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Ventilation Measurements in Large Office Buildings

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ABSTRACT

Ventilation rates were measured in nine office buildings using an automated tracer gas measuring system. The buildings range in size from a two-story federal building with a floor area of about 20,000 ft^2 (1900 m^2) to a 26-story office building with a floor area of 700,000 ft^2 (65,000 m^2). The ventilation rates were measured for about 100 hours in each building over a range of weather conditions. The results are presented and examined for variation with time and weather. In most cases, the ventilation rate of a building is similar for hot and cold weather. In mild weather, outdoor air is used to cool the building and the ventilation rate increases. In the buildings where infiltration is a significant portion of the total ventilation rate, this total rate exhibits a dependence on weather conditions. The measured ventilation rates are discussed in relation to the outdoor air intake strategy in each building. The ventilation rates are also compared to design rates in the buildings and ventilation rates based on ASHRAE Standard 62-81. Some of the buildings are at times operated at lower ventilation rates than recommended in Standard 62-81.

INTRODUCTION

Ventilation of office buildings is an important issue in relation to energy use and indoor air quality. Instead of relying on weather-induced infiltration, as is the case in most residential buildings, office buildings are generally equipped with mechanical ventilation systems to meet the space-conditioning requirements of the occupied space and to ensure adequate ventilation or outdoor air intake. The specific amount of outdoor air that is brought into the building is a function of the weather and the occupancy requirements for ventilation. The total ventilation rate is the sum of the intentional outdoor air intake plus the uncontrolled air leakage through the building envelope. The relative contributions of intentional and unintentional ventilation to the total ventilation rate depend on the leakiness of the building, the magnitude of the pressures that induce infiltration, and the intentional ventilation rate. This paper reports on measurements of ventilation rates made in nine office buildings under occupied conditions. Hourly ventilation rates were measured at a variety of outdoor weather conditions and for a total of about fifty to several hundred hours in each building. These ventilation rates are analyzed for dependence on weather conditions and compared to recommended and design levels of minimum outdoor air intake. A preliminary discussion of some of these measurements has been presented earlier (Grot and Persily 1983; Grot 1982), but since then, additional data have been collected and there has been more data analysis.

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BUILDING DESCRIPTIONS

Eight of the nine buildings in this report are federal office buildings located throughout the country and involved in a study of the thermal integrity of building envelopes sponsored by the General Services Administration (Grot et al 1983; Grot and Persily 1983). The ninth building is a privately owned office building located in Newark, NJ (Grot 1982). Table 1 lists the locations of the nine buildings along with the number of stories, occupiable floor area, and the type of ventilation system (constant or variable volume). All the buildings were constructed within the last ten years. The ventilation measurements in the Newark building involve only the main section of the building, from the third to the twenty-sixth story.

The mechanisms for controlling outdoor air intake vary among the nine buildings. In most buildings, outdoor air intake is kept to a minimum when the building is being heated or cooled in order to reduce the space-conditioning load. During mild weather, outdoor air is often used to cool the building. The amount of outdoor air intake and the times when outdoor air intake is increased are controlled by a variety of schemes. An economizer control uses the outdoor air temperature to determine when outdoor air should be used for cooling. Enthalpy control uses indoor and outdoor humidity levels in addition to temperature. The amount of outdoor air intake for cooling is generally determined by a control system that compares the discharge or return air temperature to a temperature setting. The control strategies used in each building are outlined below, along with other information on mechanical systems and the zoning of the buildings.

The Newark building tower (the third through the twenty-sixth story) is served by a single mechanical system with five fans. The number of fans in use varies from three to five depending on the space-conditioning load. Under mild temperature conditions, the level of outdoor air intake is determined by an enthalpy controller.

The Anchorage building is divided into six modules, each with its own ventilation system, which are connected by an open lobby/atrium and communicate freely. Anchorage is the only building without return fans. The mechanical systems are computer controlled and use a minimum of outdoor air during the heating season. During warmer weather, outdoor air is used to cool the building, with the outdoor air intake level determined by the supply air temperature.

In Ann Arbor, the building's main mechanical system serves most of the building with separate systems for the lobby and post office. The outdoor air intake is based on the outdoor air temperature (an economizer), and the amount of outdoor air intake is controlled by the return air temperature.

Columbia has a single mechanical system for floors two through sixteen and separate systems for the lobby and the first floor/basement zones. The mechanical system is controlled by a computer and uses an enthalpy controller to determine outdoor air intake levels.

There are two fan systems on each of the five floors of the Fayetteville building with an additional system for the courtroom on the fifth floor. The outdoor air intake is controlled manually by the building operator.

The Huron building has two mechanical systems, one for the north zone and another for the south zone. On each floor, the north and south zones are open to each other. The outdoor air intake is based on enthalpy control.

Norfolk has one mechanical system for most of the building, and a smaller system for the lobby area. The main HVAC system uses enthalpy control to regulate the outdoor air intake.

The Pittsfield building has a separate fan system for each of the its two floors. The outdoor temperature is used to determine whether outdoor air can be used to cool the building.

There are three fan systems in the Springfield building, one each for the north zone, the south zone, and the lobby/atrium. The outdoor air dampers are adjusted to maintain a supply air temperature of about 55 F (13°C) during the entire year. Thus, outdoor air is not used to condition the building unless the outdoor temperature is below the supply air temperature setting. Additional information regarding the federal buildings, including photographs, can be found in Grot et al (1983). Grot (1982) contains additional information on the Newark building.

MEASURING TECHNIQUES

The ventilation rates of the nine buildings were measured with an automated system employing the tracer gas decay technique with sulfur hexafluoride (SF_6) as the tracer. This system, designed at the National Bureau of Standards, has been used to measure air infiltration in a variety of buildings and can be operated unattended for periods of several weeks (Grot et al 1980). The measuring system consists of a gas chromatograph equipped with an electron capture detector for measuring the SF_6 concentration, samples automatically from up to ten locations, and injects tracer gas into five. The tracer gas injection and air sampling are controlled by a microcomputer, which also analyzes the data as they are collected and stores the information on floppy disks. The accuracy of the tracer gas measurements is primarily a function of the mixing of the tracer and the interior air. After the gas is injected, it mixes with the interior air for about 15 minutes before the ventilation measurement begins. The ventilation measurements are believed to be accurate within 0.1 exchanges per hour.

SF_6 was injected into the building supply ducts at hourly (Newark) or three-hour (federal buildings) intervals, and the subsequent decay in tracer gas concentration was monitored. Interior and exterior temperatures, along with wind speed and direction, were also measured during the tracer gas decay. All the ventilation measurements presented below were made while the buildings were occupied and the mechanical systems operated normally. All of the federal buildings were tested in the fall of 1982 and the winter and spring of 1983. In addition, the federal buildings in Huron, Norfolk, and Columbia were tested in the summer of 1983. The ventilation rates in the Newark building were monitored continuously from April 1981 to June 1982 with some gaps due to equipment malfunction.

RESULTS AND DISCUSSION

In most of the buildings the measured ventilation rates exhibit the expected dependence on season discussed earlier, with the lowest ventilation rates occurring during maximum heating and cooling loads. This phenomenon is evident in Figure 1, which is a plot of daily averages of ventilation rate and outdoor temperature versus time for the Newark building. These daily averages are calculated from data collected when the building was occupied, from 8 a.m. to 5 p.m. Even with the gaps in the data, the seasonal trend is obvious. During April of 1981, with outdoor temperatures between 50 and 68 F (10 and 20°C), the ventilation rates are high, between 1.0 and 1.5 exchanges per hour, because outdoor air is being used to cool the building. As the outdoor temperature increases above 68 F (20°C) in May, the outdoor air is too warm to cool the building. The chillers are then turned on, and the ventilation rate is minimized to reduce the cooling load. The ventilation rate then decreases to about 0.6 exchanges per hour. In June the outdoor temperature is also high; however, the ventilation rate has increased to about 1.0. It is not clear why this happened, but we suspect that the control system and building operation schedules were still being refined at this early stage of building occupancy. During the warm and humid conditions of August, the ventilation rate decreases again to about 0.6. In the fall of 1981, the outdoor temperature decreases to the 50 to 68 F (10 to 20°C) range and outdoor air is again used to cool the building, with the ventilation rate increasing to about 1.0 exchanges per hour. During the winter, the ventilation rates are about 0.8 with some higher rates occurring during February. After a long gap in 1982, the warm weather during June and July again leads to ventilation rates of 0.6 exchanges per hour.

This pattern in ventilation rates, lowest during the warmest and coolest temperatures and highest during mild temperature conditions, is repeated in almost all of the federal buildings. The difference between the summer (0.6) and winter (0.8-1.0) rates in Newark does not occur in all the buildings. Figure 2 is a plot of these same daily average ventilation rates, less the June 1981 data, plotted against the indoor-outdoor temperature difference. The difference between summer and winter ventilation rates is evident in this graph. This difference may be due to the existence of a cooling load in the building core, even in the winter, or to a large amount of uncontrolled air leakage (infiltration) during cold weather. We also see a wide range in the ventilation rates measured under mild temperature conditions. This variation is due in part to the fact that the ventilation rates induced by this enthalpy-controlled system depend on the outdoor humidity levels in addition to temperature. Even though dry air at a certain temperature can be used to cool the building, humid air at the same temperature may not be used for cooling.

The ventilation rates in the eight federal buildings exhibit characteristics similar to the Newark building. Plots of ventilation rate versus indoor-outdoor temperature difference for each federal building are shown in Figures 3 through 10. Table 2 shows mean ventilation rates, along with the standard deviations of these means, for 2.8 R (5 K) intervals of temperature difference for all nine buildings. The mean ventilation rates can be somewhat misleading for mild temperature conditions. As seen in the Newark building in Figure 2, the buildings with enthalpy control can be operated at low or high ventilation rates at the same outdoor temperature because of differences in outdoor humidity. This variation in ventilation rate at the same outdoor temperature also occurs in buildings with other types of control systems. Also, as discussed below, the ventilation rate at a given temperature can be affected by weather conditions in buildings for which weather induced infiltration is a significant portion of the total ventilation rate.

Figure 3 shows the ventilation rate in the Anchorage federal building as a function of temperature difference. We see low ventilation rates, about 0.25 to 0.50 exchanges per hour, during cold outdoor conditions and higher ventilation rates for temperature differences below about 11 R (20 K). None of our measurements in Anchorage was made under conditions warm enough for the building's air-conditioning system to be used for cooling and for the ventilation rate to again be minimized.

Figure 4 shows the ventilation rate of the Ann Arbor federal building plotted against temperature difference. These data exhibit a large amount of scatter due in part to some very high ventilation rates induced by high wind speeds. This implies that the infiltration rate of the Ann Arbor building is strongly dependent on wind speed and that infiltration becomes a significant portion of the net ventilation rate under windy conditions. These large wind-induced rates are not considered in calculating the Ann Arbor mean ventilation rates in Table 2. Under cold outdoor conditions, $\Delta T > 11$ R (20 K), this building is operated at about 0.5 exchanges per hour. For milder temperatures, outdoor air was used to cool the building with ventilation rates as large as 3.0 exchanges per hour. When the temperature difference was close to zero, the ventilation rates did return to 0.5 exchanges per hour. Thus, in the Ann Arbor building, the summer and winter ventilation rates were similar, as opposed to the difference observed in the Newark building.

The Columbia building's ventilation rates are shown in Figure 5. The measurements cover a wide range of warm temperature conditions (ΔT from -5.6 to 2.8 R (-10 to 5 K)), but we see no clear dependence of ventilation rate on temperature difference for the summer. If the weather dependent natural ventilation, or infiltration, is a large fraction of the net ventilation rate we are measuring, then our data may show a dependence on temperature difference. Such a dependence would tend to imply that infiltration is similar in magnitude to the intentional ventilation.

Figure 6 is the ventilation rate versus temperature difference plot for the Fayetteville building. When the building is being heated or cooled, the ventilation rate is about 0.35 exchanges per hour. Under mild temperature conditions, ΔT from 0 to 2.8 R (0 to 5 K), the ventilation rate varies between 0.35 and 1.5 exchanges per hour. The ten high ventilation rates between 1.0 and 1.5 exchanges per hour were measured under very windy conditions and probably are due to a dominance of natural ventilation or infiltration, as in the Ann Arbor building. Attempts to pressure test this building using its own supply fans, while successful in the other seven federal buildings (Grot 1982), were unsuccessful in Fayetteville because the ventilation system could not bring in enough outdoor air to raise the internal pressure significantly. Thus, we suspect that the ventilation rates of 1.0 exchanges per hour and higher are not due to mechanical ventilation alone, and that they probably contain a large component of uncontrolled infiltration induced by the high wind speeds during these measurements.

The Huron building, whose ventilation rates are plotted in Figure 7, has the lowest ventilation rates of all the buildings. Under hot and cold outdoor temperature conditions, ventilation rates of 0.2 exchanges per hour and less were measured. The cold weather ventilation measurements exhibit a dependence on both wind speed and temperature difference. This is the only building that showed a significant dependence of measured ventilation rate on temperature difference.

The ventilation rates of the federal building in Norfolk are plotted in Figure 8. In this building the winter and summer ventilation rates are comparable, both around 0.6 to 0.7 exchanges per hour. Figure 9 is a plot of the Pittsfield ventilation rates. It appears that the minimum ventilation rates during cold weather are lower than the warm weather ventilation rates.

The Springfield building ventilation rates, shown in Figure 10, exhibit an unusual pattern. The ventilation rates under warm conditions, $\Delta T < 5.6$ R (10 K), are relatively constant at about 0.6 exchanges per hour. For temperature differences greater than about 8.3 R (15 K), the ventilation rate varies from a minimum of 0.6 to a maximum of about 1.25 exchanges per hour. It is not clear if the high ventilation rates are due to intentional outdoor air intake, or to a strong dependence of infiltration on temperature difference. The outdoor air intake is controlled to maintain the supply air temperature at about 55 F (13°C), $\Delta T \approx 5.6$ R (10 K). This is indeed the temperature difference at which the ventilation rate is seen to increase. Measurements of infiltration made with the outdoor air dampers closed show a similar, but less extreme, dependence on temperature difference. Thus, the dependence of the net measured ventilation on ΔT appears to be a combination of the outdoor air intake control strategy and a significant portion of temperature-dependent infiltration.

VENTILATION REQUIREMENTS

These measurements of actual ventilation rates in occupied office buildings are compared to ventilation standards and design specifications of minimum outdoor air intake. A certain minimum ventilation rate must be maintained to remove pollutants generated inside a building. These minimum ventilation rates are determined by the building occupancy level (number of people per 1000 ft^2 (100 m^2) of floor area) and the extent and nature of the activities within the building (smoking, painting, and other pollutant-generating activities). In some of the buildings, the mechanical equipment specifications give a minimum outdoor air intake level in units of volumetric airflow. Another commonly accepted minimum ventilation rate is equal to 10% of the HVAC system's total airflow rate. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has established minimum recommended building ventilation rates (ASHRAE 1981), which are a function of occupancy levels, building type (e.g., office, store, hotel) and room type (e.g., kitchen, office, conference room).

Table 3 lists the minimum ventilation rates, in units of exchanges per hour, based on 10% of total air for all the buildings. The minimum ventilation rates based on ASHRAE Standard 62-81 (1981) are also included for the cases of both smoking and nonsmoking occupants in office buildings. In order to determine the recommended ventilation rate from the ASHRAE standard, one needs to know the floor areas of each type of room in the building and the occupancy levels in each room. Since we do not know the occupancy levels in the buildings, we used seven persons per 1000 ft^2 (100 m^2) of floor area, which ASHRAE recommends when design or actual occupancy is not known. We also assumed that all the floor area is office space, neglecting the fact that there are kitchens, bathrooms, conference rooms, and waiting areas. At the estimated occupancy level for office space, ASHRAE recommends 20 cfm (10 L/s) per person when the occupants smoke and 5 cfm (2.5 L/s) when they do not smoke. When smoking is permitted, ASHRAE recommends using the ventilation rate for smoking conditions. The Newark building has three separate 10% ventilation rates depending on how many fans are in use. The number of fans in use depends on the space conditioning load. The building design specifications suggest that three fans will be needed in January, four in March, and all five in July. Finally, the table lists a representative value for the minimum measured ventilation rate in each building.

In all the buildings, except Fayetteville, the 10% total air rate is less than the ASHRAE recommendation for smoking conditions. In Newark, Anchorage, and Norfolk, the smoking rate is twice the 10% ventilation rate. The ASHRAE nonsmoking value is less than all the 10% rates. Since smoking is permitted in all the buildings, the nonsmoking recommendation is not relevant to the operation of the buildings.

Rather than compare the different ventilation standards to each other, it is more important to compare them to the ventilation rates measured in the buildings. We will use the ASHRAE smoking recommendation for these comparisons. In Anchorage and Huron, the minimum ventilation rates when the buildings are heated or cooled are about one-third of the smoking rate. In fact, these measured ventilation rates are close to the ASHRAE nonsmoking rates. In all the other buildings, the lowest measured ventilation rates are very close to, and at times lower than, the smoking ventilation rates. Thus, all of the buildings are at times being operated at ventilation rates lower than may be desirable for the maintainance of indoor air quality. As will be discussed below, local variations in air distribution may lead to ventilation rates in specific zones that are very low.

The question of the adequacy of outdoor air intake is primarily an issue during hot and cold weather when outdoor air intake is at a minimum. This minimum outdoor air intake is often assured by having a minimum outdoor air damper position or by keeping a certain portion of the outdoor air dampers open at all times. In other cases, the outdoor air dampers are closed completely, and it is assumed that leakage through the building envelope will fulfill the minimum outdoor air requirements.

It is interesting to compare the measured ventilation rates under conditions of minimum outdoor air intake to measurements of building infiltration made with the dampers totally closed and the HVAC fans running. The measurements under the latter condition were made only in the federal buildings. These so-called infiltration rates provide a measure of the tightness of the building shell and of any leakage in the HVAC system. The measurements are not strictly a measure of the shell tightness because ventilation systems are often designed to pressurize a building, which will lead to more air leakage than that induced by the weather alone. The daytime ventilation rates during periods of minimum outdoor air intake and the 0% outdoor air infiltration rates are compared for similar weather conditions. This comparison provides an indication of how much additional air is really brought in through the outdoor air intake dampers to meet ventilation requirements and how much of the outdoor air intake results from uncontrolled air leakage. In Ann Arbor, Columbia, Pittsfield, and Springfield, the ventilation rates are about 0.2 exchanges per hour higher during occupied periods than the exchange rates when the building outdoor air dampers are closed tightly. In Anchorage and Fayetteville, the difference is only 0.1 exchanges per hour, and in Huron and Norfolk the difference is insignificant. Thus, during times of minimum outdoor air intake, little of the outdoor air enters the Huron and Norfolk buildings through the outdoor air intake vents. In the rest of the buildings, the amount of air brought in through the vents is comparable to the ASHRAE nonsmoking ventilation recommendation. Thus, either the minimum outdoor air damper settings are much too low or the building designers are relying on residual air leakage or infiltration to meet outdoor air ventilation requirments.

Table 4 shows the monthly average ventilation rates for all nine buildings based on monthly average outdoor temperatures for the cities or nearby cities and an assumed inside temperature of 73 F (23°C). The ventilation rate for each month is based on the averages in Table 2 or visual inspection of the plots of ventilation versus temperature difference (Figures 3 through 10) when the mean ventilation rate is not representative of the data. Again we see some very low monthly average ventilation rates in some of the buildings. In some cases, the monthly average ventilation rate is lower than the ASHRAE recommendation. Even when the monthly average is not below the recommendation, there will be periods during the month when the ventilation rate is lower.

VENTILATION EFFICIENCY

We have measured the ventilation rates in nine office buildings and have found that when the mechanical systems are bringing in minimum amounts of outdoor air, the ventilation rates are close to or below suggested ventilation levels. The measured rates are averages over an entire building, and there will be local variations in ventilation and uniformity of air distribution among zones, floors, rooms, and parts of rooms. Some of these variations were evident during our ventilation measurements after the injection of the SF_6 tracer. The SF_6 concentration on some of the floors does not increase at the same rate as the rest of the building. This was pointed out previously for the 16th and 20th floors of the Newark building (Grot 1982). The ratio of supply airflow to the volume of these floors was not the same for these floors as the rest of the building. It was suggested that this was due to a balancing problem or to VAV boxes or dampers not opening. Thus, the ventilation rate on these floors is lower than the measured building ventilation rate, and there is a potential for indoor air quality problems at these locations. Such situations of poor air distribution are often referred to as problems of ventilation efficiency (Sandberg 1983). There are many ways to define ventilation efficiency, but they generally quantify the departure from uniform mixing of the supply air flowing into a space with the air in that space. In addition to a floor not receiving its proper portion of supply airflow, there can also be distribution problems on a floor. Individual rooms may not receive the appropriate amount of supply air even though the floor or zone is properly ventilated. This can happen when partitions are installed in a room and obstruct the intended airflow through the space. Finally, even within a well-ventilated room, the supply air may be removed through exhaust or return ducts before it mixes with the rest of the interior air. Occurrences of such "short-circuiting" further reduce the effective ventilation rate in the occupied spaces of a building. Thus, low ventilation efficiency can reduce an already low ventilation rate to a lower effective ventilation rate for the occupants of a building. The extent of such air distribution problems in real buildings is not well known and needs to be investigated. Tracer gas techniques can be used to study air distribution and measure ventilation efficiency on a large scale (floors and zones) and on a small scale (within a room).

CONCLUSIONS

We measured ventilation rates under occupied conditions in nine office buildings. We found that for hot and cold outdoor temperatures, the buildings are operated at minimum ventilation levels to reduce space-conditioning loads. At mild temperatures, outdoor is used to cool the buildings and the ventilation rates increase significantly. The minimum ventilation rates show little temperature dependence in most of the buildings, but some of the buildings exhibit a dependence on wind speed. When ventilation does vary with weather conditions, this implies that uncontrolled air leakage or weather-induced ventilation is a significant portion of the net ventilation rate. In most of the buildings, the summer and winter minimum ventilation rates are similar, but in some buildings there is a notable difference between the two minimum ventilation rates. The minimum ventilation rates were compared to minimum outdoor air intake levels suggested by ASHRAE, and we found that most of the buildings were operated very close to or below the ASHRAE recommendation. Two of the buildings were operated well below this recommended ventilation rate. Local variations in air distribution and problems of ventilation efficiency can lead to effective ventilation rates in specific areas of the building that are significantly lower than the average rate for the building.

REFERENCES

ASHRAE. 1981. ANSI/ASHRAE Standard 62-1981, "Ventilation for acceptable indoor air quality." Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Grot, R.A.; Hunt, C.M.; and Harrje, D.T. 1980. "Automated air infiltration measurements in large buildings." Proceedings of the First Air Infiltration Centre Conference, Bracknell, UK.

Grot, R.A. 1982. "The air infiltration and ventilation rates in two large commercial buildings." Proceedings of ASHRAE/DOE Conference on Thermal Performance of the Exterior Envelopes of Buildings II, Las Vegas.

Grot, R.A.; Chang, Y.L.; Persily, A.K.; and Fang, J.B. 1983. "Interim report on NBS thermal integrity diagnostic tests on eight GSA federal office buildings." NBSIR 83-2768, National Bureau of Standards.

Grot, R.A. and Persily, A.K. 1983. "Air infiltration and airtightness tests in eight US office buildings." Proceedings of the Fourth Air Infiltration Centre Conference, Elm, Switzerland.

Sandberg, M. 1983. "Ventilation efficiency as a guide to design." ASHRAE Transactions, Vol.89 Part 2.

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TABLE 1
THE TEST BUILDINGS

Location	Number of Stories	Occupiable Floor Area ft2	Occupiable Floor Area m2	Ventilation Type
Newark, NJ	26	685,000	63,600	VAV
Anchorage, AK	6	490,000	45,500	VAV
Ann Arbor, MI	4	52,700	4,900	VAV*
Columbia, SC	16	216,000	20,100	VAV*
Fayetteville, AR	5	36,600	3,400	CV
Huron, SD	4	69,100	6,400	VAV*
Norfolk, VA	8	186,000	17,300	VAV*
Pittsfield, MA	2	18,600	1,700	CV
Springfield, MA	5	146,000	13,500	VAV*

VAV - Variable Volume   CV - Constant Volume

* Lobbies have constant volume air handlers.

TABLE 2
AVERAGE VENTILATION RATES IN THE BUILDINGS

Temperature Difference R	(K)	Newark** Mean/SD	Anchorage	Ann Arbor*	Columbia	Fayetteville
-5.6,-2.8	(-10,-5)	--	--	--	0.68/0.18	--
-2.8,0	(-5,0)	0.60/0.07	--	--	0.68/0.21	0.36/0.12
0,2.8	(0,5)	0.81/0.44	--	0.94/0.95	0.69/0.32	0.65/0.39
2.8,5.6	(5,10)	0.91/0.27	1.34/0.36	1.94/0.42	1.10/0.90	0.35/0.07
5.6,8.3	(10,15)	1.18/0.32	1.22/0.25	1.96/0.97	1.09/0.56	0.35/0.01
8.3,11.1	(15,20)	0.91/0.27	1.10/0.23	0.86/0.20	0.64/0.26	0.32/0.02
11.1,13.9	(20,25)	0.81/0.12	--	0.47/0.07	0.62/0.24	--
13.9,16.7	(25,30)	0.79/0.04	0.46/0.14	--	--	--
16.7,19.4	(30,35)	--	0.24/0.04	--	--	--
19.4,22.2	(35,40)	--	0.36/0.10	--	--	--
22.2,25	(40,45)	--	0.26/0.02	--	--	--

Temperature Difference R	(K)	Huron	Norfolk	Pittsfield	Springfield
-8.3,-5.6	(-15,-10)	--	0.73/0.09	--	--
-5.6,-2.8	(-10,-5)	0.19/0.00	0.62/0.11	0.49/0.09	0.55/0.09
-2.8,0	(-5,0)	0.16/0.04	0.58/0.07	0.43/0.09	--
0,2.8	(0,5)	0.53/0.43	0.75/0.19	1.19/0.73	0.59/0.08
2.8,5.6	(5,10)	0.52/0.00	1.00/0.32	1.25/1.15	0.62/0.08
5.6,8.3	(10,15)	0.13/0.04	1.05/0.37	0.67/0.48	0.76/0.20
8.3,11.1	(15,20)	0.14/0.06	--	0.84/0.47	0.96/0.20
11.1,13.9	(20,25)	0.32/0.14	0.70/0.09	0.38/0.14	0.95/0.22
13.9,16.7	(25,30)	0.25/0.05	0.66/0.06	--	--
16.7,19.4	(30,35)	0.26/0.07	--	--	--
19.4,22.2	(35,40)	0.29/0.04	--	--	--
22.2,25	(40,45)	0.31/0.06	--	--	--

All the ventilation rates are in units of exchanges per hour.

* Calculations neglect some very high, wind-induced ventilation rates.
** Standard deviation of the mean ventilation rate.

TABLE 3
RECOMMENDED MINIMUM VENTILATION RATES IN THE BUILDINGS

Building	10% Total Air	ASHRAE 62-81 Smoking	ASHRAE 62-81 Nonsmoking	Building Minimum
Newark	3 fans: 0.16 4 fans: 0.22 5 fans: 0.28	0.63	0.16	0.55
Anchorage	0.28	0.67	0.17	0.26
Ann Arbor	0.36	0.38	0.09	0.47
Columbia	0.28	0.41	0.10	0.62
Fayetteville	0.57	0.41	0.10	0.32
Huron	0.31	0.49	0.12	0.13
Norfolk	0.25	0.69	0.17	0.62
Pittsfield	0.32	0.42	0.10	0.38
Springfield	0.44	0.46	0.12	0.55

All the ventilation rates are in units of exchanges per hour.

TABLE 4
MONTHLY AVERAGE VENTILATION RATES

Month	Newark	Anchorage[1]	Ann Arbor[2]	Columbia	Fayetteville[3]
January	0.81	0.46	0.47	0.64	0.32
February	0.81	0.46	0.47	1.09	0.32
March	0.91	0.46	0.47	1.09	0.35
April	1.18	0.75	1.96	1.10	0.35
May	0.91	1.10	1.94	0.69	0.65
June	0.81	1.22	0.94	0.68	0.36
July	0.60	1.22	0.50	0.68	0.36
August	0.60	1.22	0.50	0.68	0.36
September	0.81	1.22	1.94	0.68	0.36
October	0.91	0.75	1.96	1.10	0.35
November	0.91	0.46	0.86	1.09	0.35
December	0.81	0.46	0.47	0.64	0.32

	Huron	Norfolk	Pittsfield[4]	Springfield[4]
Jan	0.26	0.70	0.40	1.00
Feb	0.26	0.70	0.40	1.00
Mar	0.32	1.05	0.38	0.95
Apr	0.14	1.00	0.67	0.76
May	0.52	0.75	1.25	0.62
Jun	0.53	0.58	0.50	0.59
Jul	0.16	0.58	0.50	0.59
Aug	0.53	0.58	1.19	0.59
Sep	0.52	0.75	1.25	0.62
Oct	0.13	1.00	0.67	0.76
Nov	0.32	1.05	0.84	0.96
Dec	0.26	0.70	0.40	1.00

All the ventilation rates are in units of exchanges per hour.

1 Based on outdoor temperatures from Homer, AK.
2 Based on an average of outdoor temperatures from Flint and Detroit, MI.
3 Based on outdoor temperatures from Ft. Smith, AR.
4 Based on outdoor temperatures from Hartford, CT.

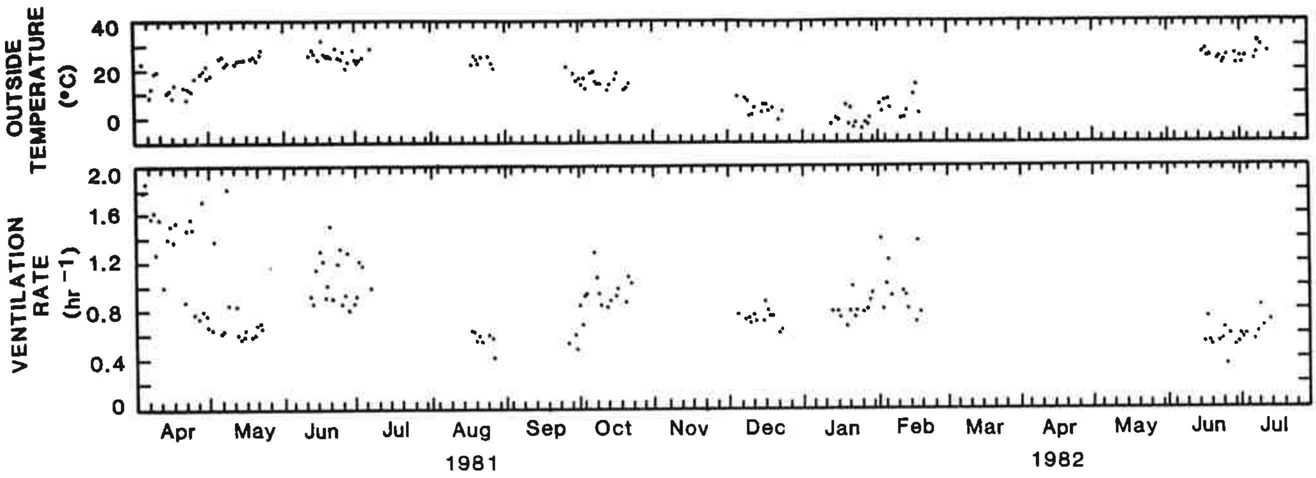

Figure 1. Ventilation rate and outside temperature versus time for the Newark building

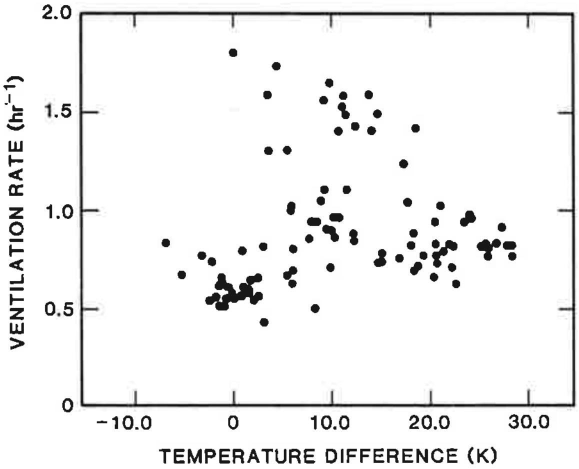

Figure 2. Ventilation rate versus inside-outside temperature difference for the Newark building

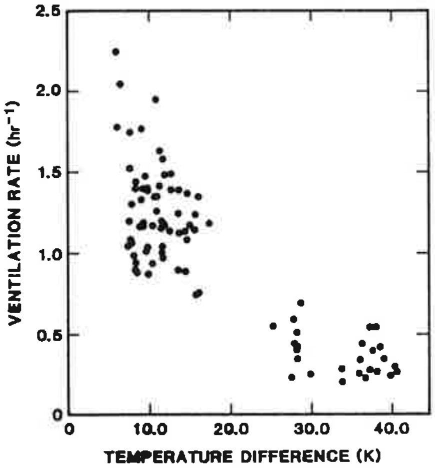

Figure 3. Ventilation rate versus inside-outside temperature difference for the Anchorage building

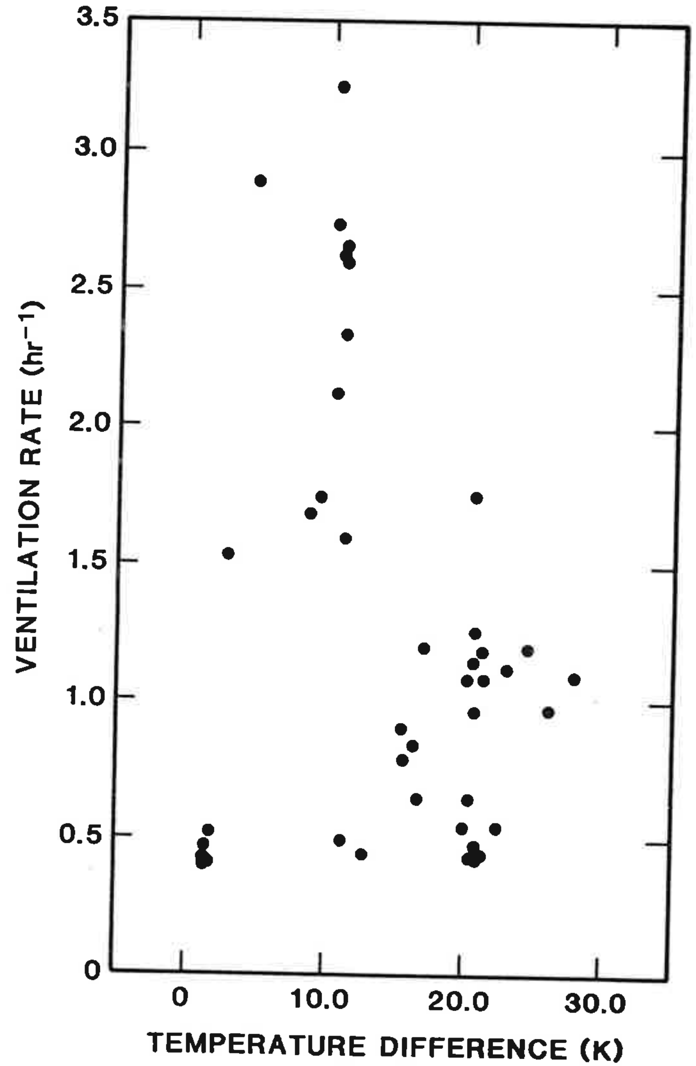

Figure 4. *Ventilation rate versus inside-outside temperature difference for the Ann Arbor building*

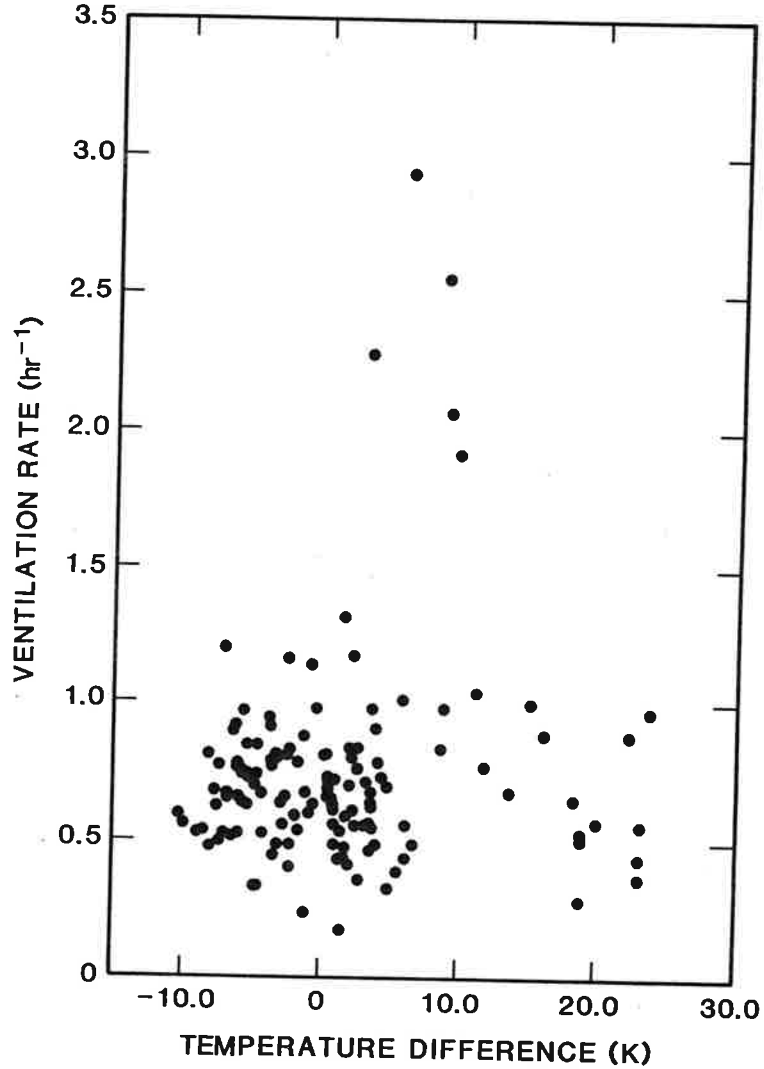

Figure 5. *Ventilation rate versus inside-outside temperature difference for the Columbia building*

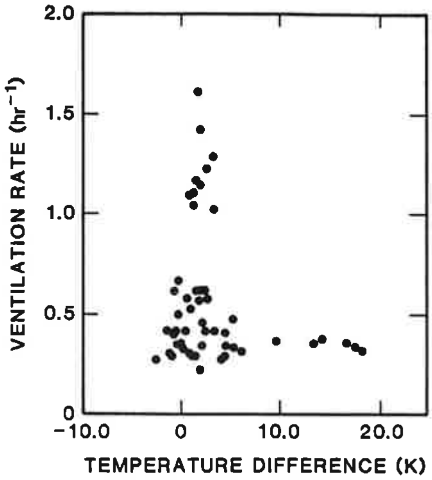

Figure 6. Ventilation rate versus inside-outside temperature difference for the Fayetteville building

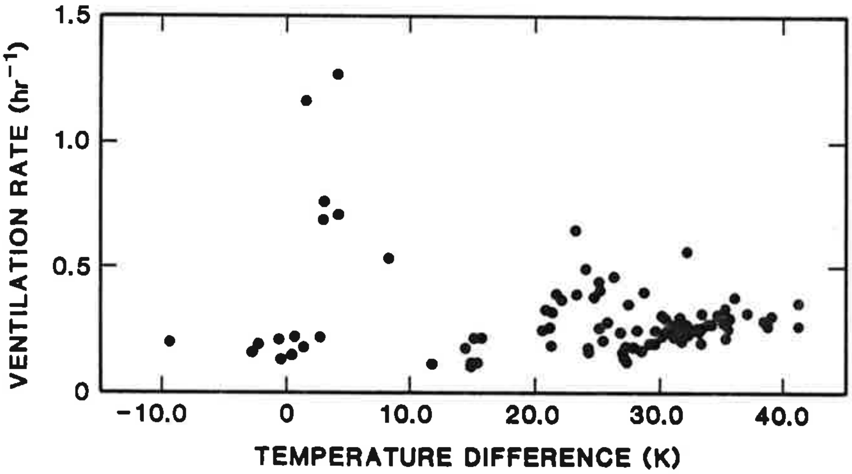

Figure 7. Ventilation rate versus inside-outside temperature difference for the Huron building

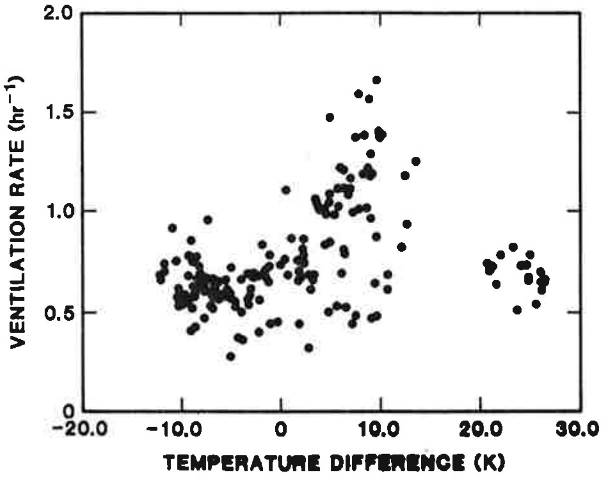

Figure 8. Ventilation rate versus inside-outside temperature difference for the Norfolk building

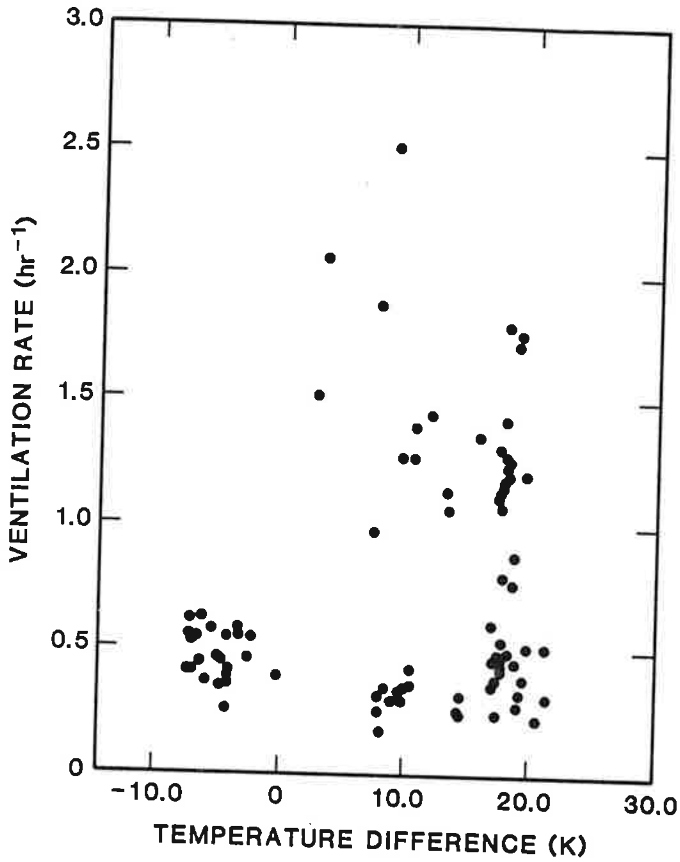

Figure 9. *Ventilation rate versus inside-outside temperature difference for the Pittsfield building*

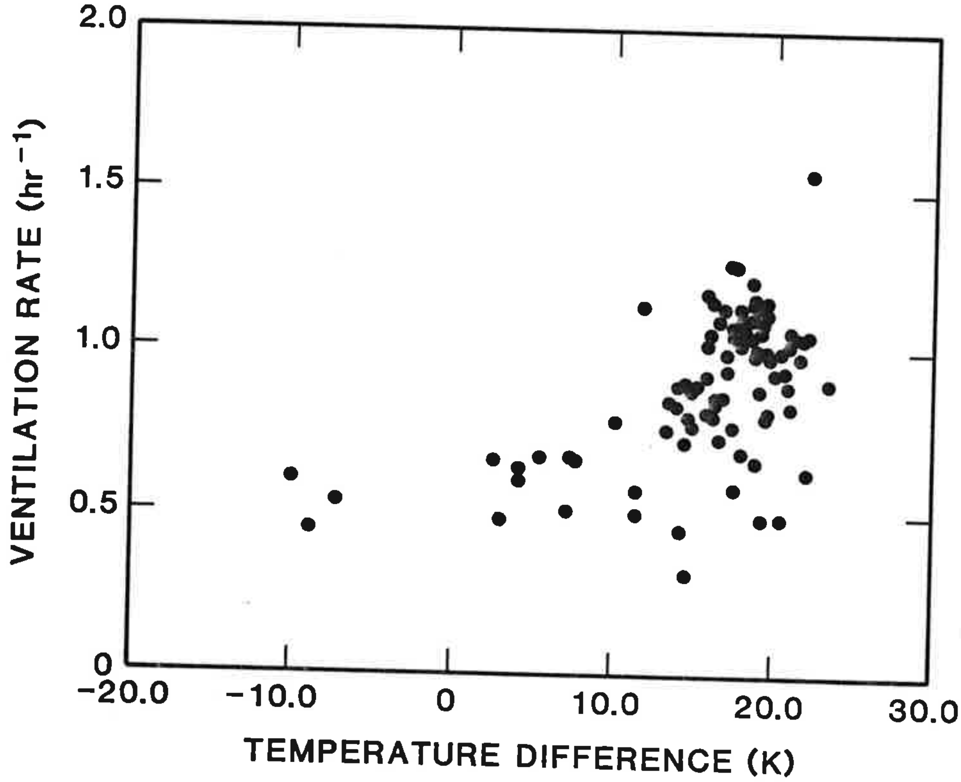

Figure 10. *Ventilation rate versus inside-outside temperature difference for the Springfield building*

Discussion

R.R. WALKER, Building Research Establishment, Garston, Watford, England: Does the air from different floors/zones mix in the air-handling unit?

PERSILY: The air from the various floors/zones which are served by a single air handler will mix within that air handler. The air from adjoining zones generally has the opportunity to mix through interior spaces and ceiling plenums.

WALKER: Did you observe different decay rates in different zones?

PERSILY: In general, the decay rates were similar in the different zones. Exceptions included lobby areas and other high-use areas (e.g., a post office).

WALKER: How long was the period of measurement?

PERSILY: The ventilation rates are calculated from tracer gas decays lasting one hour. The measurements were conducted over several weeks during each season of the year with the exception of Newark, which was monitored almost continuously for more than one year.

WALKER: If you did observe different slopes, and if there is air communication between the zones, then do you think that maybe a different slope would have been tended toward in the longer term?

PERSILY: We believe that in the majority of cases no such change in slope would occur due to the good mixing between zones. The only exception encountered was for a building in which there was an upflow of air through the structure. When the tracer concentration in the lower floors was depleted, the decay rate of the upper floors increased.

WALKER: I did notice some transient nature (changing slope) at the early part of some decay profiles you showed for various floors. Does this have a bearing?

PERSILY: The transients in the early parts of the decays are primarily due to incomplete mixing. In some buildings it takes one hour for the tracer to mix well with the interior air.

G.T. TAMURA, National Research Council of Canada, Ottawa, Ontario: In the test data, was there significant variation in the ventilation rates between the ground and typical floors?

PERSILY: As stated above, the ground floors generally exhibited higher ventilation rates. This was often true even when the building was unoccupied, ruling out the explanation of people opening and closing the doors.

C.H. JORDAN, Skidmore, Owings & Merrill, San Francisco, CA: Why does your slide indicate different ASHRAE 62-81 minimum OA air changes per hour for the several buildings, even though they are all office buildings?

PERSILY: The values for ASHRAE Standard 62-81 in Table 3 were computed as follows: Occupiable (rentable) floor area multiplied by 7 people/100m^2, multiplied by 10 L/s per person, and divided by the total building volume. The fact that the buildings varied in rentable volume to total volume led to different values in Table 3. As pointed out in the next question, this is not the most appropriate way to interpret the standard.