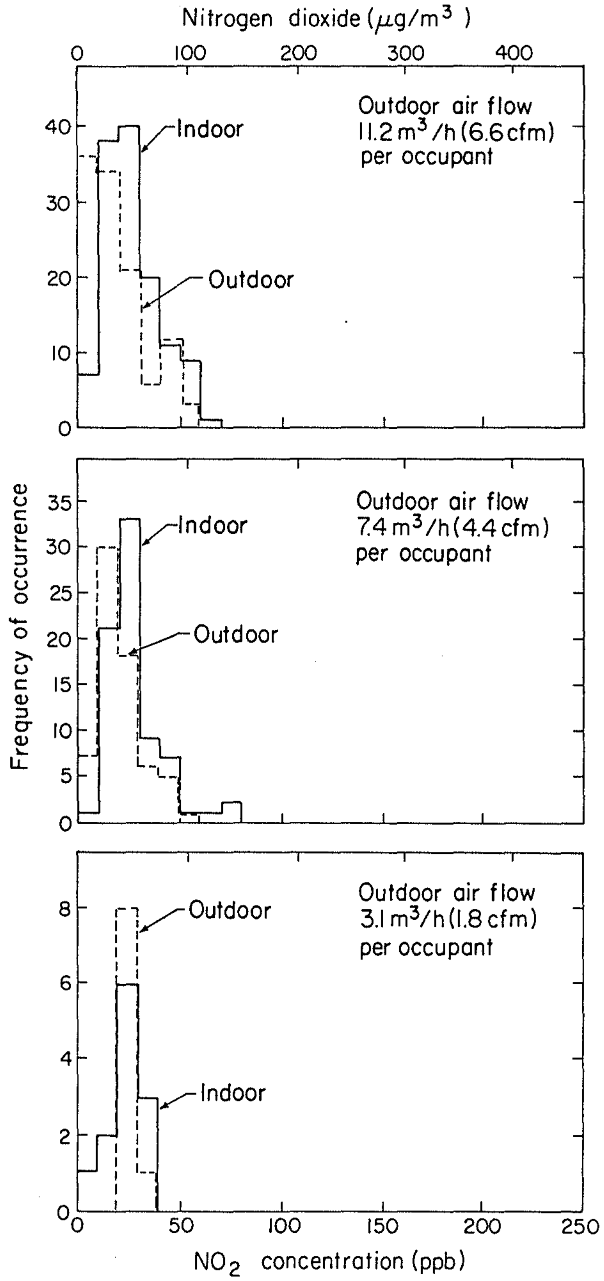
SO2 CONCENTRATIONS AT VARIOUS VENTILATION RATES
Room 20 - Fairmoor Elementary School
Sulfur dioxide (μg/m³)
0
25
50
75
100
125
Indoor
Outdoor air flow
11.2 m³ /h (6.6 cfm)
per occupant
Outdoor
30
20
10
0
Outdoor air flow
7.4 m³ /h (4.4 cfm)
per occupant
Indoor
Outdoor
Frequency of occurrence
16
12
8
4
0
NO DATA
0
10
20
30
40
50
SO2 concentration (ppb)

XBL 804-608


NO CONCENTRATIONS AT VARIOUS VENTILATION RATES
Room 20 - Fairmoor Elementary School
Nitric oxide (μg/m)
0
50
100
150
200
250
Outdoor air flow
11.2 m³/h (6.6 cfm)
per occupant
Indoor
Outdoor
Outdoor air flow
7.4 m³/h (4.4 cfm)
per occupant
Indoor
Outdoor
Outdoor air flow
3.1 m³/h (1.8 cfm)
per occupant
Indoor
Outdoor
Frequency of occurrence
NO concentration (ppb)
XBL 7910-4439

NO$_2$ CONCENTRATIONS AT VARIOUS VENTILATION RATES

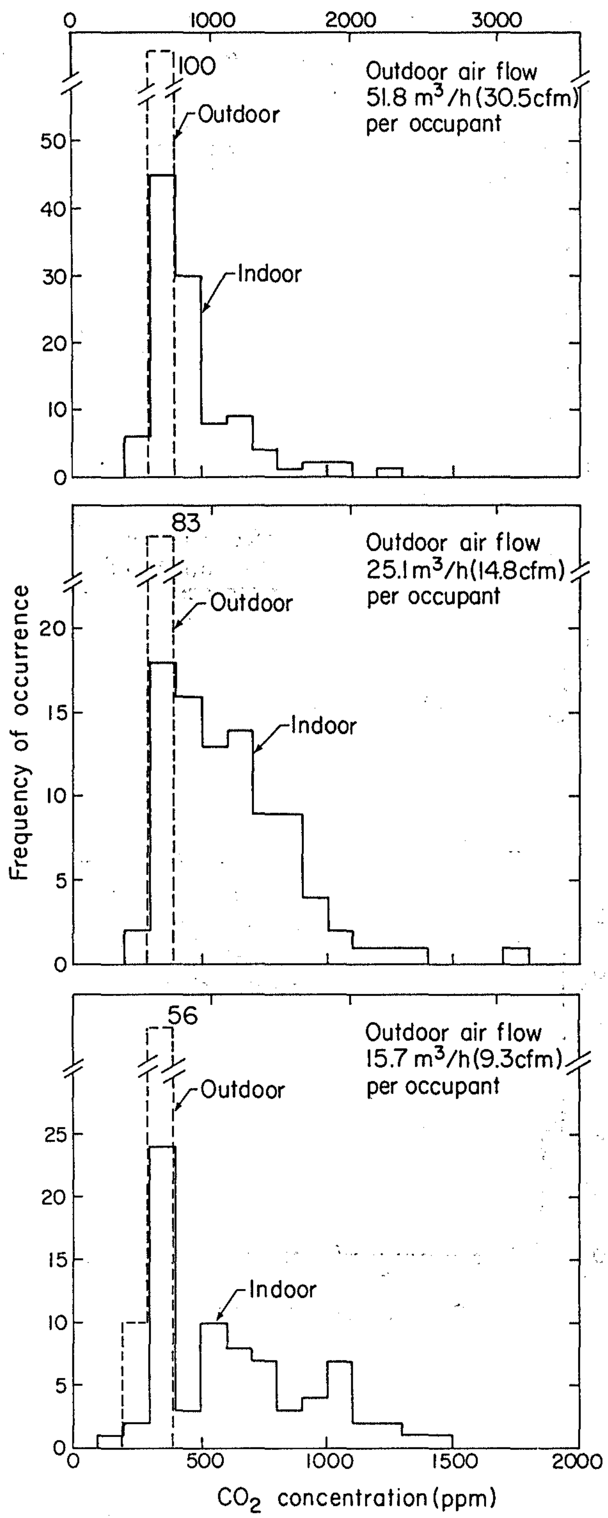
Room 20 - Fairmoor Elementary School



XBL 7910-4438

CO_2 CONCENTRATIONS AT VARIOUS VENTILATION RATES

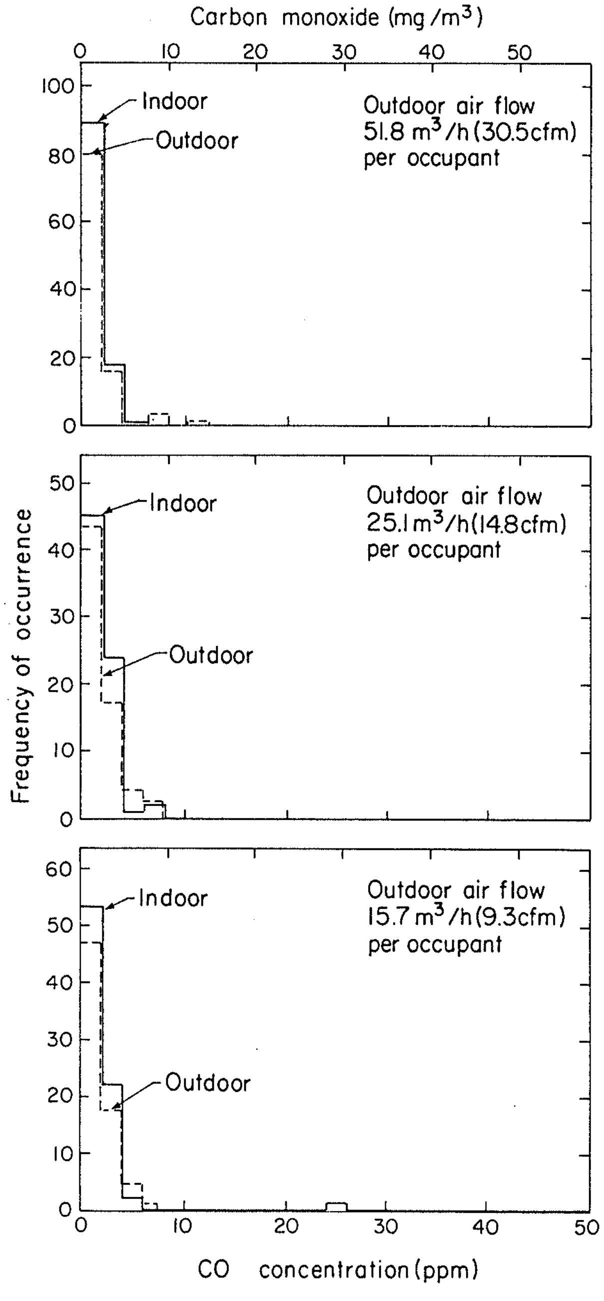
Multipurpose Room–Fairmoor Elementary School



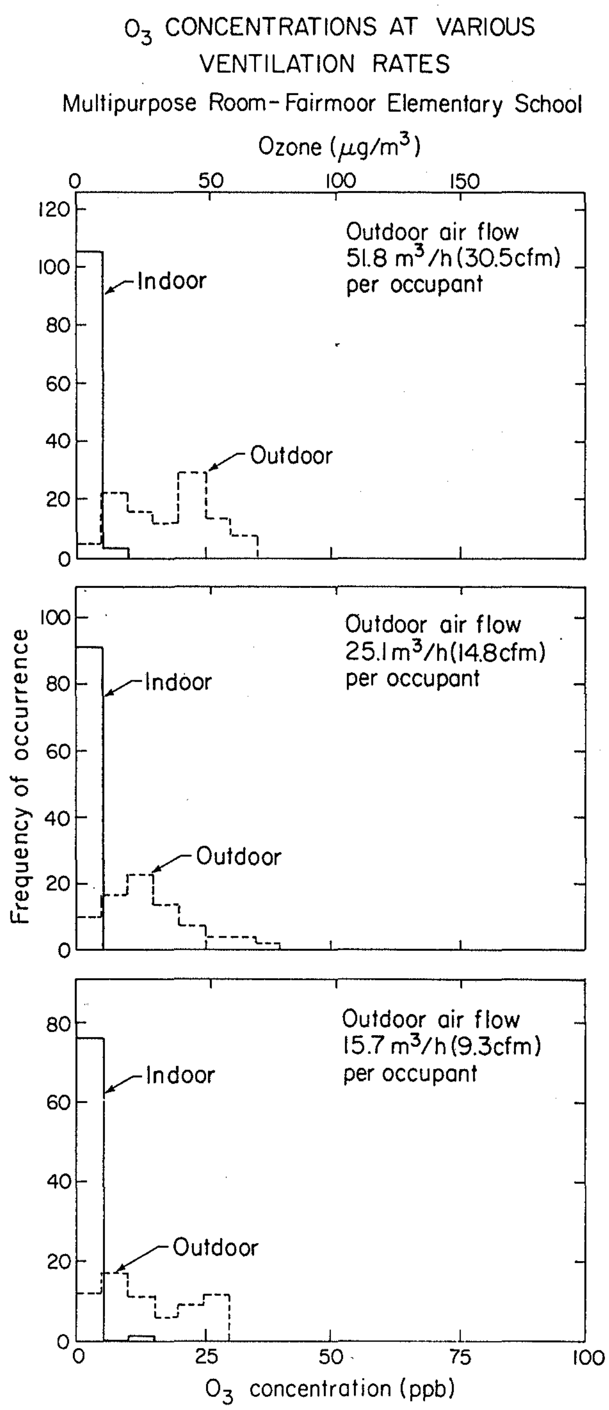
XBL 7910-4430

CO CONCENTRATIONS AT VARIOUS VENTILATION RATES

Multipurpose Room - Fairmoor Elementary School



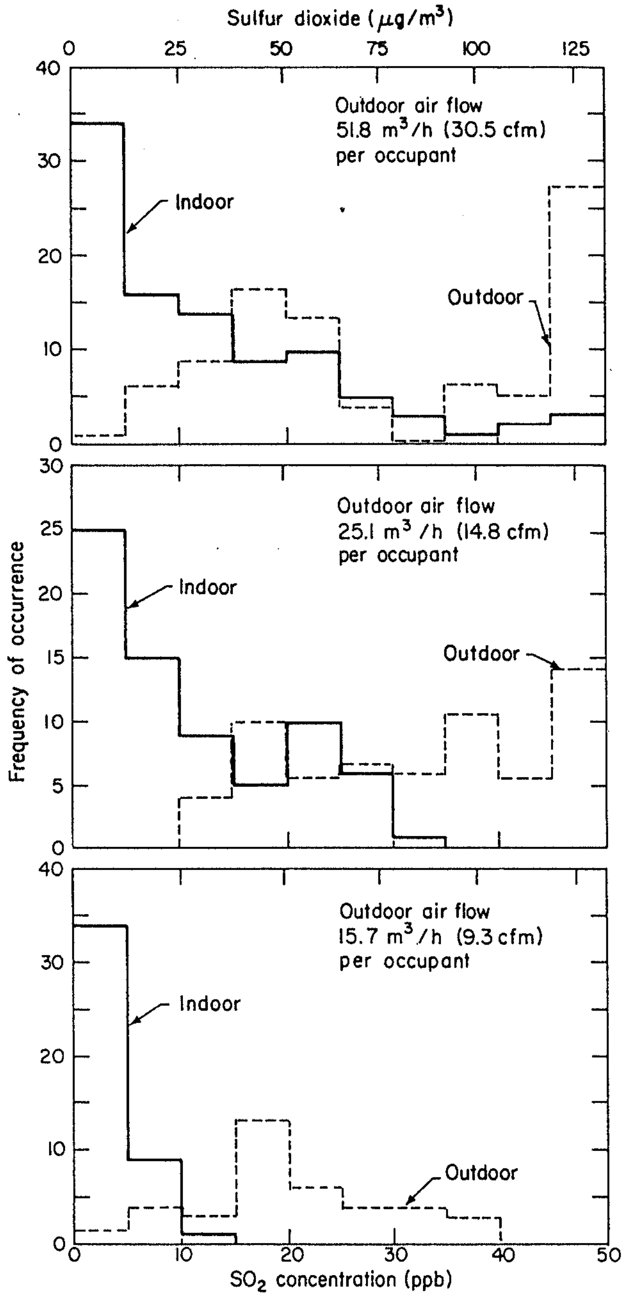
XBL 7910-4432



XBL 7910-4433

SO_2 CONCENTRATIONS AT VARIOUS VENTILATION RATES

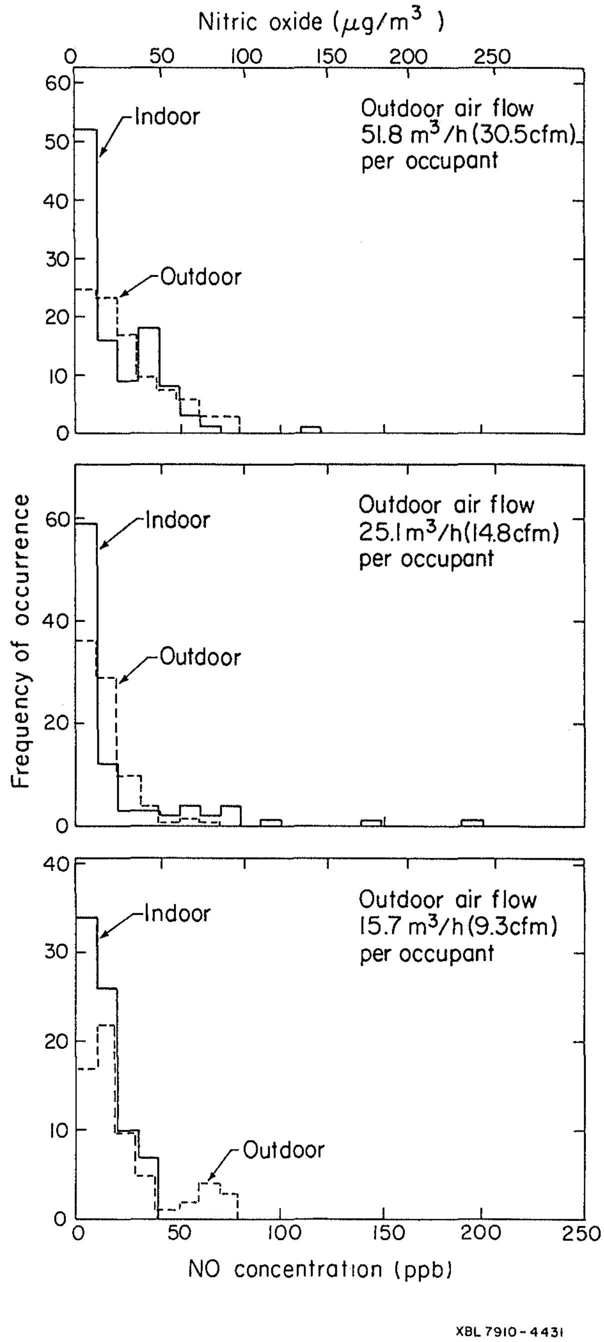
Multipurpose Room – Fairmoor Elementary School



XBL 804-609

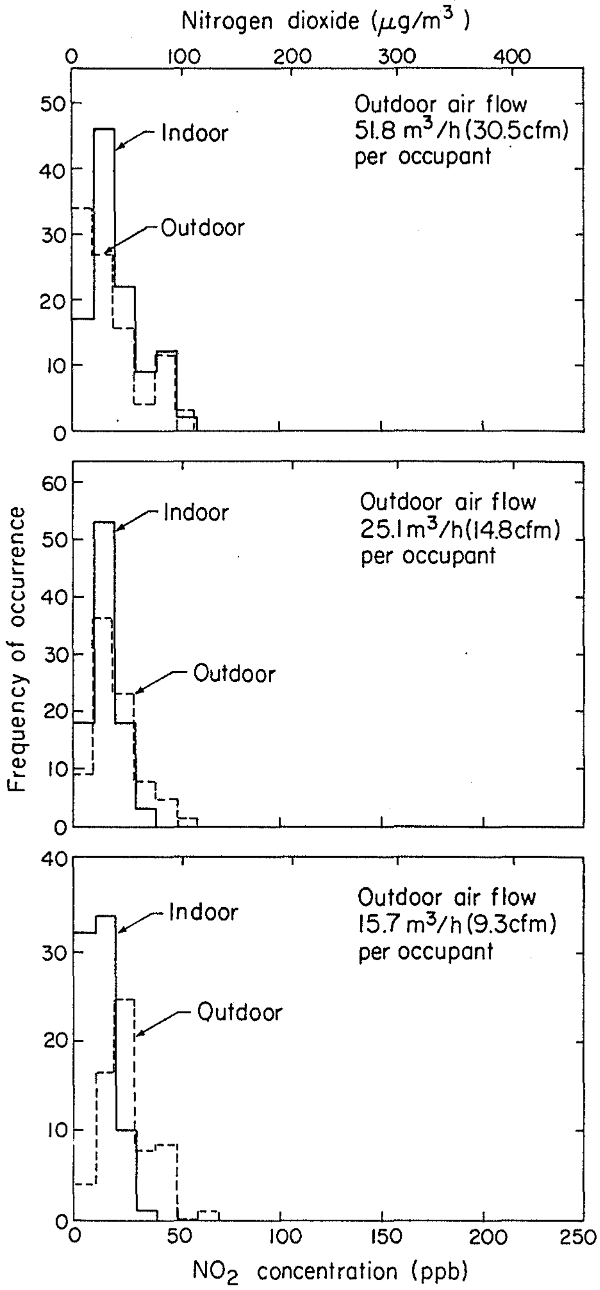
NO CONCENTRATIONS AT VARIOUS VENTILATION RATES

Multipurpose Room- Fairmoor Elementary School



NO$_2$ CONCENTRATIONS AT VARIOUS VENTILATION RATES

Multipurpose Room - Fairmoor Elementary School



XBL 7910-4434