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Measured Air Infiltration and Ventilation Rates in Eight Large Office Buildings

REFERENCE: Grot, R. A. and Persily, A. K., **"Measured Air Infiltration and Ventilation Rates in Eight Large Office Buildings,"** *Measured Air Leakage of Buildings, ASTM STP 904*, H. R. Trechsel and P. L. Lagus, Eds., American Society for Testing and Materials, Philadelphia, 1986, pp. 151–183.

ABSTRACT: Air infiltration and ventilation rate measurements were made during all seasons of the year in eight federal office buildings using an automatic air infiltration system designed at the National Bureau of Standards. The eight federal office buildings were located in Anchorage, Alaska; Ann Arbor, Michigan; Columbia, South Carolina; Fayetteville, Arkansas; Huron, South Dakota; Norfolk, Virginia; Pittsfield, Massachusetts; and Springfield, Massachusetts. These buildings ranged in size from 1730 m^2 (18 600 ft^2) for the building in Pittsfield to 45 500 m^2 (490 000 ft^2) for the Anchorage federal building. All were constructed within the last 10 years. Air infiltration rates were found to vary from 0.2 to 0.7 air changes per hour and constituted from 23% to 61% of the building design load. Minimum ventilation rates in the tighter buildings were found to be less than what would be recommended for occupied offices.

KEY WORDS: air infiltration, office buildings, tracer gas, ventilation

The air infiltration and ventilation rates of the eight federal office buildings were tested using tracer gas techniques [*1*]. The measurement employed the tracer gas decay method using sulfur hexafluoride (SF_6) as the tracer. This test was designed to produce a measure of the total air infiltration rate of each building and the rates of the major zones of the building. Sample and injection tubing was installed in each zone along with wiring for measuring interior temperatures, the status of the building's heating, ventilating, and air conditioning (HVAC) fans, and exterior weather conditions (wind speed, wind direction, and exterior temperature). The automatic air infiltration system previously designed by the National Bureau of Standards (NBS) for large

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buildings was installed in each building for a period of about a week during the fall, winter, and spring (three automated air infiltration systems were used on this project). Tests were performed both during periods of occupancy and nonoccupancy, with the outside air intake dampers operated normally and closed, respectively. Tracer gas measurements were made for a total of about 200 h in each building.

Building Descriptions

The eight federal office buildings are located in the cities shown in the map in Fig. 1, and their floor areas and volumes are given in Table 1. In general

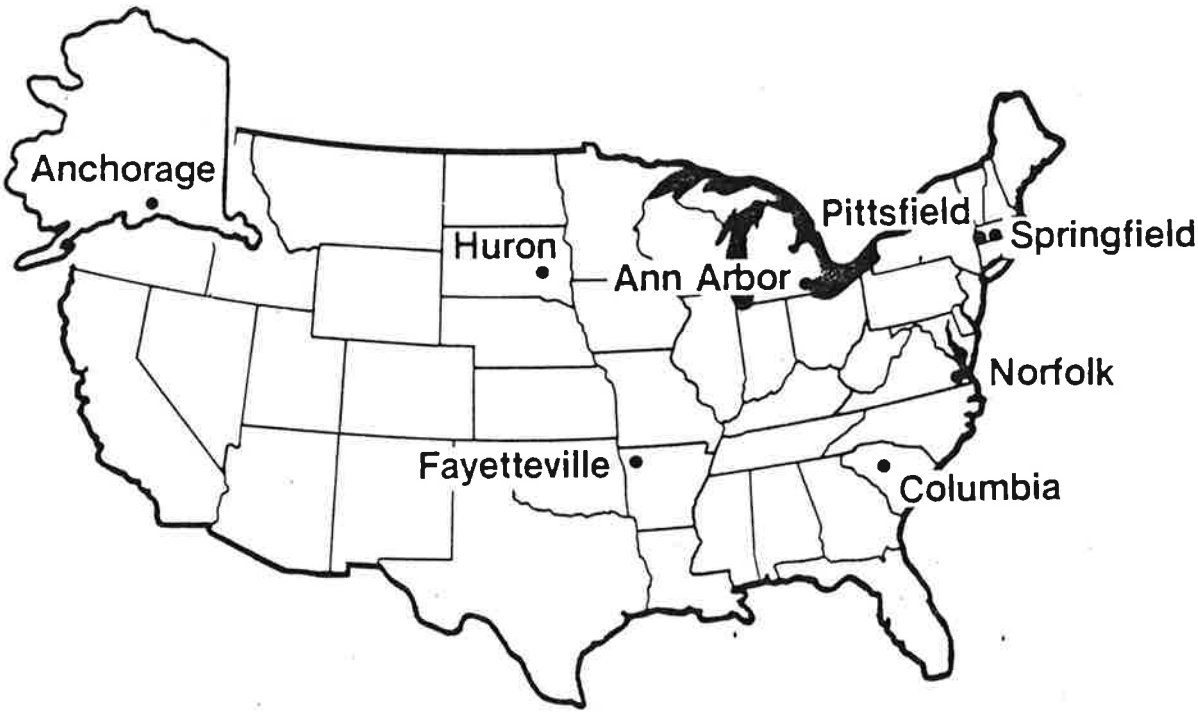


FIG. 1—*Location of the eight federal office buildings.*

TABLE 1—*Building dimensions.*

Location	Occupiable Floor Area, m^2	Volume, m^3
Anchorage	45 500	174 000
Ann Arbor	4 900	31 700
Columbia	24 700	159 000
Fayetteville	3 400	21 300
Huron	6 420	27 500
Norfolk	17 300	60 300
Pittsfield	1 730	8 520
Springfield	13 500	57 700

these are new buildings[2] (less than 3 years old) constructed to the U.S. federal energy guidelines of less than 630 MJ/m^2 per year of on-site energy and less than 1200 MJ/m^2 per year of off-site energy. The building in Fayetteville, Arkansas is 7 years old and was built before the energy guidelines for new federal office buildings were in effect. Though these buildings tend to perform better than most existing federal office buildings, none has met the energy guidelines during its first few years of occupancy.

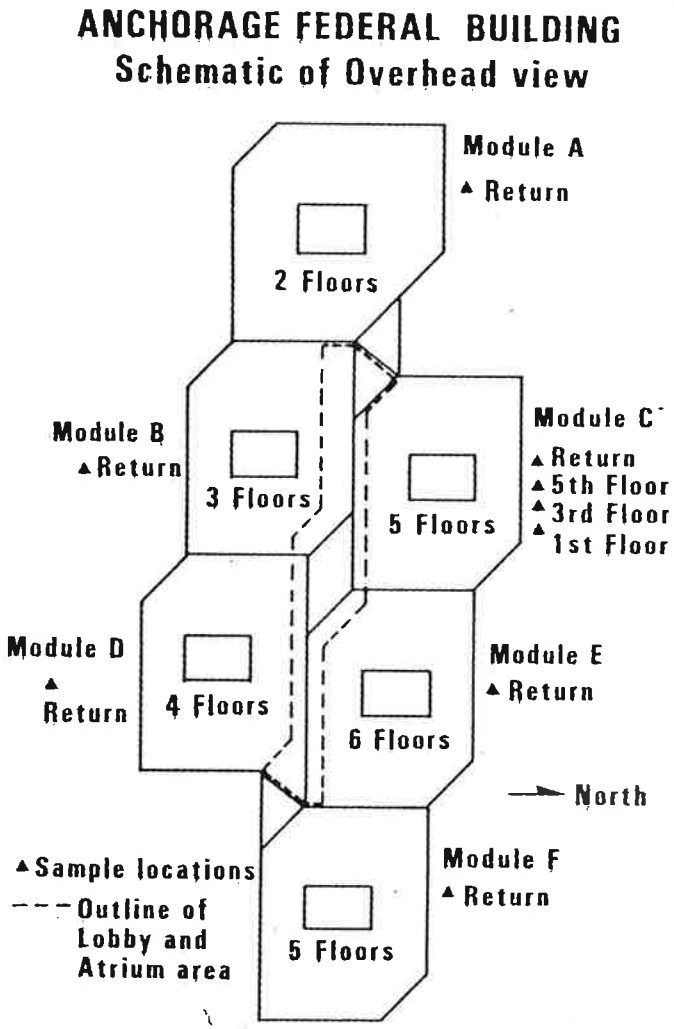
The office buildings in Anchorage, Alaska; Springfield, Massachusetts; Norfolk, Virginia; and Columbia, South Carolina had occupiable floor areas over 10 000 m^2 with varying heights. The Columbia building is 15 stories high, the Norfolk building 8 stories, the Anchorage building between 2 and 6 depending on the module, and the Springfield building 5 stories. The buildings in Pittsfield, Massachusetts; Huron, South Dakota; Ann Arbor, Michigan; and Fayetteville, Arkansas had less then 10 000 m^2 occupiable floor area. These small office buildings range in height from two to five stories. Schematic diagrams and a photograph of all buildings are given in Figs. 2 through 9.

The mechanisms for controlling outside air intake vary among the eight buildings. In most buildings, outside 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, outside air often is used to cool the building. The amount of outside air intake, and the times when outside air intake is increased, are controlled by a variety of schemes. An economizer control uses the outside temperature to determine when outside air should be used for cooling. Enthalpy control uses indoor and outdoor humidity levels in addition to temperature. The amount of outside air intake for cooling generally is determined by a control system which compares the discharge or return air temperature to some temperature setting. The control strategies used in each building are outlined in following paragraphs, along with other information on mechanical systems and the zoning of the buildings.

All but two of the buildings have variable volume air handlers in the major zones of the buildings. They are heated by perimeter heating systems which are generally hydronic. In the Norfolk building, heaters and air conditioners have been added to the air system on floors which proved difficult to heat and cool. They all have central chiller systems for cooling and for the core spaces of the buildings. The buildings in Anchorage and Springfield have underground garages.

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 outside air during the heating season. During warmer weather, outside air is used to cool the

[2]A more complete description of these buildings can be found in Ref 2.



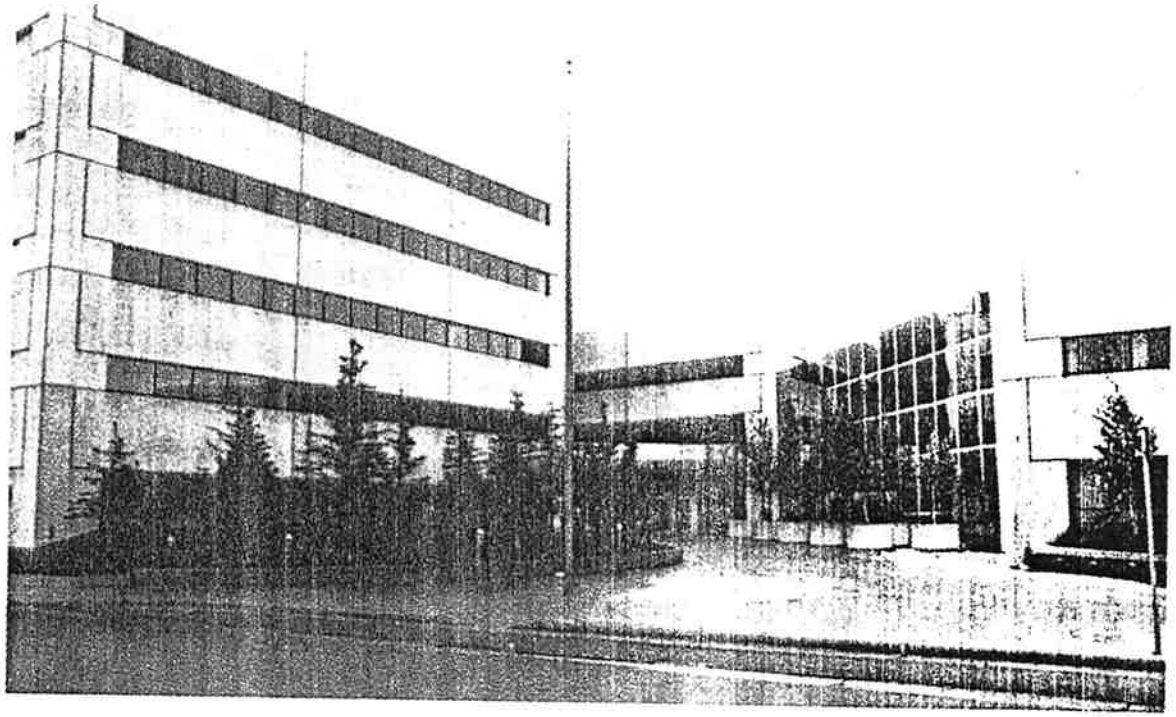


FIG. 2—*Schematic diagram and photograph of Federal building in Anchorage, AK.*

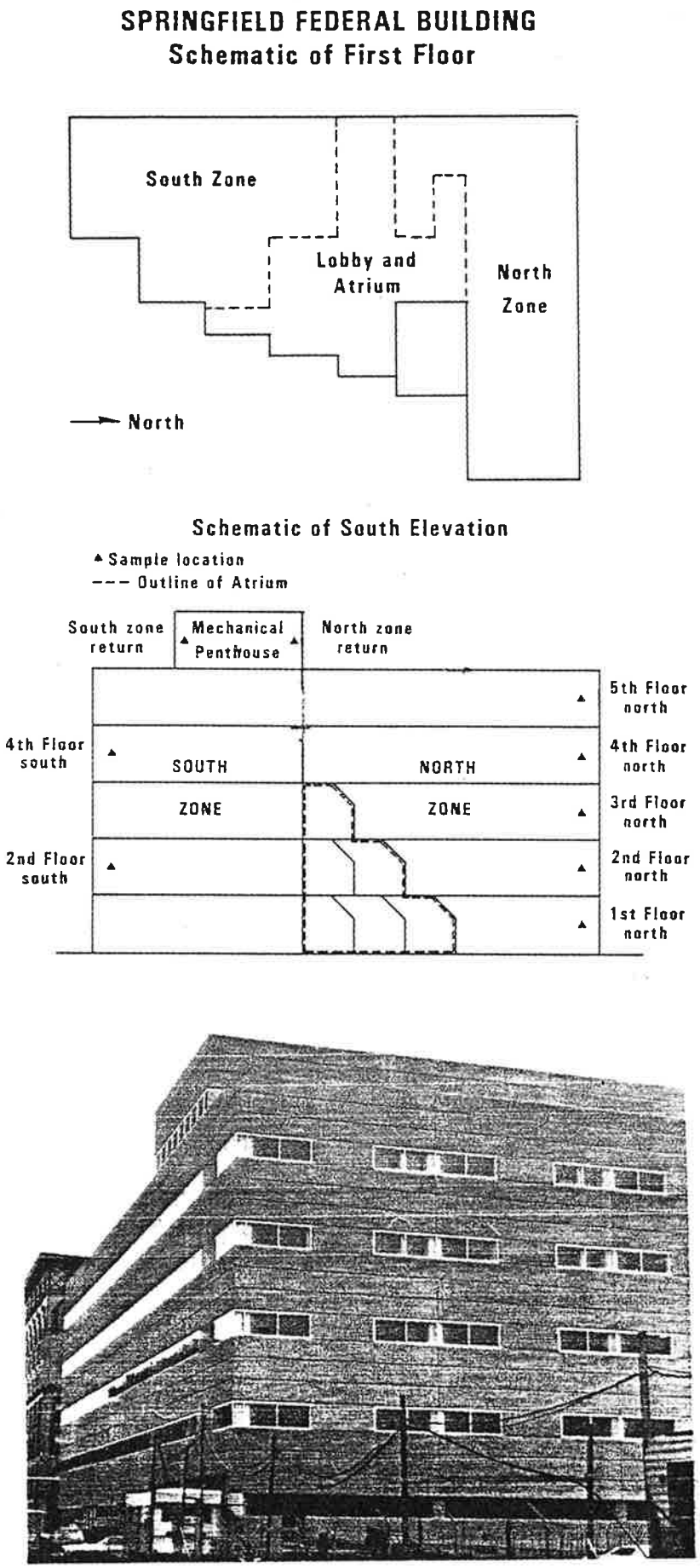


FIG. 3—*Schematic diagram and photograph of Federal building in Springfield, MA.*

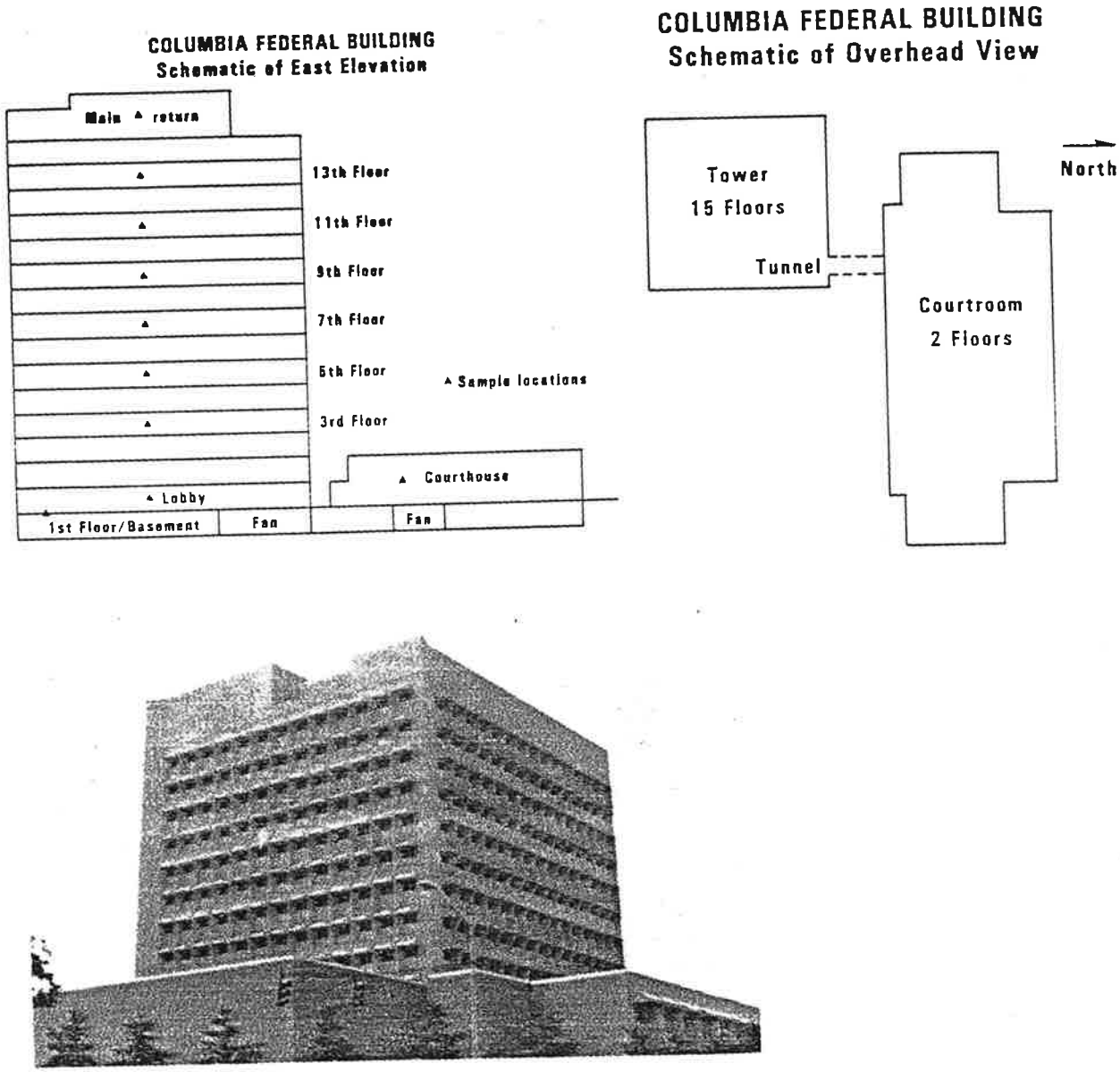


FIG. 4—*Schematic diagram and photograph of Federal building in Columbia, SC.*

building, with the outside 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 outside air intake is based on the outside air temperature (an economizer), and the amount of outside air intake is controlled by the return air temperature.

Columbia has a single mechanical system for Floors 2 through 16 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 outside 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 outside air intake is controlled manually by the building operator.

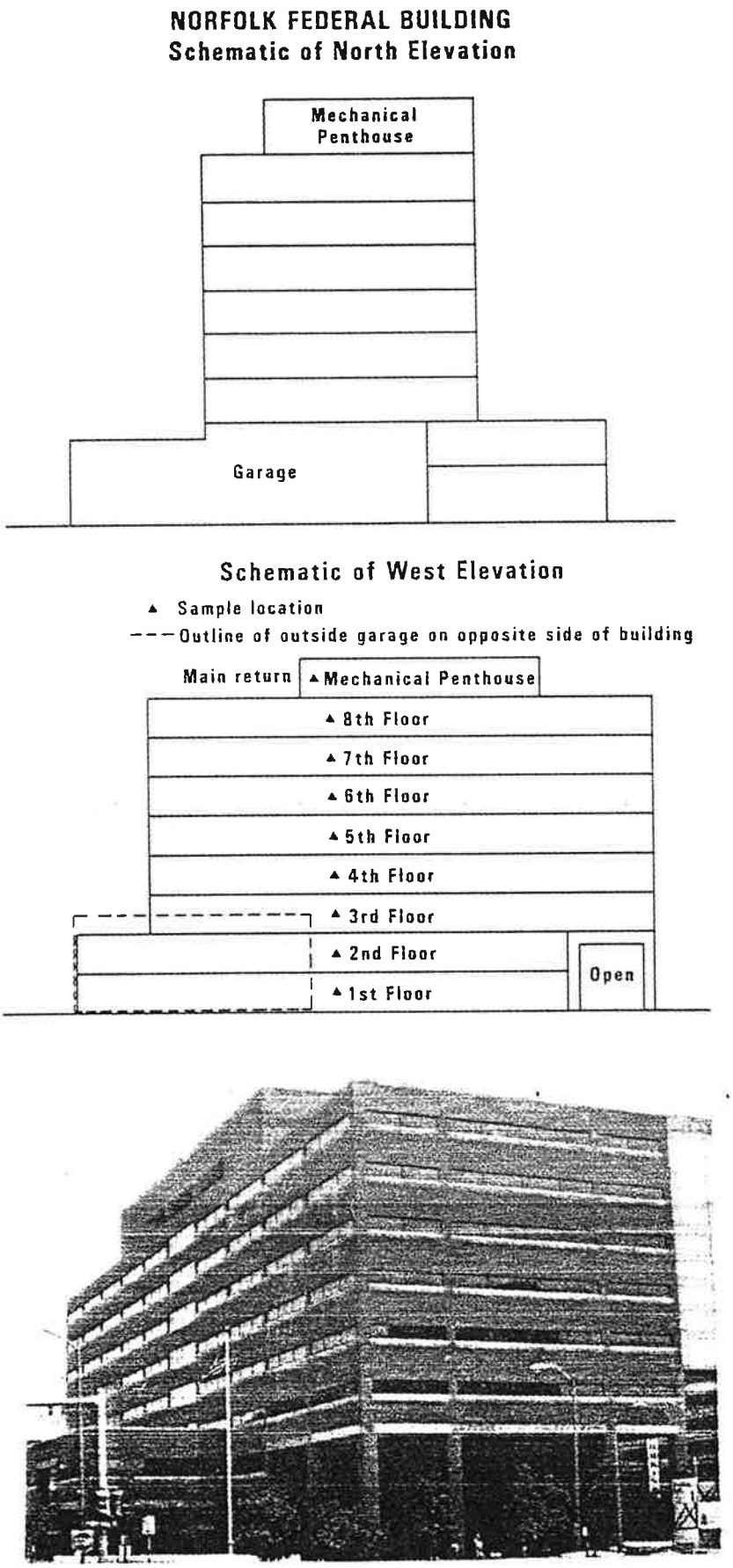


FIG. 5—*Schematic diagram and photograph of Federal building in Norfolk, VA.*

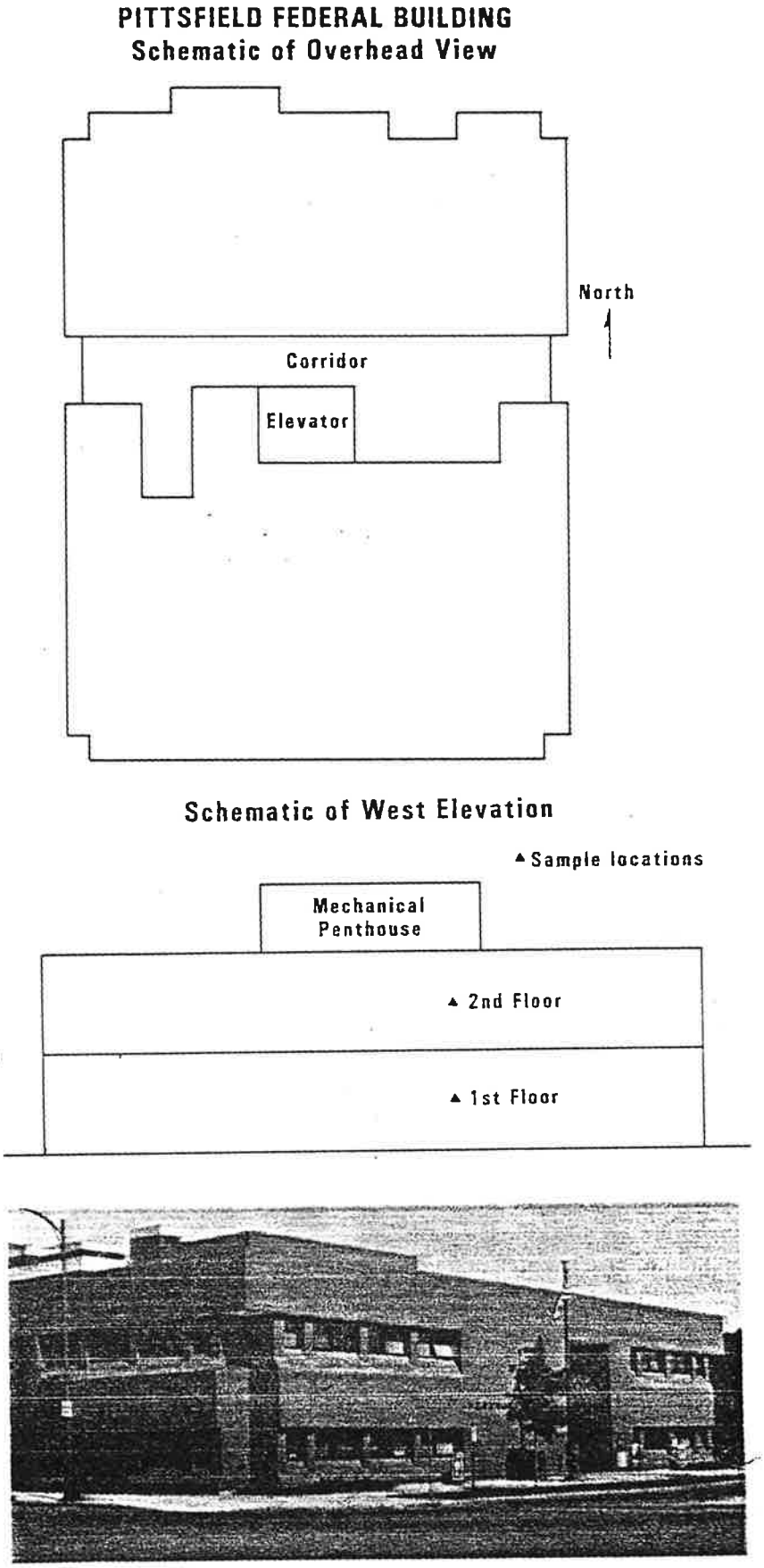


FIG. 6—*Schematic diagram and photograph of Federal building in Pittsfield, MA.*

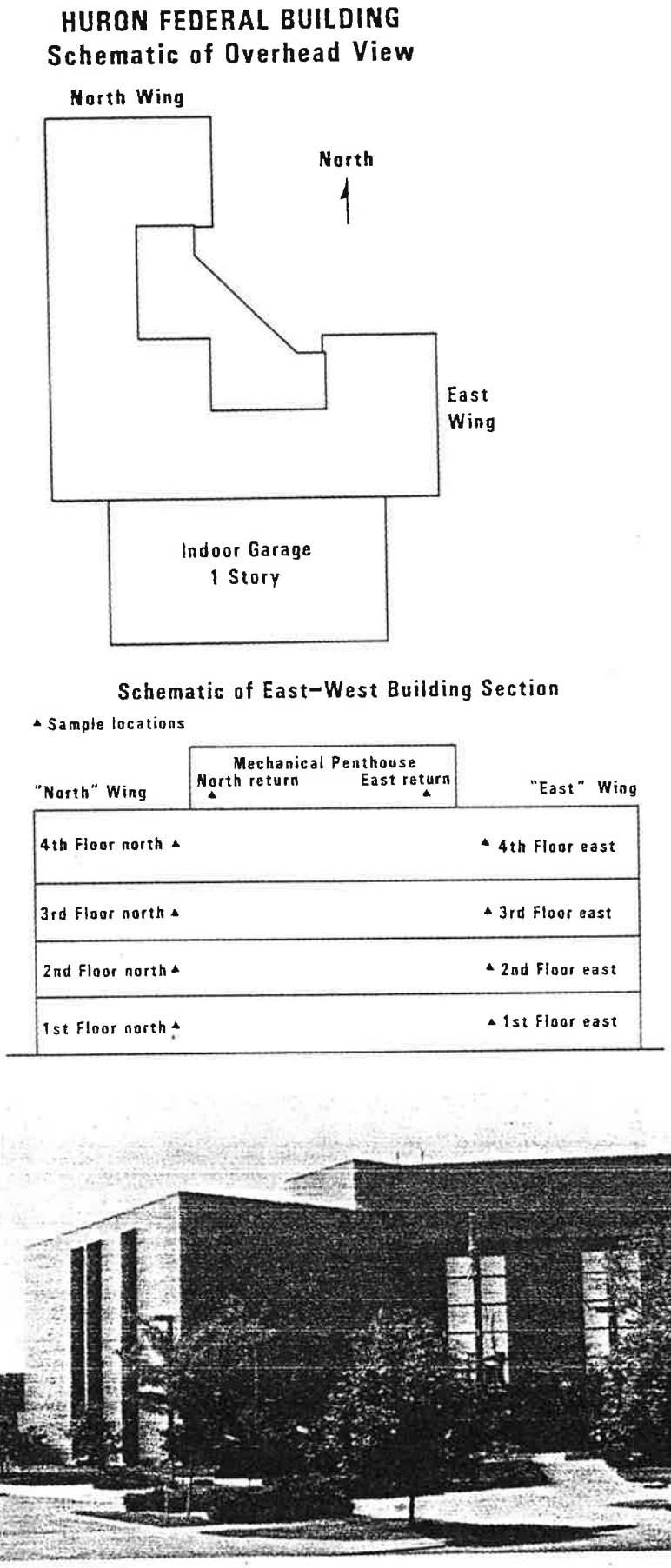


FIG. 7—*Schematic diagram and photograph of Federal building in Huron, SD.*

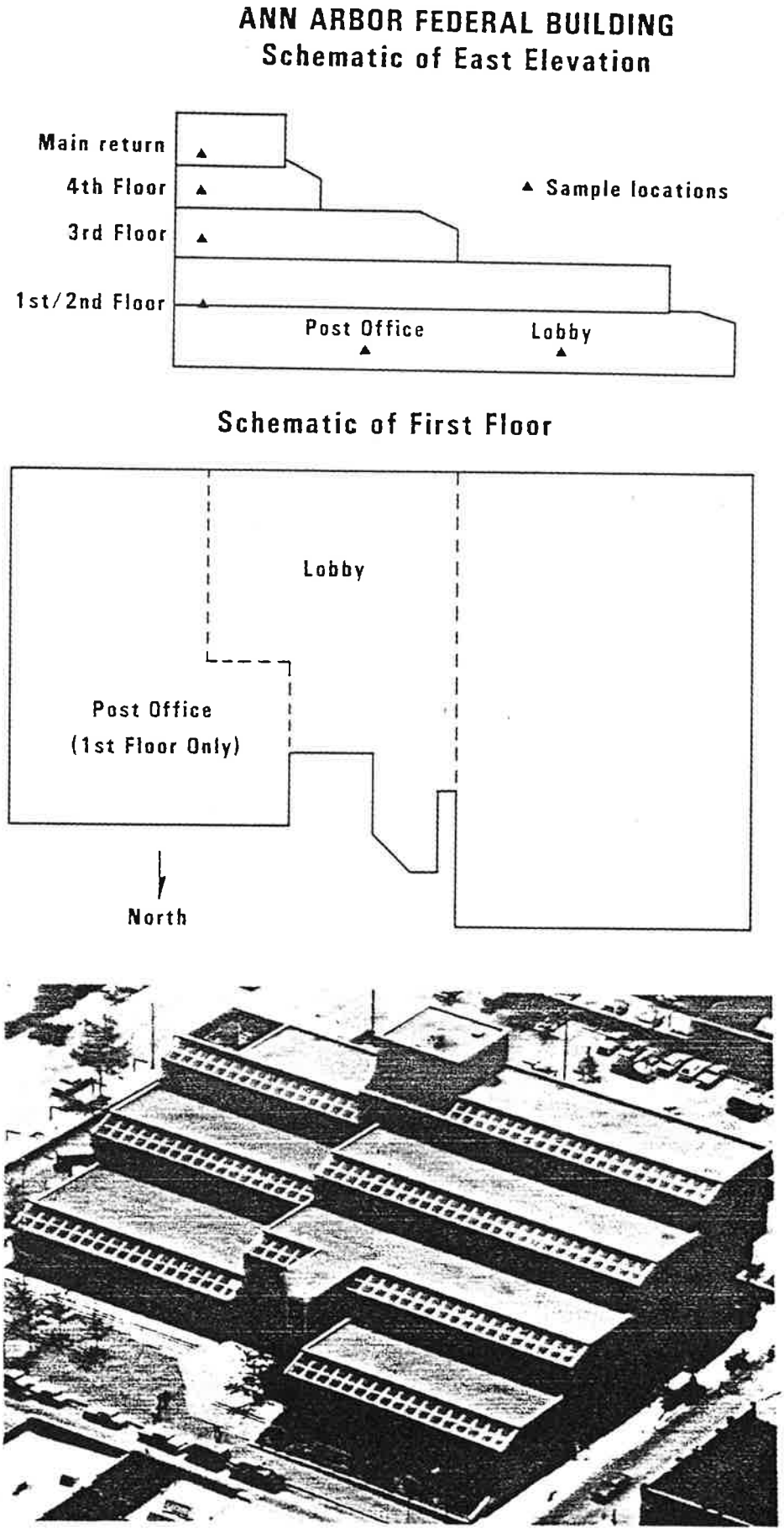


FIG. 8—*Schematic diagram and photograph of Federal building in Ann Arbor, MI.*

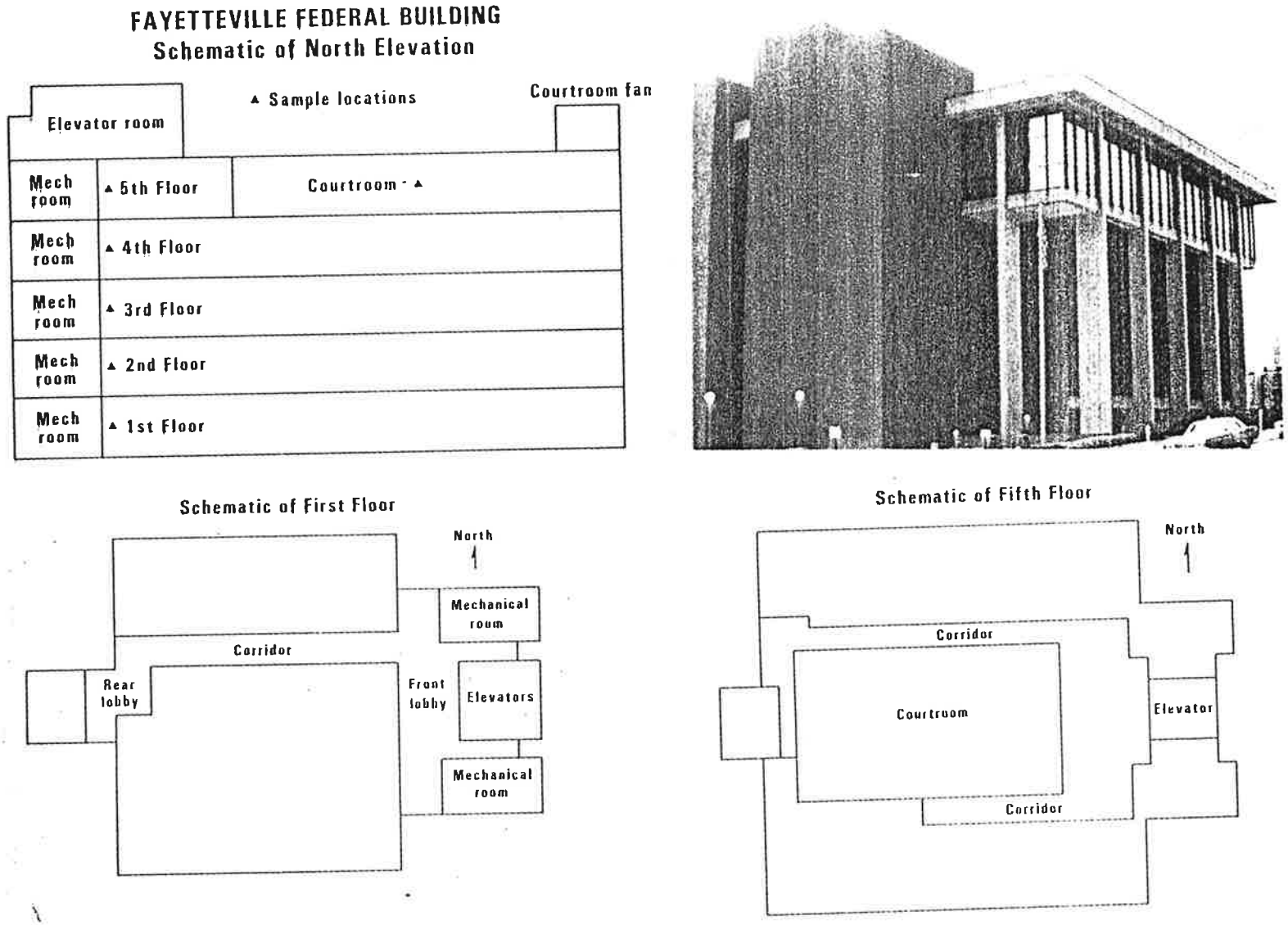


FIG. 9—*Schematic diagram and photograph of Federal building in Fayetteville, AR.*

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 outside 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 outside air intake.

The Pittsfield building has a separate fan system for each of its two floors. The outside temperature is used to determine whether outside 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 outside air dampers are adjusted to maintain a supply air temperature of about 13°C (55°F) during the entire year. Thus, outside air is used to condition the building unless the outside temperature is below the supply air temperature setting.

Method of Measurement

The air infiltration and ventilation rates of the eight office buildings were measured with an automated tracer-gas system employing the tracer-gas decay technique with SF_6 as the tracer [*2–4*]. This system, designed at the National Bureau of Standards, has been used to measure air infiltration and ventilation in a variety of buildings and can be operated unattended for periods of several weeks. The measurement system consists of a gas chromatograph equipped with an electron capture detector for measuring SF_6 concentrations. It samples automatically from up to ten locations and injects tracer gas into five. The tracer-gas injection and air sampling is controlled by a microcomputer which also analyzes the data as it is collected and stores the information on floppy disks. SF_6 was injected into the fan inlets of the building supply ducts at 3-h intervals and the subsequent decay in tracer-gas concentration at each location was monitored every 10 min for the next 3 hours. Interior and exterior temperatures, along with wind speed and direction, also were measured during the tracer-gas decay period. The plans of each building were studied and the building was divided in zones for the injection of tracer gas, and locations for sampling the tracer-gas concentrations were selected. The sample locations for these tests are shown in the building schematics in Figs. 2 through 8. The ventilation measurements were made when the buildings were occupied and operated normally. The air infiltration measurements were made during periods when the building was not occupied, and the building was operated with the dampers closed and the air handlers running in order to keep the tracer well mixed.

Results of the Air Infiltration Tests

The summary of the tracer gas test results in Table 2 show average infiltra-

TABLE 2—*Average[a] air infiltration rates on each federal building.*

Location	Changes per Hour	Percent of Design Heat Load
Anchorage	0.28	55
Ann Arbor	0.70	48
Columbia	0.40	52
Fayetteville	0.33	23
Huron	0.20	30
Norfolk	0.52	52
Pittsfield	0.32	30
Springfield	0.52	61

[a]Average excluding extreme wind speeds.

These results[3] indicate that the buildings in Huron and Anchorage are experiencing relatively low natural leakage rates. The buildings with the highest natural rates are Ann Arbor, Norfolk, and Springfield. By using the results of these tests, it is possible to estimate the contribution of air infiltration to the design load of the buildings. These estimates also are included in Table 2. As can be seen, air infiltration contributes from 23 to 61% of the building heat load.

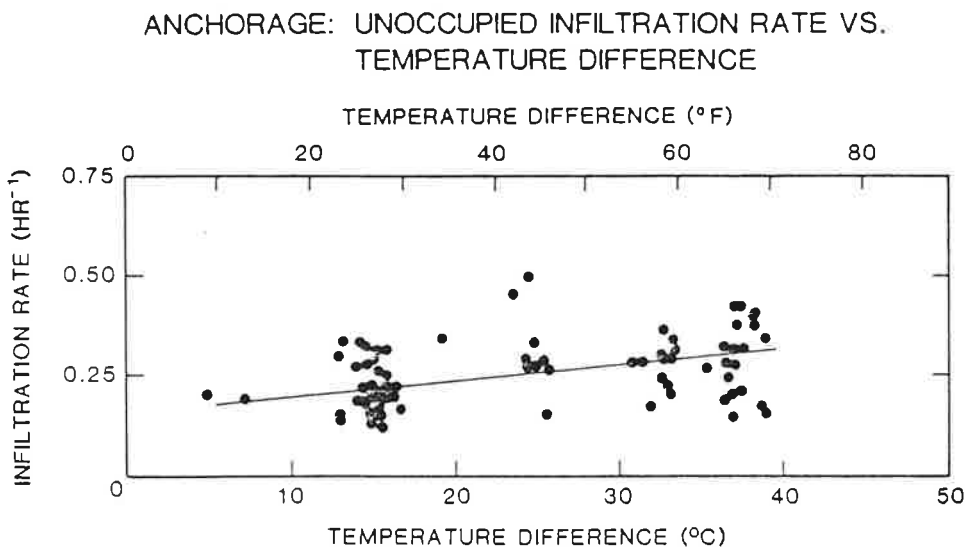
As mentioned earlier, tracer gas concentrations were measured in several locations in each building, and, in general, good mixing was achieved in all the buildings. There are, however, some specific zones which exhibit high air exchange rates compared to the rest of the building—the lobby in Springfield, the first floor in Norfolk, and the lobby in Columbia. Similarly high rates also are seen in the first floor in Fayetteville and the lobby and post office in Ann Arbor. The lobbies generally exhibit larger exchange rates due to the exterior doors in these zones. The post office in Ann Arbor has large leaky doors for loading and unloading mail.

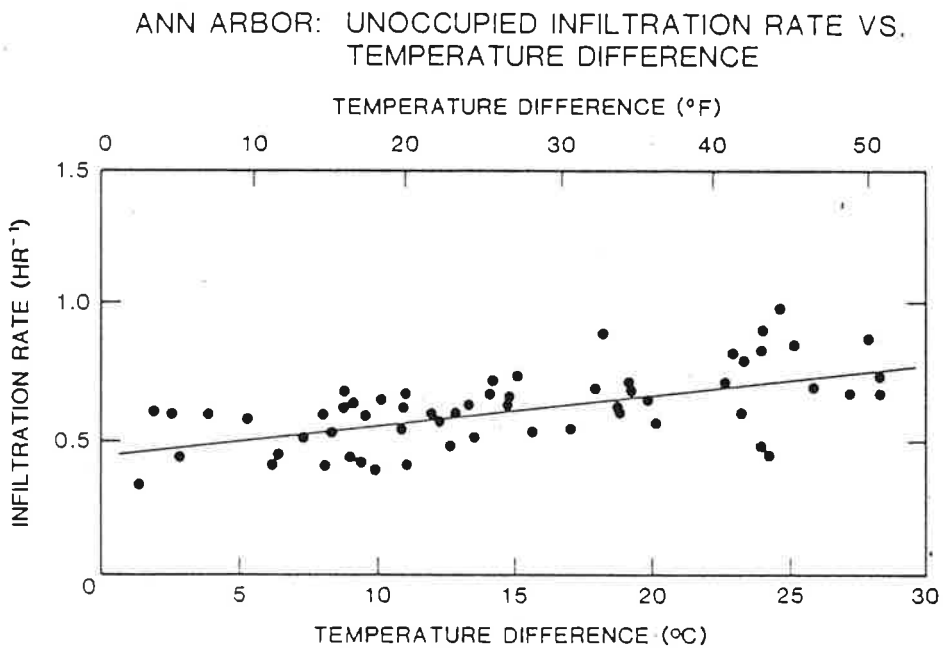
The air infiltration rates for each building are plotted against the inside-outside temperature difference ΔT in Fig. 10. Among the eight buildings there are varying degrees of dependence of infiltration on temperature difference. The most noticeable dependence occurs in the cases of Ann Arbor, Huron, Norfolk, and Springfield. These buildings, with the exception of Huron, are also the leakiest. The lines shown in Fig. 10 are based on linear regressions of infiltration against temperature difference for positive values of ΔT. The equations of these lines are given by:

Anchorage: $I = 0.16 + 0.003\,\Delta T$ $\quad R^2 = 0.18$; standard error $= 0.07$

Ann Arbor: $I = 0.44 + 0.011\,\Delta T$ $\quad R^2 = 0.35$; standard error $= 0.11$

Columbia: $I = 0.33 + 0.005\,\Delta T$ $\quad R^2 = 0.05$; standard error $= 0.12$





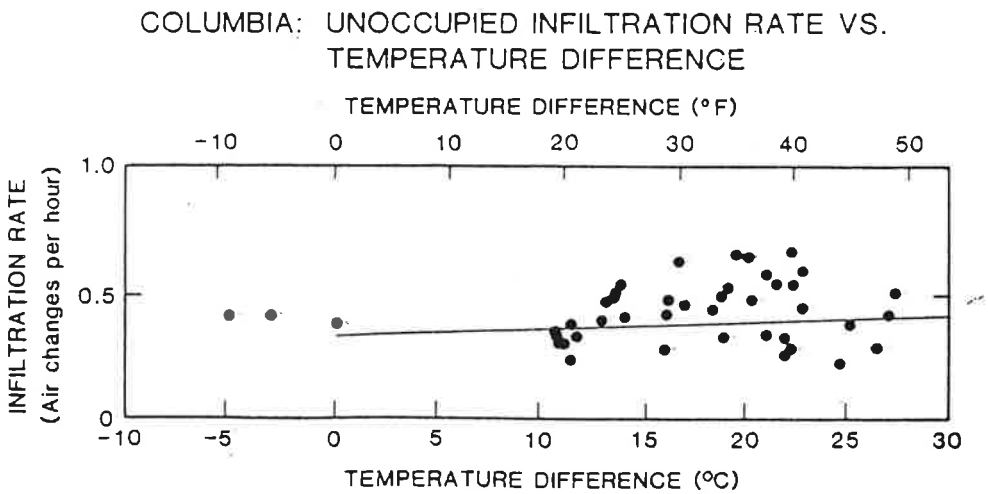
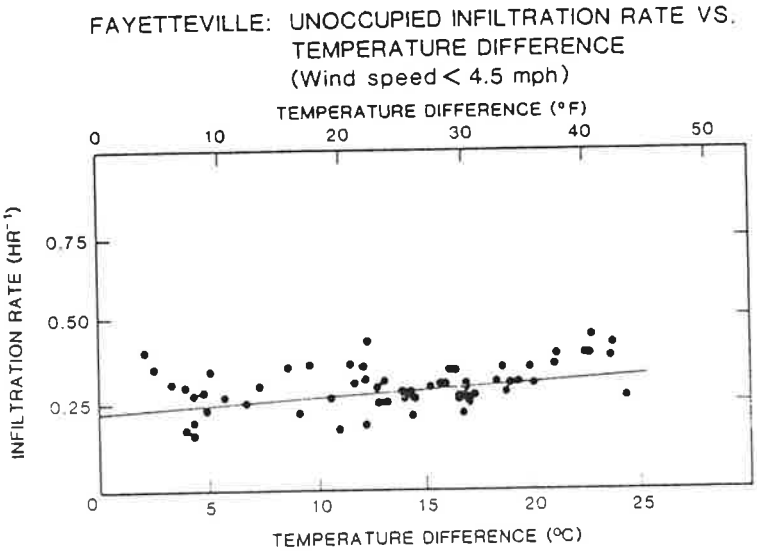
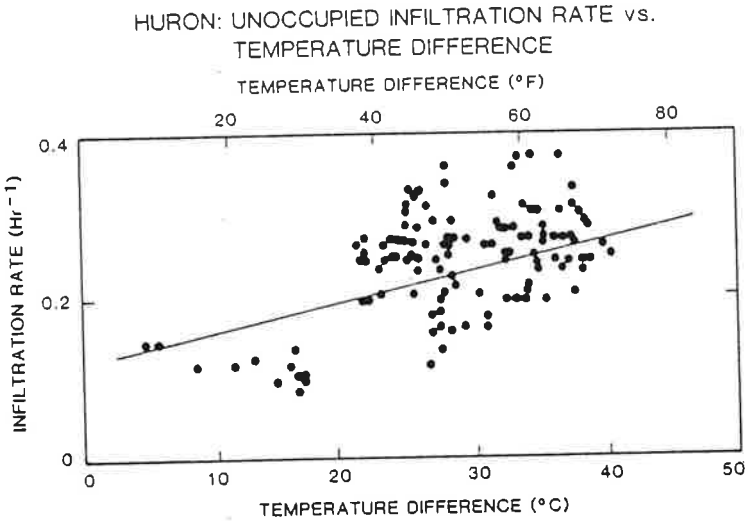


FIG. 10—*Infiltration rates versus indoor-outdoor temperature difference.*





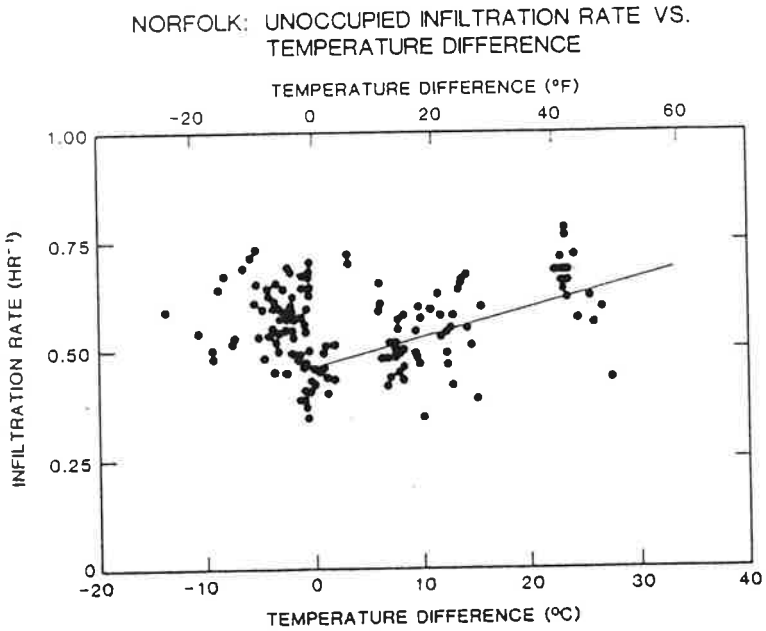
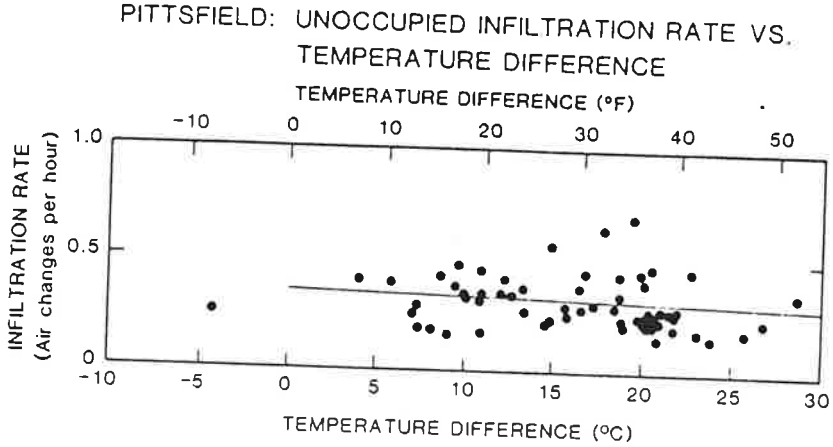


FIG. 10—*Continued.*



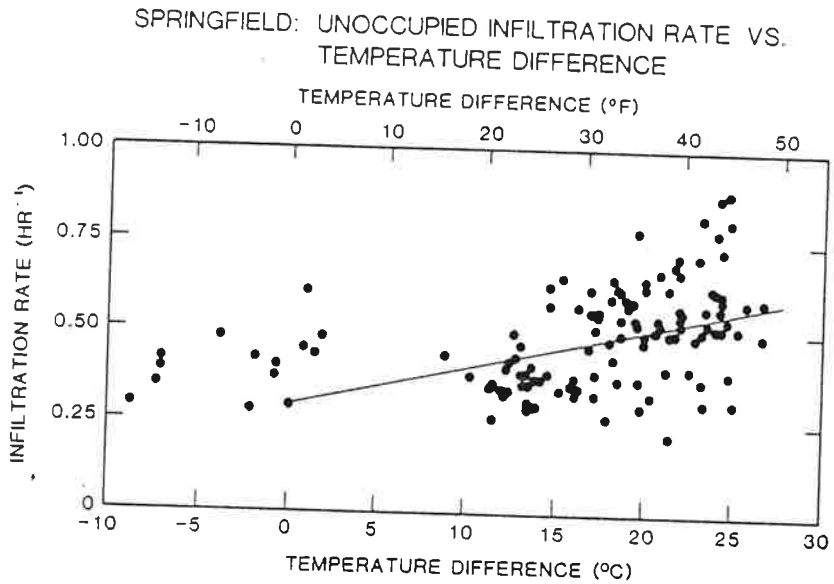


FIG. 10—*Continued.*

Fayetteville:	$I = 0.24 + 0.004\,\Delta T$	$R^2 = 0.15$; standard error $= 0.06$
Huron:	$I = 0.11 + 0.005\,\Delta T$	$R^2 = 0.26$; standard error $= 0.06$
Norfolk:	$I = 0.46 + 0.006\,\Delta T$	$R^2 = 0.29$; standard error $= 0.08$
Pittsfield:	$I = 0.35 - 0.003\,\Delta T$	$R^2 = 0.02$; standard error $= 0.11$
Springfield:	$I = 0.17 + 0.017\,\Delta T$	$R^2 = 0.28$; standard error $= 0.12$

Some of the buildings' infiltration rates also exhibited a dependence on wind speed u. Figure 11 shows several plots of infiltration against u, with regression lines drawn in. The equations of these lines are given by the following:

Ann Arbor ΔT from 20 to 25°C: $I = 0.40 + 0.113\,u$	$R^2 = 0.41$; standard error $= 0.15$
Fayetteville ΔT from 0 to 5°C: $I = -0.17 + 0.228\,u$	$R^2 = 0.67$; standard error $= 0.21$
Huron ΔT from 20 to 25°C: $I = 0.23 + 0.010\,u$	$R^2 = 0.22$; standard error $= 0.02$
Huron ΔT from 25 to 30°C: $I = 0.21 + 0.018\,u$	$R^2 = 0.48$; standard error $= 0.08$

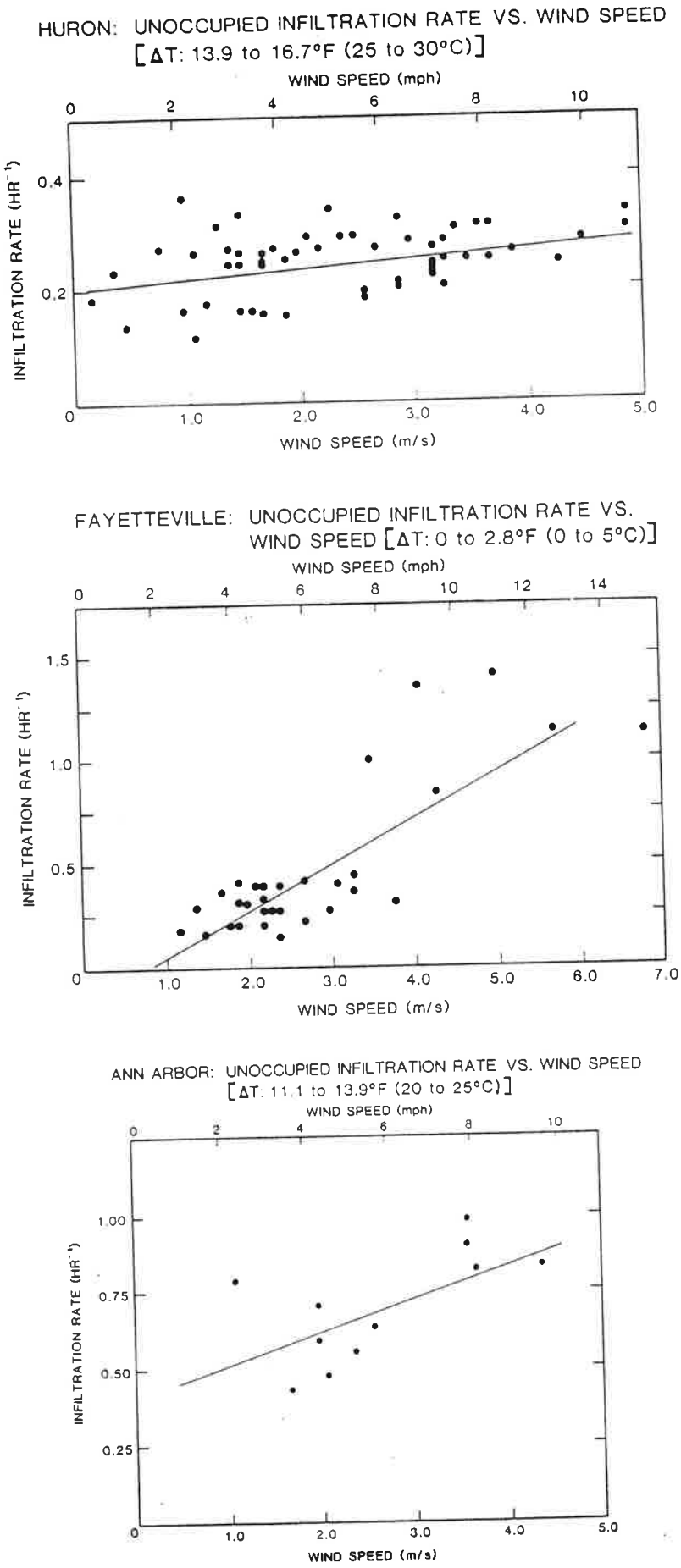


FIG. 11—*Infiltration rates versus wind speed for various buildings.*

Tables 3 through 10 give mean measured infiltration rates for each building within various ranges of temperature difference. Means are given for wind speeds less than and greater than 2.0 m/s.

In order to assess the accuracy of more complicated models for explaining the dependence of the measured air infiltration rates on the weather, the following six models were fitted to the data:

$$\text{Model 1: } I = Q(a\,u + b\,\Delta T + c\,u\,\Delta T)$$
$$\text{Model 2: } I = Q(a\,u^2 + B\,\Delta T + c\,u^2\,\Delta T)$$
$$\text{Model 3: } I = Q(a\,u + b\,\Delta T)^{0.5}$$
$$\text{Model 4: } I = Q(a\,u^2 + b\,\Delta T)^{0.5}$$
$$\text{Model 5: } I = Q(a\,u + b\,\Delta T)^{0.65}$$
$$\text{Model 6: } I = Q(a\,u^2 + \Delta T)^{0.65}$$

where Q is the induced air exchange rate at 25 Pa obtained from the pressurization test on the buildings [5] (see following article in these proceedings).

The results of these fits to the data are given in Tables 11 to 16. The R^2 given in these tables is the uncorrected R^2. The numbers in parentheses are the standard errors of the coefficients. Model 1 explains the variance in the data best for most of the buildings. The analysis of the explained variance of Model 1 is given in Table 17. Most of the variance in air infiltration is attributed to variance in the wind speed for these buildings.

TABLE 3—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed, Anchorage, AK.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
0,10	0.19	...
10,20	0.20	0.23
20,30	0.38	0.24
30,40	0.25	0.31

TABLE 4—*Average air exchange rates in various temperature difference bins during unoccupied period with dampers closed, Columbia, SC.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
−10 < 0	0.40	0.40
0 < 10	0.37	0.33
10 < 20	0.41	0.38
20 < 30	0.34	0.51

TABLE 5—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed. Norfolk. VA.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
−20 < −10	0.56	...
−10 < 0	0.56	0.55
0 < 10	0.50	0.50
10 < 20	0.49	0.54

TABLE 6—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed. Springfield. MA.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
−10 < 0	0.38	0.35
0 < 10	0.44	...
10 < 20	0.43	0.56
20 < 30	0.55	0.53

TABLE 7—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed. Pittsfield. MA.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
−10 < 0	0.25	...
0 < 10	0.29	0.37
10 < 20	0.36	0.31
20 < 30	0.26	...

TABLE 8—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed. Huron. SD.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
0 < 10	0.13	0.14
10 < 20	0.10	0.11
20 < 30	0.23	0.26
30 < 40	0.26	0.26
40 < 50	0.26	...

TABLE 9—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed. Fayetteville, AR.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
−10 < 0		0.37
0 < 10	0.28	0.50
10 < 20	0.29	0.35
20 < 30	0.39	0.35

TABLE 10—*Average air exchange rates in various temperature difference bins during unoccupied periods with dampers closed. Ann Arbor, MI.*

Temperature Difference Bin, °C	Wind < 2.0 m/s, X/h	Wind > 2.0 m/s, X/h
0 < 10	0.53	0.52
10 < 20	0.59	0.64
20 < 30	0.61	0.73

TABLE 11—*Results of fitting model 1 to the measured air infiltration data.*

Model 1

$$I = Q(a\,u + b\,\Delta T + c\,u\,\Delta T)$$

Location	No. of Points	Q	a	b	c	Standard Error	R^2
Anchorage	97	0.80	0.129[a] (0.019)	0.0123 (0.0009)	−0.00476 (0.0007)	0.10	0.91
Ann Arbor	62	0.86	0.211 (0.023)	0.0408 (0.0033)	−0.0102 (0.0012)	0.16	0.95
Columbia	46	0.67	0.345 (0.055)	0.0271 (0.0034)	−0.0140 (0.0031)	0.18	0.93
Fayetteville[b]	122	...	0.0903 (0.0071)	0.0183 (0.0011)	−0.00445 (0.00078)	0.11	0.90
Huron	153	0.45	0.130 (0.018)	0.0173 (0.0006)	−0.00384	0.12	0.96
Norfolk	171	1.45	0.182 (0.007)	0.0371 (0.0032)	−0.0167 (0.0015)	0.12	0.90
Pittsfield	67	0.95	0.193 (0.051)	0.0172 (0.0015)	−0.0113 (0.0039)	0.15	0.81
Springfield	127	1.43	0.149 (0.017)	0.0174 (0.0008)	−0.0069 (0.0010)	0.09	0.93
Combined[c]	723	...	0.182 (0.007)	0.0159 (0.0006)	−0.0053 (0.0003)	0.18	0.86

[a]Values in parentheses are the standard errors of the coefficients.
[b]Since there was no measurement of Q in this building, it was assumed to be equal to 1.0.
[c]Excluding Fayetteville.

TABLE 12—*The results of fitting Model 2 to the measured air infiltration data.*

Model 2

$$I = Q(a\,u^2 + b\,u\,\Delta T + c\,u^2\,\Delta T)$$

Location	No. of Points	Q	a	b	c	Standard Error	R^2
Anchorage	97	0.80	0.0499[a] (0.0098)	0.0124 (0.0006)	−0.00182	0.10	0.89
Ann Arbor	62	0.86	0.0798 (0.0108)	0.0393 (0.0026)	−0.00339 (0.00041)	0.18	0.94
Columbia	46	0.67	0.147 (0.034)	0.0303 (0.0025)	−0.00647 (0.00165)	0.21	0.90
Fayetteville	122	...	0.0156 (0.0022)	0.0195 (0.0012)	−0.00073 (0.00030)	0.13	0.83
Huron	153	0.45	0.0411 (0.0054)	0.0176 (0.0005)	−0.00123 (0.00017)	0.12	0.96
Norfolk	171	1.45	0.0623 (0.0045)	0.0343 (0.0025)	−0.00556 (0.00054)	0.18	0.77
Pittsfield	67	0.95	0.0479 (0.0246)	0.0170 (0.0013)	−0.00320 (0.00223)	0.16	0.78
Springfield	127	1.43	0.0568 (0.0099)	0.0178 (0.0007)	−0.00273 (0.00055)	0.10	0.92
Combined	723	...	0.0531 (0.0030)	0.0175 (0.0005)	−0.00163 (0.00011)	0.20	0.81

[a]Values in parentheses are the standard error of the estimated coefficient.

TABLE 13—*The results of fitting Model 3 to the measured air infiltration data.*

Model 3

$$I = Q(a\,u + b\,\Delta T)^{0.5}$$

Location	No. of Points	Q	a	b	Standard Error	R^2
Anchorage	97	0.80	0.00653[a] (0.00785)	0.00367 (0.00051)	0.062	0.74
Ann Arbor	62	0.86	0.07107 (0.02543)	0.02317 (0.00367)	0.209	0.87
Columbia	46	0.67	0.1137 (0.0414)	0.01323 (0.00384)	0.224	0.79
Fayetteville	122	...	0.0258 (0.0038)	0.00455 (0.00061)	0.0074	0.69
Huron	153	0.45	0.0140 (0.0076)	0.00945 (0.00068)	0.125	0.86
Norfolk	171	1.45	0.0551 (0.0039)	0.00260 (0.00080)	0.073	0.78
Pittsfield	67	0.95	0.0243 (0.0135)	0.00517 (0.00853)	0.100	0.55
Springfield	127	1.43	0.0183 (0.0071)	0.00576 (0.00050)	0.063	0.80
Combined	723	...	0.0622 (0.0051)	0.00557 (0.00049)	0.171	0.63

[a]Values in parentheses are the standard error of the estimated coefficient.

TABLE 14—*The results of fitting model 4 to the measured air infiltration data.*

Model 4

$$I = Q(a\,u^2 + b\,\Delta T)^{0.5}$$

Location	No. of Points	Q	a	b	Standard Error	R^2
Anchorage	97	0.80	0.00107[a] (0.00202)	0.00392 (0.00035)	0.062	0.74
Ann Arbor	62	0.86	0.01053 (0.00669)	0.02831 (0.00309)	0.218	0.86
Columbia	46	0.67	0.02399 (0.01273)	0.0187 (0.0028)	0.233	0.77
Fayetteville	122	...	0.00528 (0.00095)	0.00584 (0.00056)	0.078	0.65
Huron	153	0.45	0.00231 (0.00153)	0.00996 (0.00050)	0.126	0.86
Norfolk	171	1.45	0.0105 (0.0016)	0.00696 (0.00093)	0.095	0.62
Pittsfield	67	0.95	0.00518 (0.00404)	0.00577 (0.00074)	0.101	0.54
Springfield	127	1.43	0.00466 (0.00275)	0.00636 (0.00039)	0.064	0.80
Combined	723	...	0.0125 (0.0014)	0.00780 (0.00042)	0.178	0.60

[a]Values in parentheses are the standard error of the estimated coefficient.

TABLE 15—*The results of fitting Model 5 to the measured air infiltration data.*

Model 5

$$I = Q(a\,u + b\,u^{\cdot}\Delta T)^{0.65}$$

Location	No. of Points	Q	a	b	Standard Error	R^2
Anchorage	97	0.80	0.0131[a] (0.0103)	0.00574 (0.00068)	0.081	0.81
Ann Arbor	62	0.86	0.0848 (0.0259)	0.0249 (0.0037)	0.213	0.89
Columbia	46	0.67	0.128 (0.041)	0.0161 (0.0038)	0.220	0.84
Fayetteville	122	...	0.0382 (0.0078)	0.00778 (0.00074)	0.089	0.80
Huron	153	0.45	0.0172 (0.0080)	0.0122 (0.0007)	0.131	0.90
Norfolk	171	1.45	0.00876 (0.0057)	0.00331 (0.00116)	0.104	0.80
Pittsfield	67	0.95	0.0362 (0.0168)	0.00825 (0.00106)	0.124	0.66
Springfield	127	1.43	0.0300 (0.0088)	0.00881 (0.00062)	0.079	0.86
Combined	723	...	0.0791 (0.0054)	0.00755 (0.00052)	0.181	0.73

TABLE 16—*The results of fitting Model 6 to the measured air infiltration data.*

Model 6

$$I = Q(a\,u^2 + b\,\Delta T)^{0.65}$$

Location	No. of Points	Q	a	b	Standard Error	R^2
Anchorage	97	0.80	0.00132[a] (0.00268)	0.00634 (0.00046)	0.082	0.81
Ann Arbor	62	0.86	0.00799 (0.00702)	0.0328 (0.0032)	0.229	0.88
Columbia	46	0.67	0.0239 (0.0128)	0.0227 (0.0028)	0.234	0.82
Fayetteville	122	...	0.00749 (0.00120)	0.00977 (0.00070)	0.097	0.76
Huron	153	0.45	0.00248 (0.00160)	0.0129 (0.0005)	0.131	0.90
Norfolk	171	1.45	0.0168 (0.0024)	0.0102 (0.0014)	0.143	0.63
Pittsfield	67	0.95	0.00824 (0.00503)	0.00910 (0.00092)	0.126	0.65
Springfield	127	1.43	0.00737 (0.00348)	0.00983 (0.00050)	0.081	0.85
Combined	723	...	0.0144 (0.0015)	0.0107 (0.0005)	0.194	0.68

[a]Values in parentheses are the standard error of the coefficient.

TABLE 17—*Analysis of explained variance for Model 1.*

Model 1

$$I = Q(a\,u + b\,u\,\Delta T + c\,u\,\Delta T)$$

Location	Regression Variance	Fraction Attributed to U	DT	$U * DT$
Anchorage	8.8	0.79	0.16	0.05
Ann Arbor	31.2	0.86	0.08	0.06
Columbia	17.7	0.88	0.08	0.04
Fayetteville	11.9	0.72	0.25	0.03
Huron	43.9	0.77	0.21	0.01
Norfolk	22.3	0.91	0.01	0.09
Pittsfield	6.2	0.48	0.48	0.03
Springfield	14.4	0.73	0.24	0.03
Combined	133.4	0.83	0.11	0.06

NOTE: U = wind speed (m/s); DT = temperature difference.

Measured Ventilation Rates

In most of the buildings the measured ventilation rates exhibit a seasonal dependence such that the lowest ventilation rates occur during maximum heating and cooling loads.[4] This can be seen in the plots of ventilation rate versus inside-outside temperature difference for each federal building shown in Figs. 12 through 19. Table 18 shows mean ventilation rates, along with the standard deviations of these means, for 5 K intervals of temperature difference for all eight buildings. The mean ventilation rates can be somewhat misleading for mild temperature conditions. Buildings with enthalpy control are operated at low or high ventilation rates at the same outside temperature because of differences in outside humidity. This variable rate at the same outside temperature also occurs in buildings with other types of control systems.

Also, as discussed in following paragraphs, 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 12 shows the ventilation rate in the Anchorage federal building as a function of temperature difference. There are low ventilation rates, about 0.25 to 0.50 exchanges per hour, during cold outside conditions and higher ventilation rates for temperature differences below 20 K. None of the measurements in Anchorage were made under conditions which were warm enough for the building's air conditioning system to be used for cooling and for the ventilation rate to again be minimized.

Figure 13 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 was strongly dependent on wind speed and that infiltration became a significant portion of the net ventilation rate under windy conditions. Figure 20 is a plot of these ventilation rates versus wind speed for a limited range of temperature difference, and indeed a strong dependence on wind is evident. A similar dependence of infiltration on wind speed was noted earlier in Fig. 11. These large, wind-induced rates were not considered in calculating the Ann Arbor mean ventilation rates in Table 18. Under cold outside conditions, $\Delta T > 20$ K, this building was operated at about 0.5 exchanges per hour. For milder temperatures, outside 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.

The Columbia building's ventilation rates are shown in Fig. 14. The measurements cover a wide range of warm temperature conditions (ΔT from -10 to 5 K), but there is no clear dependence of ventilation rate on temperature difference for the summer. If the weather-dependent natural ventilation, or

[4]A more detailed analysis of the performance of the ventilation systems is given in Ref *6*.

infiltration, is a large fraction of the net ventilation rate which was measured, then the 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 15 shows the ventilation rate versus temperature difference plot for the Fayetteville building. When the building is being heated or cooled, the ventilation rate is about 0.34 exchanges per hour. Under mild temperature conditions, ΔT from 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 were 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, were unsuccessful in Fayetteville because the ventilation system could not bring in enough outside air to raise the internal pressure significantly. Thus, the ventilation rates of 1.0 exchanges per hour and higher are probably not due to mechanical ventilation alone and contain a large component of natural ventilation induced by the high wind speeds during these measurements. The wind speed dependence of infiltration for this building is evident in Fig. 11.

The Huron building, whose ventilation rates are plotted in Fig. 16, has the lowest ventilation rates of all the buildings examined. Under hot and cold outside 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 which showed a significant dependence of measured ventilation rate on temperature difference.

Figure 10 shows the dependence of infiltration on ΔT for this building, which also appears in the ventilation data in Fig. 16. Additional scatter in Fig. 11 is due to wind-induced infiltration. This dependence of ventilation on wind is shown in Fig. 21. Plots of infiltration versus wind speed, shown in Fig. 11, also show some dependence, though not as strong as for ventilation. It is possible that the wind effects are enhanced when the outside air intake dampers are open.

The ventilation rates of the federal building in Norfolk are plotted in Fig. 17. In this building the winter and summer ventilation rates are comparable, both around 0.6 to 0.7 exchanges per hour. Figure 18 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 Fig. 19, exhibit an unusual pattern. The ventilation rates under warm conditions, $\Delta T < 10$ K, are relatively constant at about 0.6 exchanges per hour. For temperature differences greater than about 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 outside air intake or to a strong depen-

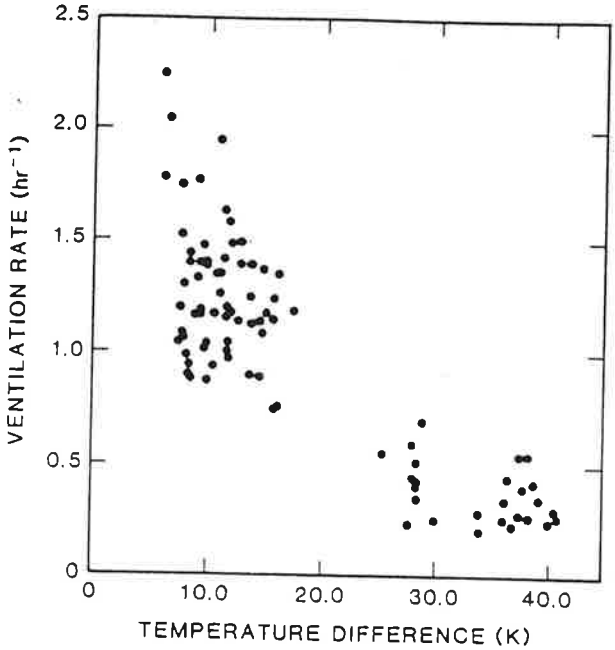


FIG. 12—*Ventilation rate versus inside-outside temperature difference for the Anchorage building.*

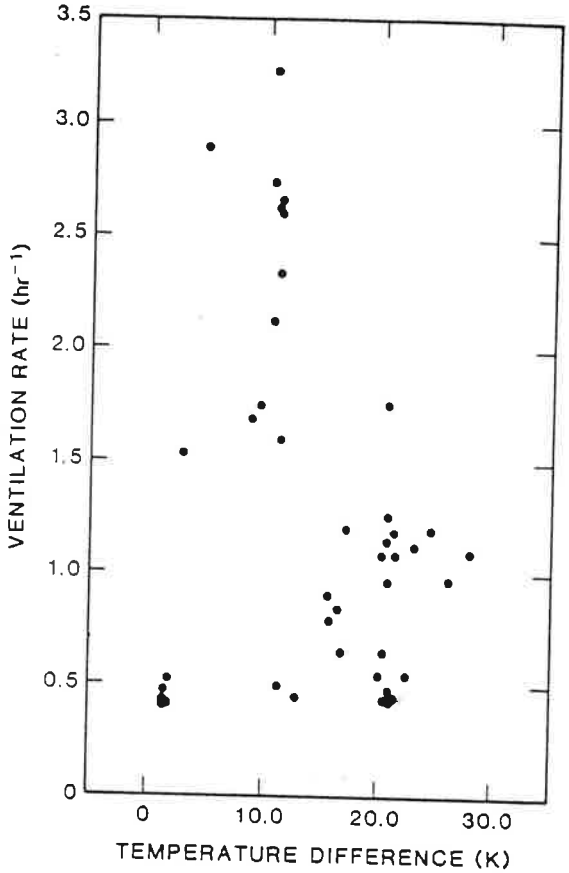


FIG. 13—*Ventilation rate versus inside-outside temperature difference for the Ann Arbor building.*

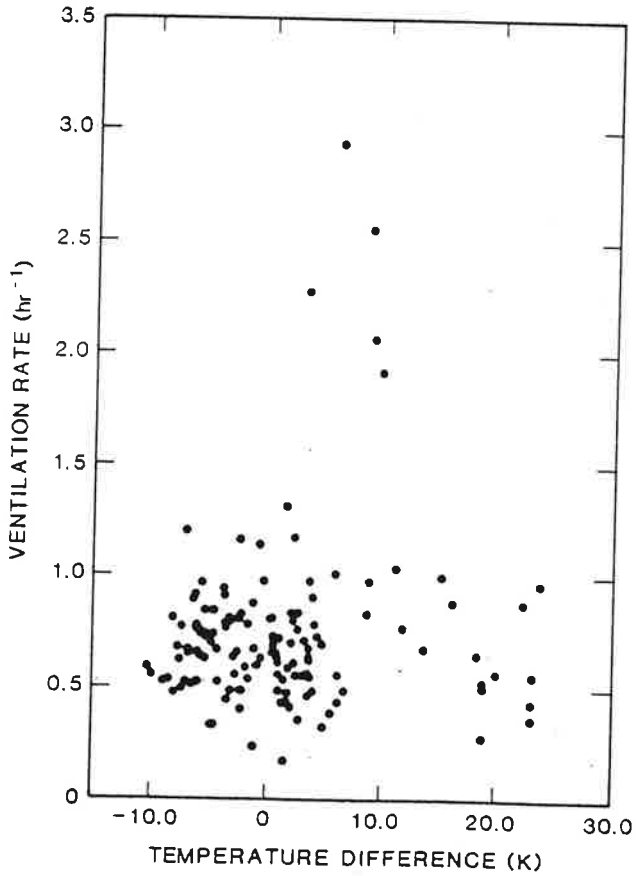


FIG. 14—*Ventilation rate versus inside-outside temperature difference for the Columbia building.*

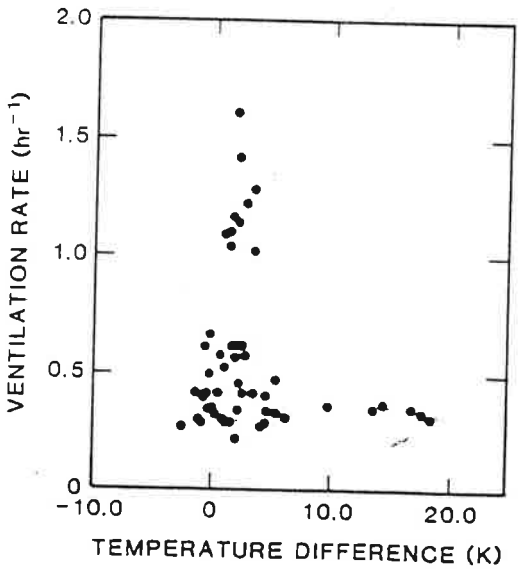


FIG. 15—*Ventilation rate versus inside-outside temperature difference for the Fayetteville building.*

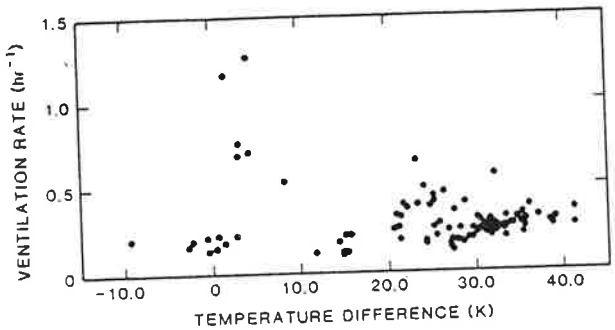


FIG. 16—*Ventilation rate versus inside-outside temperature difference for the Huron building.*

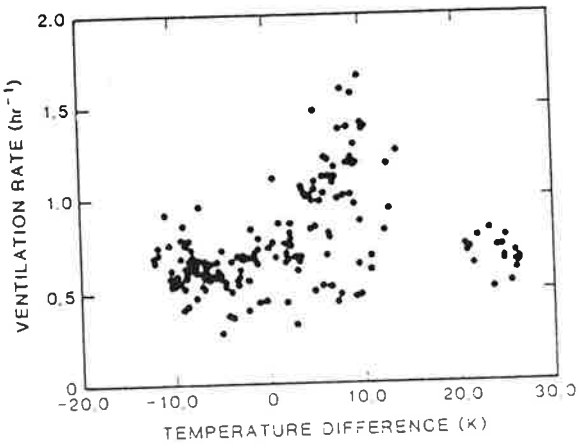


FIG. 17—*Ventilation rate versus inside-outside temperature difference for the Norfolk building.*

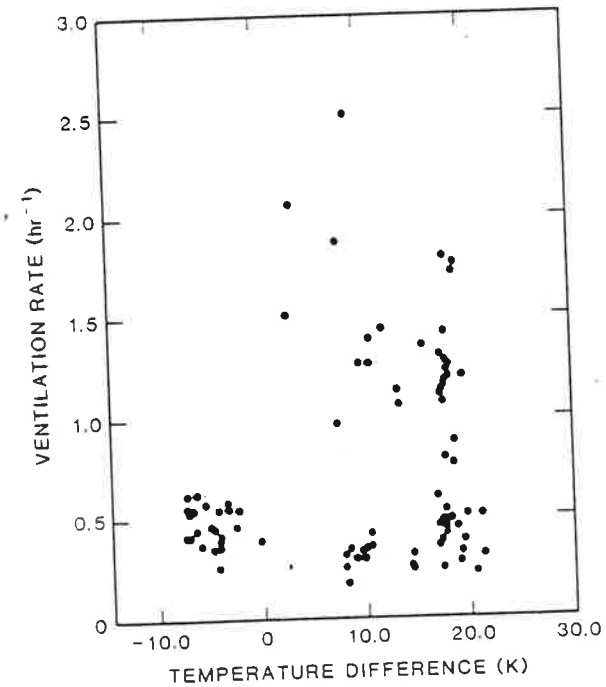


FIG. 18—*Ventilation rate versus inside-outside temperature difference for the Pittsfield building.*

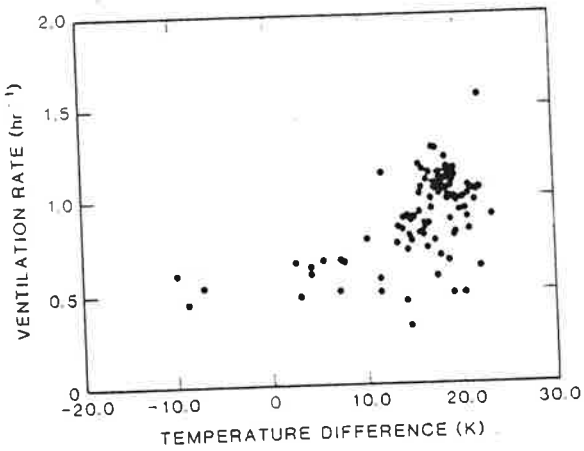


FIG. 19—*Ventilation rate versus inside-outside temperature difference for the Springfield building.*

dence of infiltration on temperature difference. The outside air intake is controlled to maintain the supply air temperature at about 13°C. This is, indeed, the temperature difference at which the ventilation rate is seen to increase. Measurements of infiltration made with the outside air dampers closed show a similar, but less extreme, dependence on temperature difference (see Fig. 10). Thus, the dependence of the net measured ventilation on ΔT appears to be a combination of the outside air intake control strategy and a significant portion of temperature-dependent infiltration.

TABLE 18—*Average ventilation rates in the buildings.*[a]

Temperature Difference, K	Anchorage	Ann Arbor[b]	Columbia	Fayetteville
−10, −5	...	...	0.68/0.18	...
−5,0	...	...	0.68/0.21	0.36/9.12
0,5	...	0.94/0.95	0.69/0.32	0.65/0.39
5,10	1.34/0.36	1.94/0.42	1.10/0.90	0.35/0.07
10,15	1.22/0.25	1.96/0.97	1.09/0.56	0.35/0.01
15,20	1.10/0.23	0.86/0.20	0.64/0.26	0.32/0.02
20,25	...	0.47/0.07	0.62/0.24	...
25,30	0.46/0.14	...	...	...
30,35	0.24/0.04	...	...	...
35,40	0.36/0.10	...	...	...
40,45	0.26/0.02	...	...	...

Temperature Difference, K	Huron, Mean/SD[c]	Norfolk	Pittsfield	Springfield
−15, −10	...	0.73/0.09	...	...
−10, −5	0.19/0.00	0.62/0.11	0.49/0.09	0.55/0.09
−5,0	0.16/0.04	0.58/0.07	0.43/0.09	...
0,5	0.53/0.43	0.75/0.19	1.19/0.73	0.59/0.08
5,10	0.52/0.00	1.00/0.32	1.25/1.15	0.62/0.08
10,15	0.13/0.04	1.05/0.37	0.67/0.48	0.76/0.20
15,20	0.14/0.06	...	0.84/0.47	0.96/0.20
20,25	0.32/0.14	0.70/0.09	0.38/0.14	0.95/0.22
25,30	0.25/0.05	0.66/0.06	...	...
30,35	0.26/0.07	...	...	...
35,40	0.29/0.04	...	...	...
40,45	0.31/0.06	...	...	...

[a]All the ventilation rates are in units of exchanges per hour.
[b]Calculations neglect some very high, wind-induced ventilation rates.
[c]Standard deviation of the mean ventilation rate.

Minimum Ventilation Requirements

The measurements of actual ventilation rates in occupied office buildings are compared to ventilation standards and design specifications of minimum fresh 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 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 outside air intake level in units of volumetric air flow. Another commonly accepted minimum ventilation rate is equal to 10% of the HVAC system's total air flow rate. The American Society of Heating, Refrigerating, and

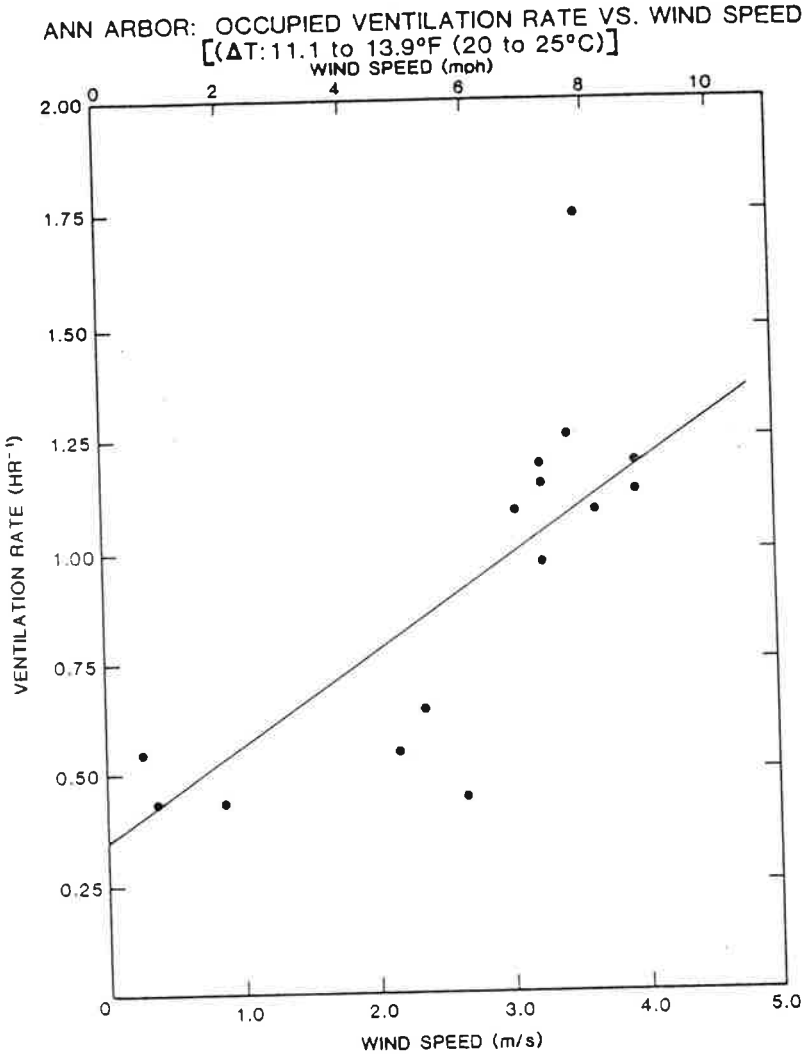


FIG. 20— *Ventilation rate versus wind speed for the Ann Arbor building.*

Air-Conditioning Engineers (ASHRAE) has established minimum recommended building ventilation rates which are a function of occupancy levels, building type (for example, office, store, hotel), and room type (for example, kitchen, office, conference room) [7]. The measured minimum ventilation rates are compared to the ASHRAE recommendation and the 10% rule in Table 19. In all the buildings, except the Fayetteville building, the 10% total air rate is less than the ASHRAE recommendation for smoking conditions. 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 these 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. The ASHRAE smoking recommendation is used 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

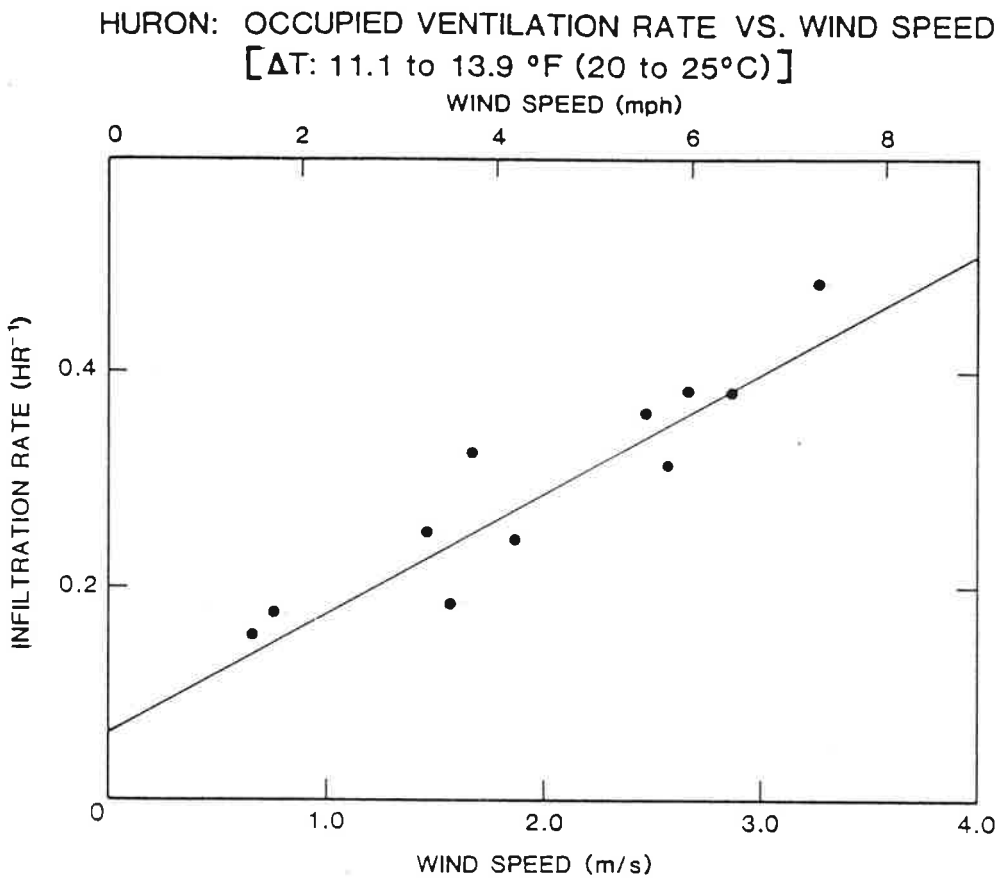


FIG. 21—*Ventilation rate versus wind speed for the Huron building.*

TABLE 19—*Minimum ventilation rates in the buildings.*[a]

Building	10% of Total Air	Measured Building Minimum	Measured Minimum as Percent of ASHRAE Recommendation[b]
Anchorage	0.28	0.26	39
Ann Arbor	0.36	0.47	70
Columbia	0.28	0.62	92
Fayetteville	0.57	0.32	48
Huron	0.31	0.13	19
Norfolk	0.25	0.62	92
Pittsfield	0.32	0.38	57
Springfield	0.44	0.55	83

[a]ASHRAE 62-81 Recommended Ventilation Rate: Smoking 0.67; Nonsmoking 0.17. All the ventilation rates are in units of exchanges per hour.
[b]Based on ASHRAE 62-81 smoking requirement.

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 which are lower than may be desirable for the maintenance of indoor air quality. As will be discussed in following paragraphs, local variations in air distribution may lead to ventilation rates in specific zones which are very low.

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

It is interesting to compare the measured ventilation rates under conditions of minimum outside air intake to measurements of building infiltration made with the dampers totally closed and the HVAC fans running. This comparison provides an indication of how much additional air is really brought in through the outside air intake to meet ventilation requirements and how much of the outside 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 outside 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 outside air intake, little of the outside air enters the Huron and Norfolk buildings through the outside 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 outside air damper settings are much too low or the building designers are relying on residual air leakage or infiltration to meet outside air ventilation requirements.

Table 20 shows the monthly average ventilation rates for all nine buildings based on monthly average outside temperatures for the cities or nearby cities and an assumed inside temperature of 23°C. The ventilation rate for each month is based on the averages in Table 18 or visual inspection of the plots of ventilation versus temperature difference (Figs. 12 through 19) when the mean ventilation rate is not representative of the data. Again, there are some very low monthly average ventilation rates in some of the buildings. In many 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.

In measuring the ventilation rates in the eight office buildings, it has been found that there are times when the mechanical systems are bringing in minimum amounts of outside air which are close to or below suggested ventilation levels. The measured rates are averages over an entire building, and there are local variations in ventilation and uniformity of air distribution among zones, floors, rooms, and parts of rooms. Some of these variations are evident during the ventilation measurements after the injection of the SF_6 tracer. The SF_6 concentration on some of the floors does not attain the same initial concentration or decrease at the same rate as the rest of the building. There are many ways to define ventilation efficiency, but they generally quantify the departure

TABLE 20—*Monthly Average Ventilation Rates.*[a]

Month	Anchorage[b]	Ann Arbor[c]	Columbia	Fayetteville[d]
January	0.46	0.47	0.64	0.32
February	0.46	0.47	1.09	0.32
March	0.46	0.47	1.09	0.35
April	0.75	1.96	1.10	0.35
May	1.10	1.94	0.69	0.65
June	1.22	0.94	0.68	0.36
July	1.22	0.50	0.68	0.36
August	1.22	0.50	0.68	0.36
September	1.22	1.94	0.68	0.36
October	0.75	1.96	1.10	0.35
November	0.46	0.86	1.09	0.35
December	0.46	0.47	0.64	0.32

Month	Huron	Norfolk	Pittsfield[e]	Springfield[e]
January	0.26	0.70	0.40	1.00
February	0.26	0.70	0.40	1.00
March	0.32	1.05	0.38	0.95
April	0.14	1.00	0.67	0.76
May	0.52	0.75	1.25	0.62
June	0.53	0.58	0.50	0.59
July	0.16	0.58	0.50	0.59
August	0.53	0.58	1.19	0.59
September	0.52	0.75	1.25	0.62
October	0.13	1.00	0.67	0.76
November	0.32	1.05	0.84	0.96
December	0.26	0.70	0.40	1.00

[a]All the ventilation rates are in units of exchanges per hour.
[b]Based on outside temperatures from Homer, AK.
[c]Based on an average of outside temperatures from Flint and Detroit, MI.
[d]Based on outside temperatures from Ft. Smith, AR.
[e]Based on outside temperatures from Hartford, CT.

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 also can 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 buildings is not 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

The average natural air infiltration rates measured in these buildings varied from 0.20 air changes per hour for the Huron federal building to 0.70 air changes per hour for the Ann Arbor federal building. The component of the design heating load from these buildings ranged from 23% for the uninsulated Fayetteville federal building to 61% for the new Springfield federal building. For four of the buildings, air infiltration contributed to over 50% of the heating loads. Two of the federal buildings, Anchorage and Huron, have low air infiltration rates (0.28 and 0.20 air changes per hour). However, even for these buildings, air infiltration was a very important part of the heating load.

Ventilation rates under occupied conditions also were measured in the eight buildings. It was found that for hot and cold outside temperatures, the buildings are operated at minimum ventilation levels to reduce space conditioning loads. At mild temperatures, outside air 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. 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 outside air intake levels suggested by ASHRAE, and it was 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 the specific area of the building which are significantly lower than the average rate for the building.

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