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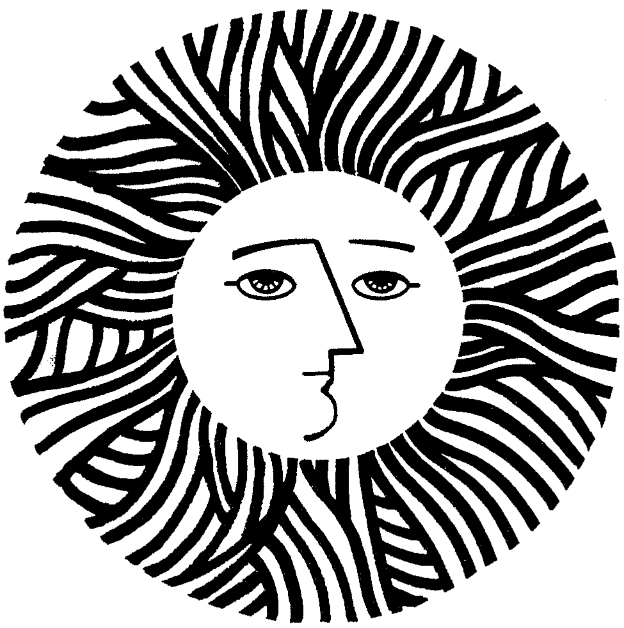
July 1979



Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

LBL-9174
EEB-Vent 79-5

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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 Applications of the U.S. Department of Energy under contract No. W-7405-ENG-48.

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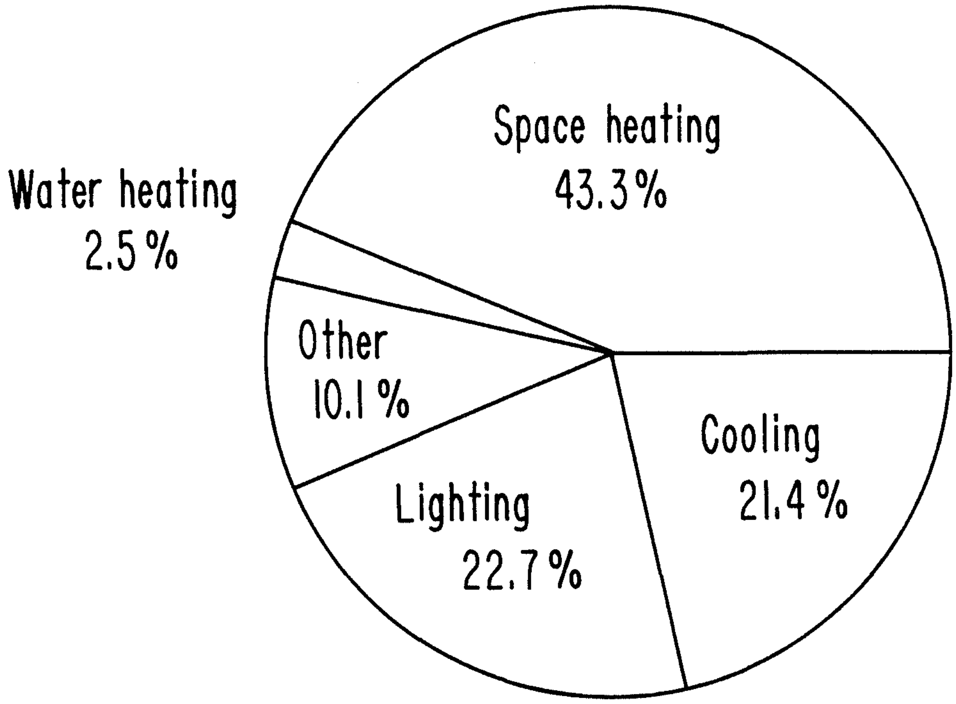
Abstract

The indoor air quality in an air conditioned California high school has been measured over a range of ventilation rates ranging from 13.3 cubic feet of outside air per minute for each classroom occupant to approximately 1.5 cfm per occupant. The purpose of this pilot study is to determine the effect of reduced ventilation on indoor air quality and energy use. Parameters measured include outside air supply rate, the occupants' subjective perception of indoor air quality, microbial burden and the concentrations of carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, and ozone in two classrooms, a hall, and outdoors. Results show that carbon dioxide was the only parameter to show a substantial increase in indoor concentration when ventilation rates were reduced; however, classroom levels of carbon dioxide still remained far below levels considered to be a health hazard. This study indicates that at Carondelet High School, moderate energy savings are possible without significant deterioration of indoor air quality, and that substantial energy savings would be possible in a more severe climatic region.

Keywords: air pollution, airborne microorganisms, bacteria, carbon dioxide, carbon monoxide, energy conservation, indoor air quality, nitrogen oxides, odors, outdoor air, ozone, psychophysical methods, school buildings, sulfur dioxide, ventilation, ventilation rate

INSTITUTIONAL AND COMMERCIAL BUILDING ENERGY USE (1975)



From: Commercial Energy Use: A Disaggregation by Fuel, Building Type and End Use, ORNL/CON-14 Oak Ridge National Laboratory, Oak Ridge, Tennessee

XBL 796-10231

Figure 1. Primary energy use for all non-residential buildings partitioned into four main functional uses.

It appears that the recommended outside air ventilation rates in ASHRAE Standard 62-73 are based largely on odor research performed by C.P. Yaglou et al. (3) at the Harvard School of Public Health forty years ago. These investigators used clothed, sedentary subjects to generate an odorous environment. They placed between 3 and 14 subjects in an airtight room (1410 ft^3) and, during a 3.5 hour period, observers periodically entered from an odorless room to rate odor levels. By varying both the number of people in the chamber and the outdoor air ventilation rate, curve C in Figure 2 was generated from Yaglou's data. In a space occupied by adults with 350 ft^3 per person, 10 cfm per person were required to control odors. Function A represents the ventilation rate necessary to maintain sufficient oxygen (19%) and function B represents the rate necessary to prevent the CO_2 concentration from exceeding 5000 parts per million (ppm), the maximum allowable CO_2 concentration established by OSHA (Occupational Safety and Health Administration) (4) and ACGIH (American Conference of Governmental Industrial Hygienists) (5). According to curve C, for adult subjects practicing "normal" hygiene, ventilation rates sufficient to control odors also satisfy oxygen and carbon dioxide criteria.

Educational facilities have been selected for special study for several reasons:

1. The U.S. National Energy Act provides support for energy conserving retrofits in schools and hospitals.

2. There is a relatively high energy use among institutional and commercial buildings.

3. A large fraction of energy use is apportioned to the heating and cooling of outside ventilation air in these buildings. Educational facilities and hospitals together consume about 3 x 10^{15} Btu/year or 4% of the total U.S. energy use.

In addition to aiding in the implementation of the National Energy Act, ventilation research is expected to provide input for the development of building energy performance standards (BEPS). The BEPS contain energy budgets for new institutional, commercial and residential buildings in various climatic zones. The Department of Housing and Urban Development (HUD) and the Department of Energy (DOE) are working together with a target date of 1980 for promulgation of these Standards. Periodic updates of the Standards will consider advances in such areas as construction and energy technologies and the state of the art of building technology.

EXPERIMENTAL FACILITIES

EEB Mobile Laboratory

The Energy Efficient Buildings (EEB) Mobile Laboratory (6) is designed for field studies of ventilation requirements and energy utilization in buildings. The laboratory was built in early 1978 to monitor the parameters listed in Table II.

Table II. Parameters Measured by the Energy Efficient Buildings Mobile Laboratory.

- Continuous Monitoring Instruments:
  - Infiltration
    - N_2O or C_2H_6(Tracer gas)
  - Indoor Temperature and Moisture
  - Outdoor Meteorology
  - Gases
    - SO_2
    - NO, NO_x
    - O_3
    - CO
    - CO_2
    - Radon (Passive Monitors)
  - Particulate Matter
    - Size Distribution
- Sample Collectors
  - Gases
    - Formaldehyde
    - Total Aldehydes
  - Particulate Matter
    - Aerosols (Respirable/ Non-respirable)
    - Bacterial Content

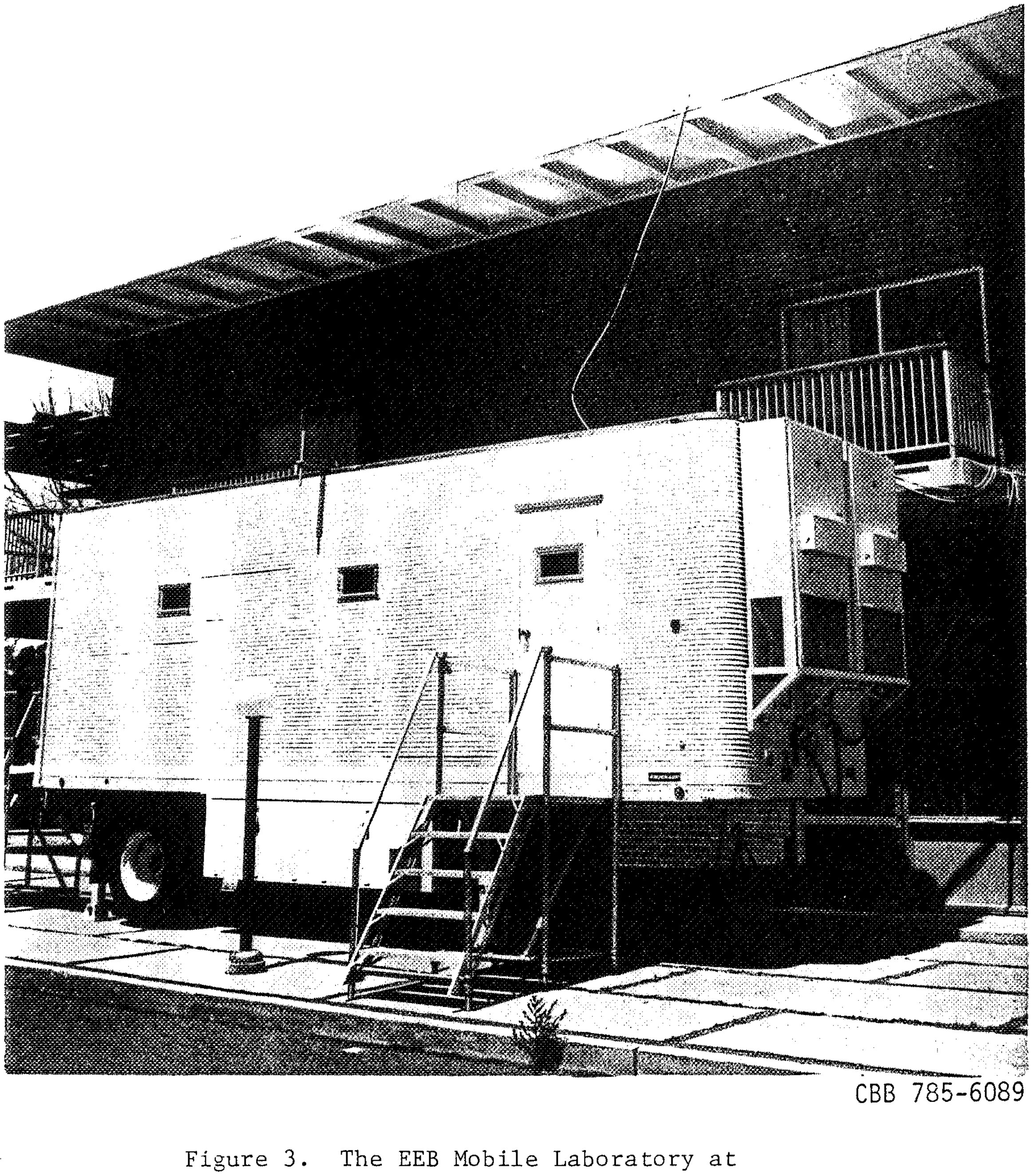


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Figure 3. The EEB Mobile Laboratory at Carondelet High School.

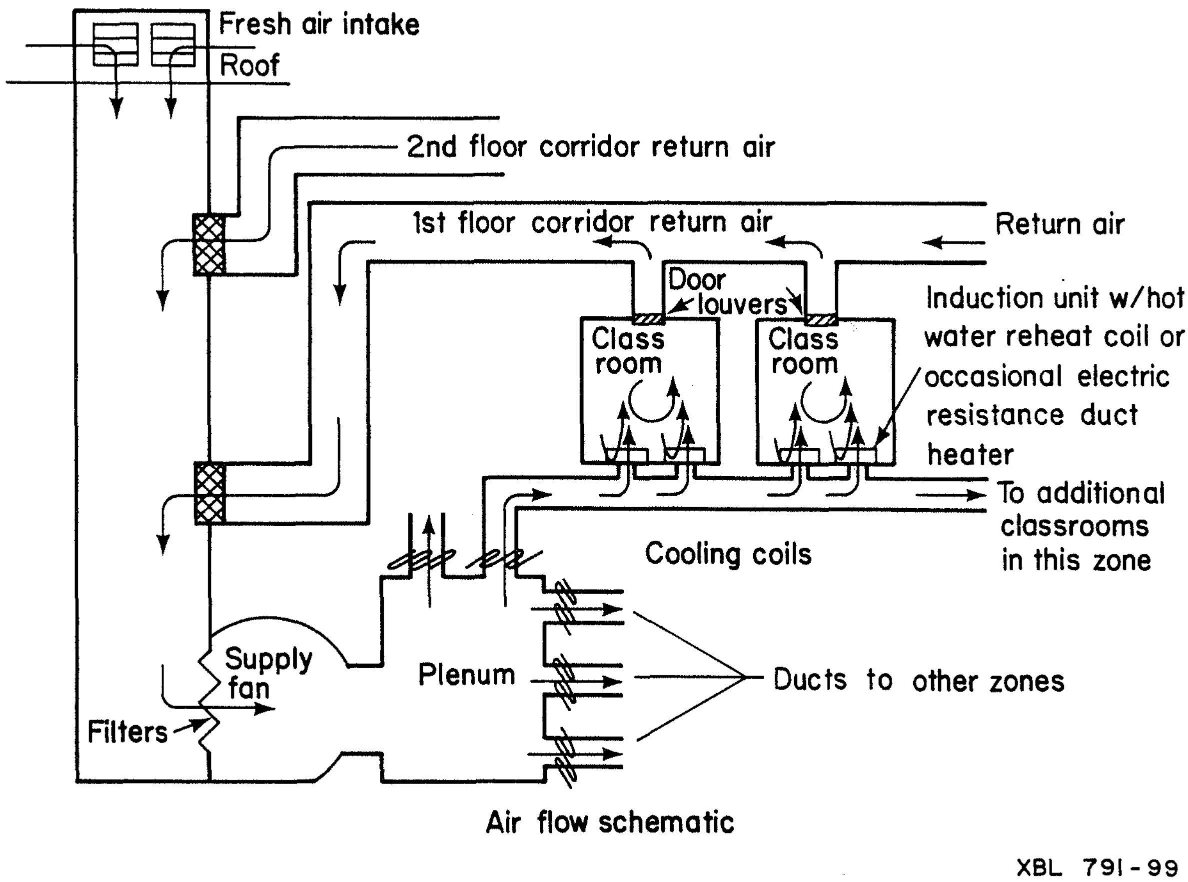


Figure 5. Schematic of ventilation system. Primary air is drawn by the supply fan through filters and directed to a plenum. The air passes over cooling coils and through ducts, each of which supplies several classrooms. If necessary, the induction units heat the air as it enters the classrooms. Classroom air then passes through door louvers into the hallway and is drawn towards air return gratings in the main supply shaft.

through these coarse particle filters. This air, called "primary air," consists of a mixture of outdoor air from the roof and recirculated air from the first and second floor hallways. The recirculated air enters the shaft through two gratings, each approximately three feet by six feet, at the first and second floor levels (Figure 7). The air mixture is drawn through the fan and forced into a large plenum chamber where it is directed into ten ducts, each supplying a zone of several classrooms. Cooling coils are located at the entrance to each duct and the air supplied to all rooms in a particular zone is cooled at this point. Air enters each classroom through two induction units, each supplying approximately 400 cfm of primary air. The induction units have heaters to warm the air as necessary. As the primary air is injected into the classroom, it causes the air already in the room to be drawn into the induction unit, thus increasing circulation in the classroom. The classroom door has louvers which allow the excess air to pass into the corridor, where it drifts toward, and eventually through, the grating into the intake shaft. This system places the entire building under positive pressure, thereby essentially eliminating infiltration. By changing the amount of outdoor air entering from the roof, which is practically all the outdoor air entering the building, the relative proportions of outdoor and recirculated air can be altered.

The main supply fan was designed to deliver 44,200 cfm of primary air from the shaft, independent of the ratio of outdoor air to recirculated air. The induction units in the classrooms each require about 400 cfm primary air to operate properly. Primary air flow was measured through four individual induction units, and the total primary flow in each classroom was found to be within 2% of 800 cfm. To determine the relative amounts of outdoor and recirculated air which make up the primary air, temperature and relative humidity measurements were made of the incoming outdoor air, recirculated air in the corridors, and of the mixture of the two (primary air). By making these measurements on days when there was a large temperature differential between the indoor and outdoor air, estimates were made to determine the net amount of outdoor air being supplied to the school under normal operating conditions.

The primary air consisted of approximately 45% outdoor air when the dampers were in their normal, fully open position. This is an average of about 28.5 cfm outdoor air per person for the entire building. For a single classroom with 27 occupants, supplied with a total of 800 cfm primary air by two induction units, this corresponds to approximately 13.3 cfm (22.6 m^3/h) of outdoor air per person.

Experimental Procedures

The outside air entering the school was measured and regulated at various flow rates in order to assess the energy savings and the impact on indoor air quality. Three sides of the air intake unit intake dampers were sealed and an air-flow measuring device and flow controller were installed on the remaining side (Figure 6). This apparatus included a rectangular duct to streamline the air flow, a matrix of connected copper tubes facing upstream to measure and average the pressure due to the air flow, and an inclined manometer to read the flow rate and velocity. In addition, a pressure sensing device was linked to a mechanical damper system to regulate the flow of outdoor air. This system compensated for variations in building pressure (due to the opening and closing of doors), variations in outdoor air velocity, and variations in the flow of exhaust air. The pressure sensing device was set to maintain the air flow in a specified range. If the flow and corresponding pressure increased or decreased beyond the desired interval, a motor was activated which closed or opened the dampers enough to return the air flow to its proper range. The air flow controlling device was not a precision instrument, but flows were held to within ten percent of the desired rate.

The air quality inside two classrooms, a corridor, and outdoors was monitored under three ventilation rates. The first rate was the normal operating mode with the roof dampers in the fully open position. The second and third rates restricted total outdoor air to the school. The amounts of outdoor air supplied to the entire school in the three cases were: 20,000 cfm, 3700 cfm, and 2300 cfm, per student respectively. It should be noted that a decision to restrict the outdoor air to 2300 cfm was not made until it had been established that the indoor air quality at 3700 cfm was still very good. In a typical classroom with 27 students receiving 800 cfm primary air, these rates correspond to 13.3, 2.5, and 1.5 cfm of outside air per student (in S.I. units, 22.6, 4.2, and 2.5 m^3/h respectively).

RESULTS AND DISCUSSION

Ventilation Rate and Chemical Indoor Air Quality

Data were collected for ventilation rates of 20,000 cfm, 3700 cfm, and 2300 cfm, which represent the volume of outside air supplied to the entire building each minute. It should be noted that data were collected for only a few days for each rate, and that classroom attendance was slightly irregular, since the monitoring took place during the last few weeks of the school year.

Carbon dioxide was the only pollutant detected in significant concentrations inside the school. This is not surprising, since there were no obvious indoor sources of pollution other than the occupants themselves. The school borders on a main thoroughfare; during periods when increased levels of ozone were present outdoors, smaller but measurable concentrations were observed indoors. Indoor concentrations of these pollutants actually decreased as the outdoor air ventilation rates were reduced.

Figure 8 shows the CO_2 buildup and decline during a typical day at the restricted outdoor air ventilation rate of 3700 cfm for the entire school. Concentrations in the two classrooms, a hallway and outdoors are shown. As can be seen, the variations in the two classrooms closely parallel each other. The lack of occupancy during the lunch hour results in reduced CO_2 concentrations in the classrooms. The hall serves to smooth these variations as the air from many classrooms and the large indoor court area mix. The outdoor concentrations are shown for comparative purposes.

Because the air quality in the two classrooms and hall was found to be nearly identical, the following discussion refers to only one indoor site; however, the conclusions are intended to apply to the entire school.

Figure 9 shows three histograms of the frequency of occurrence of CO_2 concentrations in one classroom and outdoors for all data points between 8:00 a.m. and 3:00 p.m. on school days. These diagrams show the ranges of concentrations observed for each ventilation rate and how these ranges shifted as the ventilation rates were reduced. Although CO_2 concentrations inside the classroom increased as ventilation rates were lowered, at no time did they exceed 2000 ppm, and only occasionally did they exceed 1500 ppm. This should be compared to the National Institute for Occupational Safety and Health (NIOSH) recommended ten-hour maximum of 10,000 ppm (8); the American Conference of Governmental Industrial Hygienists (ACGIH) recommended 8-hour maximum of 5000 ppm (5); and the Occupational Safety and Health Administration (OSHA) recommended 8-hour maximum of 5000 ppm (4). These concentrations refer to a time weighted average concentration for up to 8 and 10-hour workshifts in a 40-hour work week. Studies have shown that humans may be repeatedly exposed to these concentrations day after day without adverse health effects (8).

The ratio of indoor concentration to outdoor concentration for carbon dioxide was calculated for all data points between 8:00 a.m. and 3:00 p.m. on school days for each ventilation rate. Histograms summarizing this ratio are shown in Figure 10. Although limited data was available at the most restricted ventilation rates, the increase in this ratio is evident as the ventilation rates were reduced.

Figure 11 shows the variations of ozone with ventilation rate. Ozone concentrations were generally lower when the flow of outdoor air into the school was reduced. This behavior is characteristic of reactive pollutants when the primary sources are outdoors and the building envelope functions as a barrier. The indoor/outdoor ratios are shown in Figure 12. Inasmuch as these ratios decreased as ventilation rates were reduced, this component of indoor air quality improved.

Figure 13 illustrates the effects of reduced ventilation on carbon monoxide concentrations. The indoor and outdoor concentrations were nearly equal at all ventilation rates. Significant indoor sources of carbon monoxide (such as cigarette smoke) were not expected at this school.

Because this was the first field site for the EEB Mobile Laboratory, some equipment problems were experienced and data are not complete for all parameters. Sulfur dioxide results are not given because of electronic drift problems but indoor concentrations tended to be lower than outdoor ones and no concentrations higher than 30 ppb were measured. Concentrations of the nitrogen oxides were measured only during the early part of the study and found to be less than 70 ppb and comparable at all locations. Because of the small amount of quantitative data, the results of monitoring these parameters are not illustrated. Table III summarizes the current ambient air quality standards (9, 10) relevant

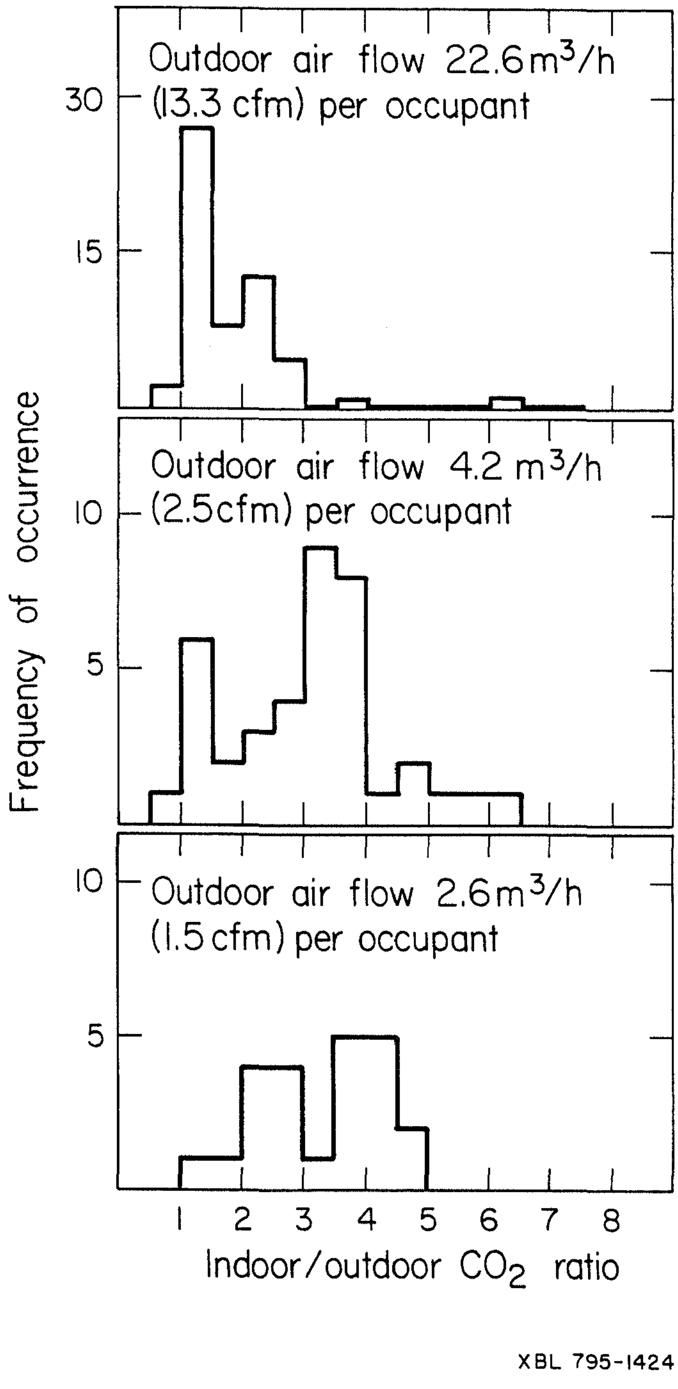
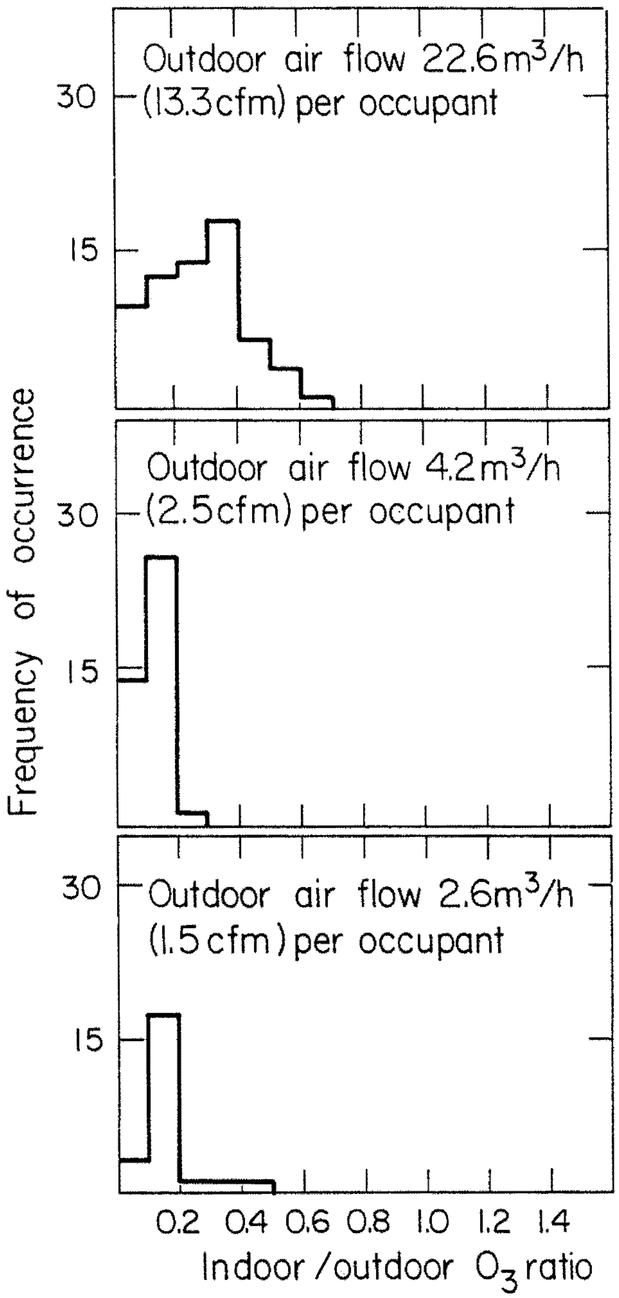


Figure 10. Histograms showing the frequency distribution of indoor/outdoor CO_2 ratios at three ventilation rates. The data points used to compute these ratios were obtained from 10-minute sampling intervals on school days during school hours.



XBL 795-1425

Figure 12. Histogram showing the frequency distribution of indoor/outdoor O_3 ratios at three ventilation rates. The data points used to compute these ratios were obtained from 10-minute sampling intervals on school days during school hours.

Table III. Relevant 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.
Nitrogen dioxide (NO_2)	100 μg/m^3 (50 ppb)	year	470 μg/m^3 (250 ppb)*	1-3 hrs.
Ozone (O_3)			240 μg/m^3 (120 ppb)	1 hr.
Sulfur dioxide (SO_2)	80 μg/m^3 (30 ppb)	year	365 μg/m^3 (140 ppb)	24 hrs.
California (other than EPA)				
Carbon monoxide (CO)			46 mg/m^3 (40 ppm) 11 mg/m^3 (10 ppm)	1 hr. 12 hrs.
Nitrogen dioxide (NO_2)			470 μg/m^3 (250 ppb)	1 hr.
Ozone (O_3)			200 μg/m^3 (100 ppb)	1 hr.
Sulfur dioxide (SO_2)			1310 μg/m^3 (500 ppb) 105 μg/m^3 (40 ppb)	1 hr. 24 hrs.

*Proposed

Exhibit 1. Indoor air quality questionnaire.

Date ______________________ Room No. ______________________

Male __________ Female __________

No odor	____ 1	____ 2	____ 3	____ 4	____ 5	____ 6	____ 7	____ 8	____ 9	Strong odor
Pleasant odor	____ 1	____ 2	____ 3	____ 4	____ 5	____ 6	____ 7	____ 8	____ 9	Unpleasant odor
Cold	____ 1	____ 2	____ 3	____ 4	____ 5	____ 6	____ 7	____ 8	____ 9	Hot
Drafty	____ 1	____ 2	____ 3	____ 4	____ 5	____ 6	____ 7	____ 8	____ 9	Stuffy
Humid	____ 1	____ 2	____ 3	____ 4	____ 5	____ 6	____ 7	____ 8	____ 9	Dry
Quiet	____ 1	____ 2	____ 3	____ 4	____ 5	____ 6	____ 7	____ 8	____ 9	Noisy

attempting to establish whether the data are correlated with Andersen sampler data in order to determine if an instrument of this type would be suitable for general microbial burden monitoring.

The raw data appear in the form of numbers of colonies per stage. They may be transformed to percent of the total sample per stage, and the cumulative percentage distribution can be plotted on a log-probit grid, shown in Figure 15, from which the number median diameter (NMD) can also be obtained. Data are presented in the form of number of colony-forming particles (CFP)* per cubic meter of air. As the study proceeds, these values will be correlated with ventilation rates and other factors such as temperature and relative humidity.

A summary of microbial data from Carondelet High School is shown in Table IV. There is an increase in the number of CFP/m^3 and in the NMD of the particles with occupant density. This is consistent with theory since CFP originating from human activity (i.e., mostly skin shedding) tend to be larger than those from other sources. However, only the rise in NMD appears to be statistically significant.

It is not known why the number of airborne CFP is consistently higher in Room 11 than in Room 10. Surprisingly, an increase in the amount of fresh air almost always produced an increase in the number of viable airborne molecules. This result was unexpected and tends to indicate that there might be a significant source of CFP in the outside air.

The change in number of CFP/m^3 as a function of time of day is shown in Figure 16. It can be seen that the respirable burden (particles 5 μm in diameter or less) was greatest at 7:00 a.m. and declined during the day. The total number of microbes increased markedly between 7:00 a.m. and 10:00 a.m. One possible explanation is that there were two populations of airborne bacteria in the school: one (large-size CFP's) rising and the other (respirable CFP's) decreasing during the day. No firm conclusion about the variations of airborne bacteria with time and ventilation rates can be made with these limited data. The results at Carondelet do show, however, that decreasing the ventilation rate did not increase the microbial burden in the classrooms.

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*An airborne particle may contain many or no viable bacteria. The presence of a colony after the sample medium is incubated indicates the collected particle had at least one viable cell; how many more cells may have been present cannot be ascertained. Hence, they can only be referred to as "colony forming particles" rather than bacterial numbers.

Table IV. Summary of Data on Airborne Colony Forming Particles Collected at Carondelet High School.

Outside Air Ventilation Rate (cfm/person)	Room 11 (CFP/m^3)		Room 10 (CFP/m^3)	
	Occupied	Unoccupied†	Occupied	Unoccupied†
13.3	160(5.4)	54(4.3)	107(5.4)	27(2.4)
2.0*	115(6.6)	47(3.5)	75(5.8)	37(2.8)

+ = 7:00 a.m. sample; ventilation turned on at 6:30 a.m.
( ) = The Number Median Diameter (NMD) in μm.
* = Data combined at 1.5 cfm and 2.5 cfm per person outside air ventilation rate.

Energy Savings

Carondelet High School is located in a region of California with mild winters (a 3000-degree [Fahrenheit] day heating season) and a dry hot climate in the summer. Since the school is closed during the summer recess except for administrative offices, and there is essentially no latent cooling load, most of the HVAC system energy savings (83%) occurs during the heating season.

Total energy use, including space heating and cooling, water heating and lighting, for Carondelet High School costs $41,000 per year at 1978 prices for natural gas and electricity. This yearly energy cost is the sum of energy costs for two separate buildings (there is one combined utility bill), one housing the 40 classrooms (56,000 ft^2) and the other consisting of a gymnasium plus art rooms (16,000 ft^2). The utility bill is divided into two parts: electrical energy mostly for space cooling and lighting ($30,000), and natural gas for water and space heating ($11,000). Ventilation rate changes were made only in the main building which we estimate as having utility bills of $31,000 per year assuming energy use is proportional to floor area.

In order to calculate the estimated energy savings for a particular school building, we need to know the magnitude of the reduction in outside air that is consistent with good indoor air quality and the magnitude of the ventilation heating load. Data obtained by LBL (at Carondelet High School and at a second school (13) and by other experimenters (14) suggests that a reduction in the outside air ventilation rate of 10 cfm per person for classroom occupancy is readily achievable. The data also indicates that 2.5 cfm per person of outside air appears to be sufficient to maintain CO_2 levels below 5000 ppm and odor intensity below the annoyance threshold for classroom occupants.

The heating load in Btu/cfm is computed by binning the dry bulb temperature into 5 degree wide bins centered at $\overline{T}_i$, and using the following equation

$$\frac{Btu}{cfm} = 1.10 \sum_i (70 - \overline{T}_i)\ t_i$$

where t_i is the number of hours during the school year that the outside dry bulb temperature T_i is in the range $(\overline{T}_i - 2.5)$ to $(\overline{T}_i + 2.5)$ during the school day. In the above summation, it is assumed that heat is needed when the outside dry bulb temperature is 65°F or less. The weather data is obtained from the Air Force, Army and Navy Manual (15) where $\overline{T}_i$ is the midpoint of the various five-degree wide temperature bins.

Table V is a compilation of yearly ventilation heating loads for selected cities in the United States. For most cities in the table, the degree days can be used to obtain an approximate value of the ventilation heating load for the 9:00 a.m. to 5:00 p.m. period. The greatest energy savings for schools will occur in the Northeast and North Central regions of the United States. Cooling loads have not been calculated here, but for buildings operating year-round, considerable energy and peak power savings can also be expected during the summer in most regions of the United States. As can be seen from Table V, the yearly energy savings from outside air reduction in colder climates will be more than double the savings at Concord, California (Concord has a daytime winter climate similar to that of San Francisco).

The energy cost savings during the heating season for the main building can be computed in the following manner:

$$\text{energy savings} = 24{,}244\ \frac{\text{Btu}}{\text{cfm}}\ \left(\frac{17{,}000\ \text{cfm}}{.60}\right)\ \left(\frac{\$2.75}{10^6\text{Btu}}\right)\ \left(\frac{5\ \text{days}}{7\ \text{days}}\right) = \$1{,}340.$$

Therefore, in the main classroom building, almost 16% of the cost of natural gas (used for space and water heating) can be saved by a 17,000 cfm ventilation rate reduction.

In the above equation, 17,000 cfm is the total reduction in outside air ventilation. This corresponds to an average reduction from 28.5 cfm to 5 cfm per person for the entire building and to a reduction from 13.3 cfm to 2.5 cfm per person in individual classrooms. The heating system efficiency is assumed to be 60% and the price of natural gas $2.75 per million Btu.

At Carondelet High School, the initial outside air ventilation rate (13.3 cfm/occupant) falls within the range of recommended ventilation rates for classrooms in ASHRAE Standard 62-73 (see Table I) whereas 2.5 cfm per person of outside air would be below the ASHRAE minimum of 5 cfm per person. However, increased air flow when doors were opened probably brought the total outside air ventilation rate to a value somewhat higher than 2.5 cfm per person.

The cooling load for the summer months (excluding summer recess) can also be estimated from equation (1) since there is little or no latent cooling load for this climate. Assuming a constant energy efficiency rating for the air conditioner of 6.0, the energy saved from a 17,000 cfm reduction in outside air is calculated as follows:

$$\Delta E(\text{Kwh})_e = 1.10\ \frac{(17{,}000\text{cfm})}{6.0}\ \sum_i\ (\bar{T}_i - 70)\ t_i\ \frac{(5\text{days})}{(7\text{days})}$$

$$\Delta E = 6839\ (\text{kwh})_e$$

Energy cost savings = 6839 $(\text{kwh})_e$ x $.04/$(\text{kwh})_e$ = $275, plus peak power charges.

Therefore, the total energy savings realized by reducing the outside air ventilation rate by 17,000 cfm is more than $1,600 or 5.2% of the total energy cost for the main classroom building. However, this estimate may be low since the gym probably has higher energy use per square foot than the main building due to the need for more outside air (for odor control) and more hot water. It is important to note that in a mild climate such as in Concord, California, space heating and cooling together account for only a relatively small fraction (approximately 33%) of total energy cost thereby limiting the potential energy cost

CONCLUSIONS

Results of the field monitoring project at Carondelet High School indicate no significant change as a result of decreased ventilation in any of the air quality parameters measured, with the exception of carbon dioxide. While CO_2 levels increased, concentrations were still far below levels considered to be a health hazard. In fact, the air quality improved in the school for some parameters (such as ozone) when the ventilation rate was reduced. Results of the survey of subjective impressions of indoor air quality showed no deterioration of student comfort caused by decreased ventilation rates. Results also show that decreasing the ventilation rate did not increase the microbial content in the classroom.

Based upon field monitoring results at Carondelet School, it appears that in classrooms, the outside air ventilation rate can be safely reduced to 2.5 cfm/occupant, a value significantly lower than the ASHRAE minimum of 5 cfm/occupant. Since the amount of outside air entering the school could be decreased without any adverse effect on the health, safety, or comfort of the occupants, moderate energy savings could be achieved by lowering the fresh air ventilation rates at Carondelet High School. However, in more severe climates, the energy savings achieved by a reduction in outside air ventilation rates should be much higher.

The field monitoring activities at Carondelet High School represent a pilot study. As the results from future studies are ascertained, we expect to establish the relationship between outside air ventilation rates and indoor air quality in schools, hospitals and residential buildings.

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