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Meeting the Objectives of Energy Conservation and Ventilation for Acceptable Indoor Air Quality in the Classroom

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ABSTRACT

This study explores the occupancy and operational characteristics of typical public schools in Maryland, then examines alternative HVAC design strategies and concepts to minimize the adverse energy consequences of increased ventilation as might be required to comply with ASHRAE Standard 62-1989. *A VAV system with fan-powered terminals is analyzed for energy demand and use considering alternative strategies that include estimates of occupancy and several approaches to ventilation demand control. The significance of total air circulation rate to indoor air quality is also evaluated.*

Control of gaseous and particulate bioeffluents generated by occupants is regarded as the primary function of the ventilation in general use classrooms.

An air-conditioning concept tailored to the specific ventilation and thermal comfort needs and to the functional characteristics of the classroom setting is presented. The performance of this concept is compared to the classroom ventilation prescribed by Standard 62-1989. *From this comparison, the question is examined, "Can the outdoor air rate of 15 cfm per person be reduced for this application and yet provide acceptable indoor air quality?"*

INTRODUCTION

The outdoor ventilation rates prescribed by the ventilation rate procedure in *ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 1989) are increased over the previous standard for many applications. Few are likely to be affected more dramatically than the classroom. When the standard's estimated maximum occupancy is combined with the ventilation rate, the amount of outdoor air to be supplied to a classroom is 0.75 cfm per ft^2 (3.8 L/(s·m^2)) of floor space. This rate can be more than half the total air supply needed for cooling. Moreover, since the rate is required to be the minimum total airflow (as well as the outdoor air component), VAV terminals will be limited to a 2:1 turndown ratio or less. To avoid overcooling with cooling loads less than 50% of design, reheat will be necessary. In most climates in the USA, preheat will also be required.

Consternation over increased energy use and heating and cooling capacity requirements for schools appears to be well founded.

CLASSROOM MODEL

As a first step to analyze this concern and to develop strategies for reducing the impact, statistical data describing class size and other parameters for Maryland and the rest of the country, available through the Maryland Department of Education, were examined. In addition, a survey of classroom characteristics and of the HVAC systems that serve them was conducted with 11 (of a total of 24) county educational systems throughout the state participating. From these sources, a classroom model was developed for analysis of the HVAC requirements. The study is limited to public school elementary and secondary general classrooms (for language arts, social studies, math) and adjacent corridors. With care, some of the results are capable of extrapolation to science and vocational classrooms and other school settings. Classroom and class sizes of elementary and secondary schools are fairly similar. The secondary school classrooms were reported to be typically occupied for six or seven periods per day, each lasting 45 to 50 minutes. Elementary classroom learning sessions are likely to be longer but with less total occupancy during the day. Despite minor dissimilarities, a common model representative of both situations was selected.

The state of Maryland, USA, is the model site. Data describing the site and physical and occupancy characteristics are included in Appendix A.

HVAC system characteristics are subsequently discussed more fully. The study is based upon a variable-air-volume system with either a fixed amount of outdoor air for ventilation or a fixed rate per occupant. One HVAC system serves multiple classrooms, each a temperature-controlled zone, and is independent of other systems serving other school areas, i.e., offices, auditorium, gymnasium. The selected period of operation was 7 a.m. to 5 p.m., somewhat longer than indicated by the survey returns. System operation was reported most often to have ceased within an hour following classes, but some operated for extended hours to

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accommodate staff and after-school programs. Some schools may also operate during evening hours for community meetings.

The average class size is quite close to 25 persons. This size is further corroborated by a nationwide survey of elementary schools, indicating averages of 22 for kindergartens and 26 for 4th to 6th grades.

CLASSROOM HVAC CONSIDERATIONS

The predominant type of heating and air-conditioning system in classrooms is currently not variable-air-volume but unit ventilators. Many schools equipped with unit ventilators have no mechanical cooling provision. VAV was chosen for the study model as currently being the method of choice for classroom applications, although unit ventilators are still applied. Moreover, any evaluation of the ventilation provided by unit ventilators must recognize that outdoor ventilation rates are, at best, difficult to balance, with continued reliability of such balancing even more doubtful.

Survey responses did not indicate a clear preference between these two system types, but VAV had a slight edge regarding perceived indoor air quality. IAQ complaints reported in order of incidence were:

- Thermal discomfort (80% of complaints)
- "Stuffiness" (70%)
- Odors (20%)

The cause of thermal discomfort was frequently identified as malfunctioning or mismanaged room terminal controls.

Development of a model classroom permits evaluation of ventilation requirements, the energy consequences of ventilation, and strategies for minimizing energy use while meeting ventilation objectives. Heating and cooling loads were calculated based on *ASHRAE Handbook* methods. Energy use was determined for those days throughout the year classes were in session using the ASHRAE modified bin weather method procedure for energy calculations coupled with simulation of a fan-powered VAV system with reheat and an auxiliary heating system for use during nonoperating hours. Weather data were compiled for Andrews Air Force Base, near Washington, DC.

To determine the outdoor air ventilation rate, several sources are available. In Maryland, priority choices would be the Building Officials and Code Administrators (BOCA) Mechanical Code and *ASHRAE Standard 62-1989*, generally considered state of the art. The standard calls for 15 cfm (8 L/s) of outdoor air per person, which could result in 0.75 cfm/ft^2 (3.8 L/(s·m^2)). The BOCA code currently would permit as low as 8.3 cfm (3.9 L/s) per person or, based upon a specified minimum occupant density, 0.42 cfm/ft^2 (2.1 L/(s·m^2)) of outdoor air. Corridors would be required by the ASHRAE standard to be provided with 0.1 cfm/ft^2 (0.05 L/(s·m^2)) vs. BOCA's 0.02 cfm/ft^2 (0.01 L/(s·m^2)). The prudent engineer opts for the ASHRAE path—but with concern over the initial and energy cost implications of such a decision.

The environmental contaminants of interest in the classroom setting can be identified as:

1. *Odorous bioeffluents* emitted by the occupants. Some odors may also originate from organic decay or outgassing of particulate contaminants collected by air-conditioning components.

2. *Microorganisms*. Two or more sources are commonly identifiable: the occupants, through shedding or aerosolizing through respiration, coughing, or sneezing, and air-conditioning components acting as reservoirs or amplifiers of bacteria or fungi dispersed into the room during operation. Unit ventilators with mechanical cooling, wet coils, and condensate pans are next of kin to fan coil and water-source heat pumps impugned as sources (Morey 1985).

3. *Volatile Organic Compounds (VOCs)*. Classroom sources include building materials, art supplies, perfume, cleaning agents.

While ventilation may succeed in diluting emissions, the primary path to good IAQ is source control, which is especially true of VOC emissions. Moreover, ventilation has little if any potential for control of contamination within air-conditioning system components.

Major objectives assigned to the classroom HVAC system are (1) low initial and operating costs, (2) thermal comfort, (3) pathogen removal, and (4) odor dilution. Further discussion of classroom design criteria is appropriate.

Relative humidity: Humidities above 60% contribute to thermal discomfort and odor perception. Low humidity in winter is a recognized contributor to schoolchildren's absenteeism (Green 1982), yet HVAC systems that provide for humidification are rare. This consideration is of greater importance in cold climates, where the moisture content of the ventilation air is low for long periods. The higher the outdoor ventilation rate, the lower the room humidity is likely to be during cold weather unless humidification is provided.

Total air exchange: No specific criterion for total air ventilation is imposed on the designer. However, the rate of air circulation can relate to complaints of "stuffiness." Total circulation, coupled with the use of filters in the recirculated airstream, can limit the level of airborne, disease-bearing particulates in the breathing environment (Green 1985).

PROPOSED HVAC CONCEPT

An air-conditioning concept tailored to meet these objectives and criteria is depicted in Figure 1. This concept is essentially a conventional VAV system with fan-powered, series arrangement terminals. Air supply to the room is constant. Air recirculated from the room to the terminal during periods of less than full (design) primary airflow is filtered. In the flow pattern illustrated, the recirculated air exits the room low, carrying airborne particulates; passes through a conveniently accessible filter; then is ducted back to the VAV mixing box.

A promising approach to the classroom air distribution is displacement ventilation from the floor to the ceiling to take advantage of occupant-generated thermal plumes to convey filterable contaminants upward and out to the filters. This is a future consideration. How would the proposed concept (abbreviated as FAFVAV) compare to conventional VAV (CVAV) and a ventilation-only system (VS) (possibly supplementing a water-source heat pump installed in the classroom)?

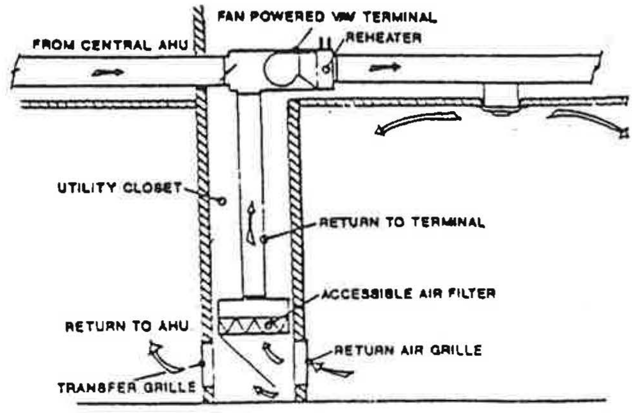


Figure 1 Fan-powered VAV classroom HVAC

System performance with respect to CO_2, a surrogate for gaseous bioeffluent, is dependent on the outdoor air ventilation rate and CO_2 concentration in air recirculated from other spaces. The recirculated air will be a blend from all spaces returned for reprocessing in the central air unit. If the average CO_2 concentration in this recirculated airstream is lower than in the classroom, supplying the recirculated air will produce a lower CO_2 level in that room than will a ventilation-only system or any system that features recirculation internal to the room. Depending upon the building and HVAC layout, either VAV system type being compared may perform better than the VS system whenever the total airflow from the system is above the minimum setting of the terminal box. This setting, according to the standard, must equal the outdoor ventilation rate.

Design total air circulation to the model classroom, as determined by the cooling load, is 1.3 cfm/ft^2 (0.4 m^3/(min·m^2)) for a west-side classroom. At full load, both the CVAV and FAFVAV concepts perform the same with respect to total room air exchange (in and out of the room) and particulate control. The VS system will have a lower total air exchange and, consequently, inferior particulate control. As the demand for primary supply air is reduced in response to thermostat control, the performance of the CVAV terminal will diminish toward that of the VS system.

Figure 2 illustrates the comparative effectiveness of the three HVAC concepts with respect to airborne microbials. For the purposes of this analysis, a generation rate of airborne microbials (bacteria and fungi) of 424 CFU/min per person was deduced from an assumed 1000 CFU/m^3 in the room (a value not inconsistent with data reported by Thorstensen et al. [1990]) and a ventilation rate of 15 cfm per person. Microbial particles are reported to range in size from 0.5 to 200 μm (Burge 1988; Morey 1988).

Filter efficiencies based upon particle size predict that at least 60% of microbial removal appears obtainable with filters having ASHRAE dust spot efficiency as low as 25% to 30%, while 90% removal capability is likely with 60% or higher efficiency filters (ASHRAE 1988). Generation rates and viable particle sizes can be expected to vary widely. Nonetheless, the performance comparison of the three concepts is believed valid. The comparison assumes the same efficiencies for filtering recirculated air in the central air-handling units as in the FAFVAV recirculation path.

ENERGY-SAVING STRATEGIES

The FAFVAV system concept also serves as a basis for evaluating strategies for limiting energy demand and use.

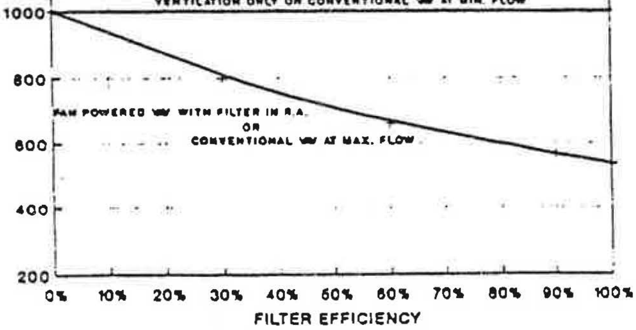


Figure 2 Comparing HVAC systems for classroom microbial contaminants

Estimating Classroom Occupancy

Table 2 of *Standard 62-1989* lists the estimated maximum occupancy of a classroom at 50 persons per 1,000 ft^2 or 100 m^2 Direction is further given to use the actual anticipated occupancy if it differs from the listed value. Design outdoor temperatures do not represent extremes for a locality but are prudent maximums not likely to be exceeded except for a small percentage of the time. Consistent logic should apply to the maximum occupancy in determining the classroom ventilation air supply.

The maximum occupancy chosen for the model is 23 persons, based on an enrollment of 25 with 2 absentees. The classroom outdoor ventilation requirement is determined to be 345 cfm (163 L/s), not 607 cfm (287 L/s), which would result from the Table 2 occupancy estimate.

Realistic predictions of occupancy can result in lower fan, refrigeration, and boiler capacity requirements as well as reduced energy use.

Demand-Controlled Ventilation (DCV)

"A DCV system is a ventilation system in which the air flow rate is governed by airborne contaminants.... A DCV system can consist of a time clock control, and/or a presence control, and/or a sensor control" (Raatchen 1990).

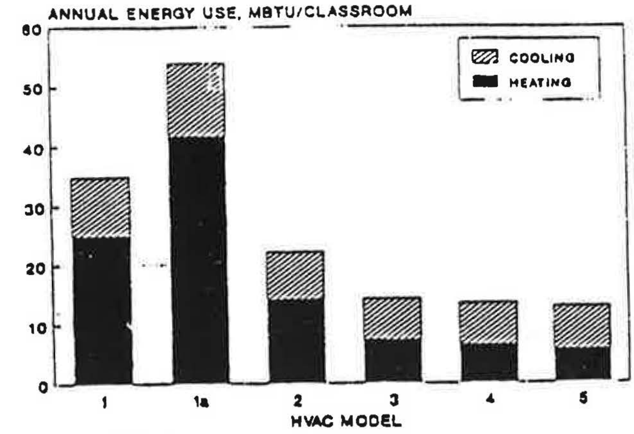
Many schools operate the classroom HVAC system one hour prior to and after the class day. Some operate during evening hours for school programs and as a service to community organizations but at a reduced occupancy. Programmed control of the system's outdoor air supply and air economizer cycle can drastically reduce ventilation when the classrooms are sparsely occupied. Since the percentage of outdoor air to total air for the classroom system can be quite high, energy savings can accrue from reduced preheating, cooling, and reheating of air. Programming can be manual or time controlled. Either way, the concept should be incorporated into the control system design.

Control of ventilation air can also be accomplished by sensing the CO_2 concentration either within the classrooms or in the common return airstream where an average concentration is sensed. Carbon dioxide control is most advantageous if occupancy is highly variable or if the infiltration rate through classroom windows and doors is high. Additional control, no matter how beneficial, carries an additional maintenance burden, which the school or school system should accept in advance. CO_2 sensors generally require periodic recalibration.

Figures 3 and 4 compare the capacity and energy use for these strategies for five scenarios or models.

Model 1 examines a single classroom and its corridor area operating with fixed minimum outdoor flow during the operating hours of 7 a.m. to 5 p.m. except as overridden by the economizer cycle. The *Standard 62-1989* Table 2 estimated maximum occupancy is employed. Model 1a extends the operation of Model 1 into evening hours, ending at 9 p.m. Model 2 is similar to Model 1, except the actual anticipated occupancy is considered with the system operating from 7 a.m. to 5 p.m. Model 3 is similar to Model 2, but ventilation is substantially reduced, minimum VAV terminal airflow constraints eliminated, and humidification discontinued by automatic programming during the four hours when the classroom is virtually unoccupied. Model 4 is similar to Model 3 but has a CO_2 sensor in the system return air regulating the amount of outdoor air during class hours. Model 5 is similar to Model 3, except the minimum ventilation rate is reduced during occupancy to 10 cfm (5 L/s) per person.

Energy demand and use are based upon heating being produced by a hot water boiler, chilled-water refrigeration with a



COOLING INCLUDES FANS, AUXILIARIES

Figure 3   Heating and cooling energy use

COP of 3.5, medium-pressure air distribution at a supply temperature of 55°F (13°C), and supply fan equipped with inlet guide vanes operating at a full-load efficiency of 80%. Changeover to free cooling by use of the economizer occurs at 55°F outdoor temperature. Auxiliary power for cooling tower fans and chilled and hot water pumping is included. Heating, when the air system is not operating, is provided by hot water convection.

The results of the energy comparison show that through realistic estimates of occupancy and by varying the total system ventilation as occupancy changes, a savings on the order of 20 MBTU (21 GJ) per year for each classroom is possible, yet the classroom remains in compliance with *Standard 62-1989*. The energy use would compare closely with that now required by the BOCA code, even if demand-controlled ventilation techniques were not employed.

The savings may be translated into financial terms. At $9 per MBTU for energy, $180 per classroom is saved annually. The savings may be realized both for new construction as well as retrofitting existing school buildings. In the latter situations, school officials worry whether compliance with *Standard 62-1989* will mandate larger heating and cooling plants. The capacities of existing refrigeration equipment and boilers may prove to be adequate if appropriate strategies are employed. Air systems, however, likely will require upgrading with regard to central air-handling unit controls and classroom terminals. The capacities of heating and cooling plants when the total ventilation rate is realistically estimated are about two-thirds of those needed when estimating occupancy as suggested by the standard.

Comparing timed programmed control to CO_2 sensor control of ventilation indicates there is small advantage to the latter approach. The smallness is not surprising since, in our model, occupancy during class hours was not varied and is predictable. However, the CO_2 sensor control is likely to be of considerable advantage in an auditorium or gymnasium, where occupancy is quite variable and more difficult to profile into a timer program.

REDUCED VENTILATION

Consider Model 5 for which the ventilation rate was reduced to 10 cfm (5 L/s) per person. This, of course, does not comply with the standard. Gunnarsen has made the observation, concerning the ready adaptability of persons to human bioeffluents, that reduced ventilation is reasonable in rooms "where persons enter an unpolluted room at the same time.... Classrooms...are good examples of this"(Gunnarsen 1990).

To examine the consequences of such a reduction in the ventilation rate per person, a prediction of the concentrations of CO_2 during a typical day in a secondary school classroom was calculated (see Appendix C). The results for ventilation rates of 15 and 10 cfm (7 and 5 L/s) per person are plotted in Figure 5.

The predicted CO_2 concentrations permit an appraisal of both visitor and occupant satisfaction with respect to occupant-produced bioeffluent odor.

Fanger (1988) relates 20% visitor dissatisfaction (conversely, 80% satisfaction) to a ventilation rate of 15 cfm/olf (7 L/(s·olf)). An olf is defined as the emission rate of bioeffluents from a standard person, i.e., an adult office worker, averaging five baths a week. This emission rate is extended here to apply to an American adolescent.

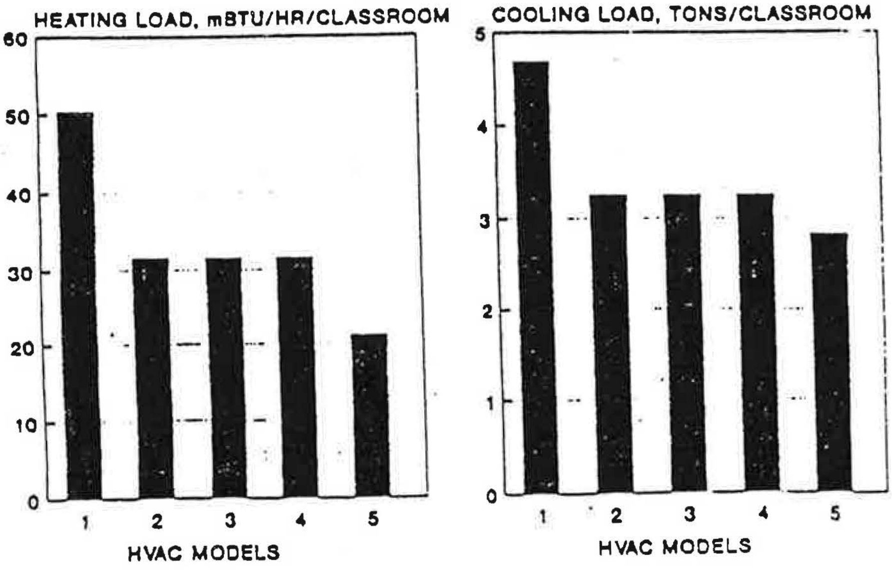


Figure 4   Heating and cooling capacity requirements

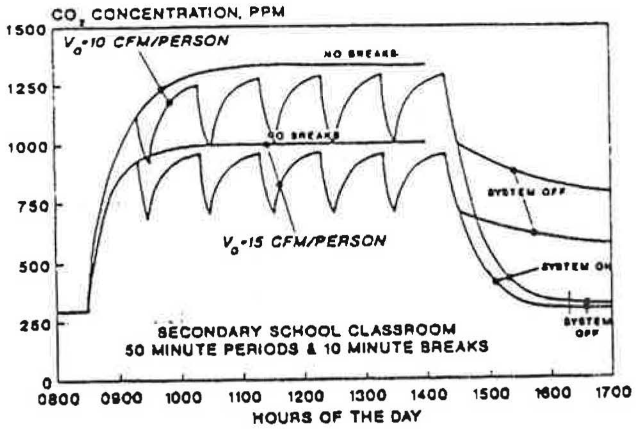


Figure 5 *CO_2 concentration in the classroom*

The peak CO_2 concentrations shown in Figure 5 are about 1,270 ppm produced by a constant outdoor ventilation rate of 10 cfm (7 L/s) per person. Based on steady-state CO_2 generation, this CO_2 level is the equivalent of 11 cfm of outdoor ventilation.

Based on Fanger's equation,

$$PD = 395e^{-1.83q^{.25}} \tag{1}$$

where

PD = percent dissatisfied

q = ventilation rate, L/(s·olf)

It can be determined that PD for visitors entering at the peak is 26% vs. 20% for the peak with 15 cfm of outdoor air. At the end of breaks, the reduced ventilation rate will be within the standard's yardstick of acceptability.

With faith that the responses of school occupants (not trained judges) entering a classroom from a corridor (itself not devoid of bioeffluent) can be predicted within reasonable tolerance despite psychological, sociological, and neuro-physiological variations of individuals and the awesome complexity of olfaction (Freeman 1991), the lower ventilation rate might be expected to shift the reaction of one of the 23 in the entering class from satisfactory to unsatisfactory perception.

The adaptation of people to human bioeffluent odors as reported by Gunnarsen and Fanger (1988) and others (Cain 1974) would occur within several minutes. Thus any benefit of the higher ventilation rate once class is underway appears to disappear.

By sustaining the total rate of filtered air circulation removing most of the airborne pathogen-carrying particles, the dilution benefit afforded by the higher rate of outdoor ventilation is negligible in this regard. Any synergistic, sensation-adding effect that conceivably could result through the comingling of bioeffluents with low-level emissions from certain other dissimilar sources within the classroom has not been assumed. Rather, the dilution of each internally produced contaminant is assumed to occur in direct proportion to the rate of ventilation air, free of that contaminant, following the procedure described in Appendix E of the ASHRAE standard. Consequently, continuous emissions of VOCs from building materials and similar sources are regarded separately and as being of sufficiently low magnitude by virtue of source control to be held to a satisfactory level by the ventilation needed for occupant bioeffluent.

Accidents, housekeeping procedures, remodeling or other such occurrences that produce situations with undesirable levels of VOCs or other airborne pollutants in the classroom will be mitigated more effectively by the higher ventilation rate. However, the improvement may be quite marginal. Unavoidable episodes of this nature are better remedied by specific short-term ventilation strategies, such as shifting the controls of the air-handling unit to supply all outdoor air, operating return air fans for exhaust, or simply opening windows.

The lower rate of outdoor air ventilation, in addition to saving energy and initial cost, offers improved classroom relative humidity during the winter. The model set a minimum of 25% RH as a criterion, although 30% is the bottom of the comfort envelope described in Standard 55-1981R (ASHRAE 1989). Unless the central air handler has humidifying capability, 25% RH is difficult to maintain even in a moderate climate such as Maryland's. For the study model, without humidifying, 28% RH can be maintained during design winter conditions in occupied classrooms supplied with 10 cfm (5 L/s) of outdoor air. Whereas with 15 cfm (7 L/s), only 21% can be held. The 25% minimum can result in many areas even with colder winters than Maryland's if the lower ventilation rate is supplied. With the higher ventilation rate, the classroom relative humidity will run about 8 percentage points lower. The value of maintaining minimum relative humidity in the classroom as a prevention for respiratory illness has been well documented (Green 1985) but remains underappreciated in the quest for good indoor air quality.

DISCUSSION AND SUMMARY

Design and control strategies offer opportunities for our schools to have good IAQ without burdensome demands on heating and cooling capacities and energy costs. ASHRAE, in the course of its standard revision procedure, should reconsider the prescribed ventilation rate for schools as well as the importance of total filtered air circulation for many applications (Wheeler 1990) in the light of the new information forthcoming since *Standard 62-1989* was developed. With roughly one million classrooms in public schools throughout this country alone, the impetus for such consideration indeed exists.

Specific classroom HVAC recommendations resulting from this study are:

1. Design to meet *Standard 62-1989*. For VAV systems, maintain a constant ventilation rate per person and preset the minimum total classroom airflow at that value.
2. Estimate the number of occupants realistically.
3. Select an HVAC concept, such as the one studied, that will produce a continuous high rate of room air exchange.
4. Select filters for effective removal of microorganisms.
5. Employ demand-controlled ventilation to save energy.
6. Provide humidification for a minimum relative humidity as close to 30% as practicable.
7. Consider a reasonable level of maintenance and operation.
8. Collaborate with the user toward a common understanding of design provisions and objectives.

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APPENDIX A

MODEL CHARACTERISTICS

Site:

Latitude: 39°North
Outdoor summer design conditions: 90°F (32°C) DB, 76°F (24.5C) WB
Outdoor winter design temperature: 14°F (-10°C)
Indoor summer design conditions: 75°F (24°C), 55% RH
Indoor winter design conditions: 72°F (22°C), 25% RH
Indoor unoccupied minimum temperature: 55°F (13°C)

The physical characteristics of the classroom selected are:

Floor area: 810 ft^2 (75 m^2)
Ceiling height: 8 ft, 10 in. ((2.7m)
Exterior wall area (1 wall): 270 ft^2 (25 m^2)
Window glass area: 81 ft^2 (7.5 m^2)
Orientation: composite of NESW
Wall and glass U-factors: 0.15, 0.6 Btu/(h·Ft^2·°F) (0.85,3.4 W/(m^2·°C))
Composite glass and shading factor: 0.41
Lighting: 2 W/Ft^2 (21.5W/m^2)
Floor area of adjacent interior corridor, proportional to one classroom: 150 ft^2 (13.9 m^2)

Occupancy characteristics for the model are:

Average class enrollment: 25 people
Normal attendance: 23 people
Beginning of daily class use: 8 a.m. to 2 p.m.
Classes in session five days a week less holidays,
Christmas, spring, and summer breaks.
Total session days: 182 days per year.

APPENDIX B

COMPARING CLASSROOM HVAC SYSTEMS REGARDING CFU LEVELS

$$C_s = \frac{N + C_o V_o (1 - E_f)}{R V_r E_f + V_o} \tag{2}$$

where

C_s = resultant overage space concentration, CFU/m^3
N = microbial in-room generation rate, 425 CFU/min per person
C_o = microbial concentration in outdoor air, assumed to be zero for the varieties generated in the room
V_o = outdoor air supplied, 0.42 m^3/min per person
RV_r = filtered recirculated air, 0.37 m^3/min per person for FAF-VAV system, 0 for VS system.
E_f = filter efficiency for viable airborne particulates

Estimated occupancy: 50 persons/1,000 m^3

APPENDIX C

The following formulae are employed to predict CO_2 concentrations. Equation 3 is applied to predict room concentration (C_s) after time (t) following occupancy when initial room concentration (C_i) equals that in the outdoor air, C_o. Equation 4 is applied to predict C_s after time (t) following departure of class ($N = 0$) where C_i at the beginning of the time period equals C_s resulting from the previous occupancy. Equation 5 is applied to predict C_s after time (t) following occupancy after a class break when C_i is higher than C_o

$$C_s = C_o + N/V_o\ (1 - e^{-V_o t/V_s}) \tag{3}$$

$$C_s = C_o + (C_i - C_o)\ e^{-V_o t/V_s} \tag{4}$$

$$C_s = C_o + N/V_o + (C_i - C_o - N/V_o)\ e^{-V_o t/V_s} \tag{5}$$

where

V_s = space volume, ft^3 (m^3)
C_s = space contaminant concentration. For CO_2, a fraction CO_2/air, i.e., 0.001 (1,000 ppm)
V_o = Outdoor air ventilation rate, ft^3/(min·person) (L/(s·person))
C_o = contaminant concentration in outdoor air. For CO_2, a fraction CO_2/air, i.e., 0.0003 (300 ppm)
N = contaminant generation rate, ft^3/(min·person) (L/ (s·person)) For CO_2, 0.0104 ft^3/(min·person) (0.005 L/(s·person))
C_i = space contaminant concentration, t=0
t = time from start of each activity phase, minutes