MEASURED VENTILATION AND INFILTRATION RATES IN EIGHT U.S. GOVERNMENT OFFICE BUILDINGS

by

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Abstract

Ventilation and infiltration rates were measured in eight office buildings using an automated tracer-gas measurement system. The buildings range in size from a two-story building with a floor area of about 2000 m^2 to a 15-story office building. The maximum floor area is 45,000 m^2. The ventilation rates were measured for about 100 hours in each building over a range of weather conditions. The infiltration rates were measured over a one-week period in each of the fall, winter, and spring periods. Infiltration tests were made both during occupancy and non-occupancy periods. The results are presented and examined for variations with time and weather. In most cases, the ventilation rate of a building is similar for hot and cold weather. In mild weather, outside air is used to cool the buildings and the ventilation rate increases. In the buildings where infiltration is a very 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 outside air intake strategy in each building.

Key Words: Building ventilation; mechanical ventilation; office building ventilation; tracer-gas measurement of ventilation; ventilation.

The Measurements of Ventilation and Infiltration Rates in Eight Office Buildings

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Introduction

This paper reports on the measurements and analsis of the relative contributions of intentional and unintentional ventilation to the total ventilation of eight office buildings. 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 with outside air. The specific amount of outside air which is brought into the building is a function of the outside weather and the occupancy requirements. The total ventilation rate is equal to the sum of the intentional outside air intake and the uncontrolled air leakage through the building envelope. The ventilation rates of office buildings were measured under a variety of outside weather conditions and for a period of about 50 to several hundred hours in each building. Infiltration was measured over week-long periods in the fall, winter, and spring with the buildings occupied and unoccupied. These ventilation and infiltration rates were analyzed for dependence on weather conditions. The findings presented in this paper are based on previously published material [1, 2, 3].

Descriptions of the Buildings

The eight Federal office buildings are located in the cities shown in the map in Figure 1. In general, these are new buildings (less than 5 years old) constructed accordingly 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, AR is an exception at 7 years old and built before the energy guideline for new Federal office buildings was in effect. Though these buildings tend to perform better than most existing Federal office buildings, none has met the design energy guidelines during its first few years of occupancy. For the purpose of this study the buildings in Anchorage, AK; Springfield, MA; Norfolk, VA; and Columbia, SC are considered to be large office buildings (over 10,000 m^2 of occupiable floor area). The Columbia building is 15 stories high, Norfolk 8 stories, Anchorage between 2 and 6, depending on the module, and Springfield 5 stories. The buildings in Pittsfield, MA; Huron, SD; Ann Arbor, MI; and Fayetteville, AR are considered as small office buildings (less than 10,000 m^2 of floor area). These small office buildings range in height from 2 to 5 stories. Schematic diagrams and a photograph of each building are given in figures 2 through 9. All but two of the buildings have variable volume air handlers in major zones of the buildings. They are heated by perimeter heating systems which are generally hydronic. The building in Columbia has two perimeter heating systems. In the Norfolk building, supplemental heaters and air conditioners have been added to the air systems on the floors which proved difficult to heat and cool. They all have central chiller systems for cooling the core spaces of the buildings. The buildings in Anchorage and Springfield have underground garages. The Norfolk building has an exterior garage.

The mechanisms for controlling outside air intake vary among the eight buildings. The outside air intake is kept to a minimum when the buildings were being heated and cooled in order to reduce the space conditioning load. During mild weather, outside air is used to cool the buildings. The amount of outside air intake and the times when outside air intake is increased is 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 is generally 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 below, along with other information on mechanical systems and the zoning of the buildings.

The Anchorage building is divided into six modules, each with its own ventilation system, which are connected by an open lobby/atrium and can intercommunicate freely. Anchorage is the only building without return fans. The mechanical systems are controlled by the computer and use a minimum amount of outside air during the heating season. During warmer weather, outside air is used to cool the 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 control is based on the outside air temperature (an economizer), and the amount of outside air intake is controlled by the return air temperature.

The Columbia building has a single mechanical system for floors 2 through 15 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.

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 communicate with each other. The outside air intake is based on enthalpy control.

The building in Norfolk has one mechanical system for most of the building, and a second 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). This supply air setting is varied somewhat during the year. Thus, outside air is not used to condition the building unless the outside temperature is below the supply air temperature setting.

Table 1 summarizes the ventilation types used in the buildings.

Measurement Technique and Instrumentation

The ventilation rates of the eight buildings were measured with an automated tracer-gas system employing the tracer-gas decay technique with sulfur hexafluoride (SF_6) as the tracer [4, 5]. 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 (1). The measurement system consists of a gas chromatograph equipped with an electron capture detector for measuring the SF_6 concentrations, it samples automatically from up to ten locations and injects tracer gas into five locations. 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. The accuracy of the tracer-gas mesurements is primarily a function of the mixing of the tracer and the indoor air. After the gas is injected, a waiting period of about 15 minutes allows the mixing of he tracer by the ventilation fans before the concentration measurements begin. The accuracy of ventilation measurements is within about 0.1 exchanges per hour.

Test Procedures

o Ventilation

SF_6 was injected into the fan inlets of building supply ducts at 3-hour intervals, and the subsequent decay in tracer-gas concentration was monitored in the building every 10 minutes for 1/2 hour. Interior and exterior temperatures, along with wind speed and direction, were also measured during the tracer-gas decay period. All the ventilation measurements presented below were made while the buildings were occupied and the mechanical systems operated normally. The sample locations for each building are shown in Figures 2 through 9. All of the buildings were tested in the fall of 1982, and the winter and spring of 1983. In addition, the buildings in Huron, Norfolk, and Columbia were tested in the summer of 1983. These measurements, under normal occupied conditions, include the uncontrolled infiltration. In other words, the decay rates of the SF_6 concentration measure the total exchange rates in the zones. There was no simple method for measuring the supply air rate to each zone through the mechanical ventilation systems.

o Infiltration

The air infiltration under natural conditions was measured using the same SF_6 system and sample locations. These tests were made with the outdoor air intake and exhaust dampers closed. The infiltration rates measured during unoccupied conditions were done with the HVAC fans running in order to keep the interior air well mixed. Having the fans running could induce additional air infiltration due to pressurization or depressurization near the leaks in the envelope (e.g., ruturn plenums bounded by outside walls). Thus, the measured infiltration rates could differ from those during typical unoccupied periods when the fans are not operating. The magnitude of this difference is important and should be determined when such infiltration measurements are made. This effect will be further investigated in the future. The fan-off infiltration can be measured by injecting the tracer with fans operating and sampling the concentration after a mixing period of at least 20 minutes. The fans would then be turned off for several minutes and turned on again for the sampling period. This procedure could then be repeated to establish a tracer gas decay rate with the fans off.

Results and Discussion

The monthly average ventilation rates for these buildings are tabulated in Table 2. The ventilation trends are shown in Figure 10 for various outside temperatures for most of the buildings. Tables 3 to 10 compare the ventilation and infiltration rates for each building for various outdoor temperatures. They give the average ventilation air exchange rates for various temperature bins. Infiltration rates for wind speed less than 2.5 M/S and for wind speeds greater than 2.5 M/S are tabulated. The infiltration rates are graphically shown in Figure 11 as a function of outdoor temperatures for some of the buildings when the wind velocity was less than 2.5 M/S. Figure 12 shows similar data for three buildings when the wind velocities were greater than 2.5 M/S.

A study of the data in Figure 10 and Tables 3 to 10 show three distinct patterns in the ventilation rates in the eight buildings. The building in Huron shows little change in the ventialtion rate during occupied periods over all temperature bins with the possibility that the ventilation rate raises for the temperature bin 10 to 20°C. The building in Anchorage shows this raise in ventilation in mild weather clearly. The buildings in Norfork and Ann Arbor have low ventilation rates at both low and high outdoor temperatures with increasing ventilation rates in the temperature bin 10 to 20°C. This increase may be due to use of outdoor air for cooling the buildings. The building in Springfield has a fairly constant ventilation rate in the temperature bins down 10 to 20°C and an increasing ventilation as the temperature decreases. This is probably due to the increase in infiltration as the temperature decreases for this building (Figures 11 and 12). These trends in the data are indicated by the dotted lines in Figure 10. The dotted lines indicate the average ventilation rates in each temperature range.

The air infiltration rates for most of the buildings are shown in Figures 11 and 12. In general, though there is considerable variation in the data, it can be seen that lower outdoor temperatures produce higher air infiltration rates and higher wind speeds produce higher air infiltration rates. Fitting a regression line to the data in Figures 11 and 12 produce the following relationships between the temperature and air infiltration rates:

<u>Wind Speed Less than 2.5 M/S</u>

Norfolk:

$I = 0.59 - 0.0072T_{out}$ $\qquad r^2 = 0.38$

Springfield:

$I = 0.58 - 0.0192\ T_{out}$ $\qquad r^2 = 0.20$

Ann Arbor:

$I = 0.70 - 0.0056\ T_{out}$ $\qquad r^2 = 0.03$

Huron:

$I = 0.20 - 0.0058\ T_{out}$ $\qquad r^2 = 0.03$

<u>Wind Speed Greater than 2.5 M/S</u>

Norfolk:

$I = 0.64 - 0.0085\ T_{out}$ $\qquad r^2 = 0.60$

Ann Arbor

$I = 0.80 - 0.0115\ T_{out}$ $\qquad r^2 = 0.15$

Huron:

$I = 0.24 - 0.0021\ T_{out}$ $\qquad r^2 = 0.07$

where:

I = infiltration rate, change/hr,

T_{out} = outside temperature, and

r^2 = regression coefficient.

Summary and Conclusion

Ventilation rates were measured under occupied conditions in eight office buildings, and infiltration rates were measured under both occupied and unoccupied periods. The uncontrolled infiltration portion of the total ventilation rates varied from about one-half to nearly all of the ventilation rate for the buildings, except when additional outdoor air was used during mild weather periods. This is a surprisingly high fraction of infiltration, especially since these are nearly all newer buildings and presumed to be tighter than those built earlier. The total ventilation rates varied between 0.3 and 0.7 air changes per hour (Ach). These appear to be reasonable values for modern office buildings. If these buildings had been constructed so that no infiltration occurred, the ventilation rates at design conditions would probably have been much too low according to ASHRAE Standard 62-1981.

It was found that for hot and cold outside air temperatures, the buildings are operated at minimum ventilation levels to reduce space conditioning loads as intended. At mild temperatures, outside air is used to cool the buildings and the ventilation rates increases significantly. The minimum ventilation rates show little dependence on temperature difference 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 infiltration is a significant portion of the total ventilation rate. In most of the buildings, the summer summer and winter minimum ventilation rates are similar, but in some buildings there is a notable difference between the two minimum ventilation rates.

Acknowledgement

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References

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Table 1 Ventilation Types Used in the Test Buildings

Location	Number of Stories	Occupiable Floor Area (m^2)	Ventilation Type
Anchorage, AK	6	48,470	VAV
Ann Arbor, MI	4	5,270	VAV*
Columbia, SC	16	21,600	VAV*
Fayetteville, AR	5	3,660	CV
Huron, SD	4	6,910	VAV*
Norfolk, VA	8	18,570	VAV*
Pittsfield, MA	2	1,860	CV
Springfield, MA	5	14,560	VAV*

VAV - Variable Volume
CV - Constant Volume

*Lobbies have constant volume air handlers.

Table 2 Monthly Average Ventilation Rates (in exchange/hr)

Month	Anchorage[1]	Ann Arbor[2]	Columbia	Fayetteville[3]
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

	Huron	Norfolk	Pittsfield	Springfield[4]
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

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

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)	0.33	0.27	0.31
(-10 < 0)	0.44	0.33	0.25
(0 < 10)	1.15	0.24	
(10 < 20)	1.29	0.27	0.36
(20 < 30)			

Table 3 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Anchorage, AK

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.62	0.36	
(0 < 10)	0.54	0.44	0.49
(10 < 20)	1.69	0.41	
(20 < 30)			

Table 4 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Columbia, SC

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)	0.33	0.27	0.31
(-10 < 0)	0.44	0.33	0.25
(0 < 10)	1.15	0.24	
(10 < 20)	1.29	0.27	0.63
(20 < 30)			

Table 5 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Norfolk, VA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	1.02	0.62	0.78
(0 < 10)	0.93	0.52	0.77
(10 < 20)	0.68	0.36	
(20 < 30)	0.58		

Table 6 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Springfield, MA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)		0.25	
(0 < 10)	0.74	0.30	0.27
(10 < 20)	0.92	0.29	0.34
(20 < 30)	0.59	0.45	

Table 7 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Pittsfield, MA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)	0.29	0.27	0.26
(-10 < 0)	0.26	0.24	0.26
(0 < 10)	0.25	0.16	0.18
(10 < 20)	0.23	0.12	
(20 < 30)	0.67		

Table 8 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Huron, SD

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)		0.43	
(0 < 10)	0.31	0.31	0.38
(10 < 20)	0.36	0.30	0.30
(20 < 30)	0.66	0.28	0.71

Table 9 Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed -- Fayetteville, AR

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Infiltration (Wind < 2.5 M/S) (X/HR)	Infiltration (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.60	0.57	0.79
(0 < 10)	0.64	0.70	0.81
(10 < 20)	1.92	0.56	0.62
(20 < 30)	0.43	0.46	

Table 10 Average Air Exchange Rate in Various Temperature Bins During Occupied Periods and Unoccupied Periods With Dampers Closed — Ann Arbor, MI

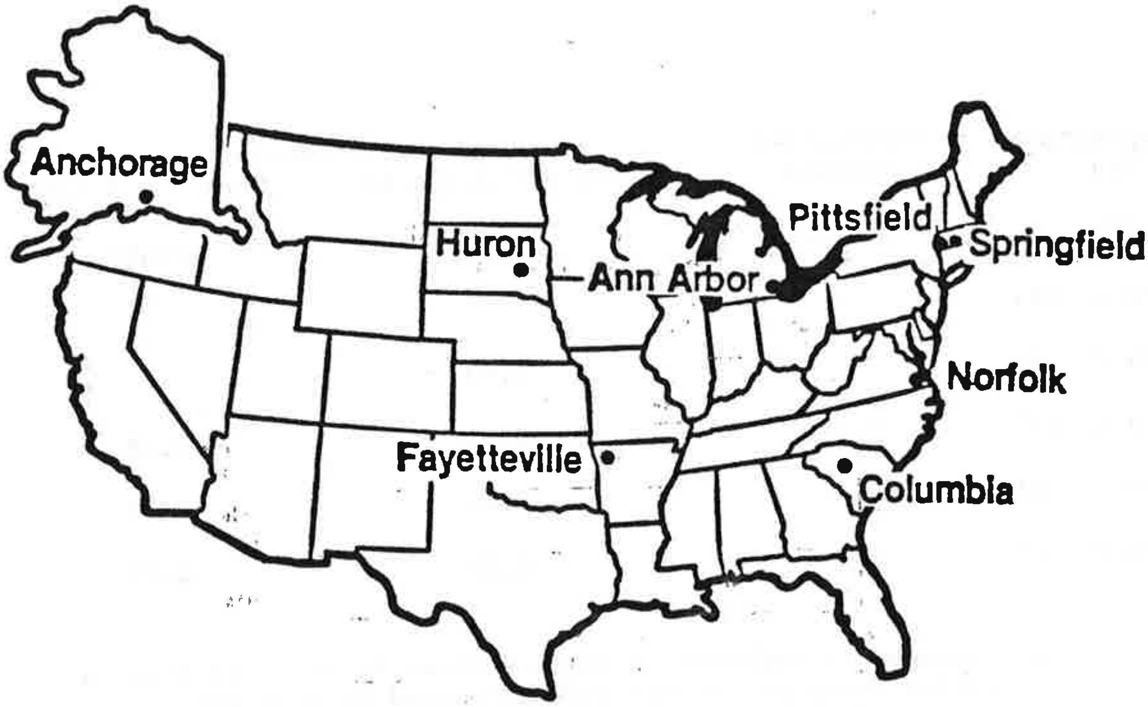


Figure 1. Location of Eight Federal Office Buildings in the U.S.A.

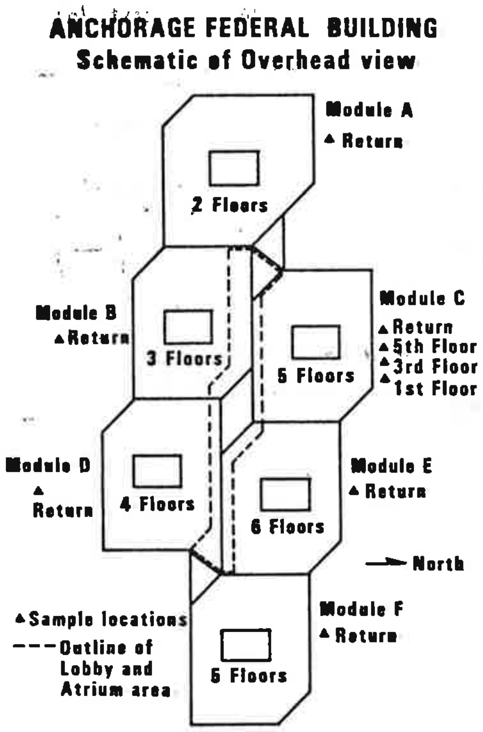
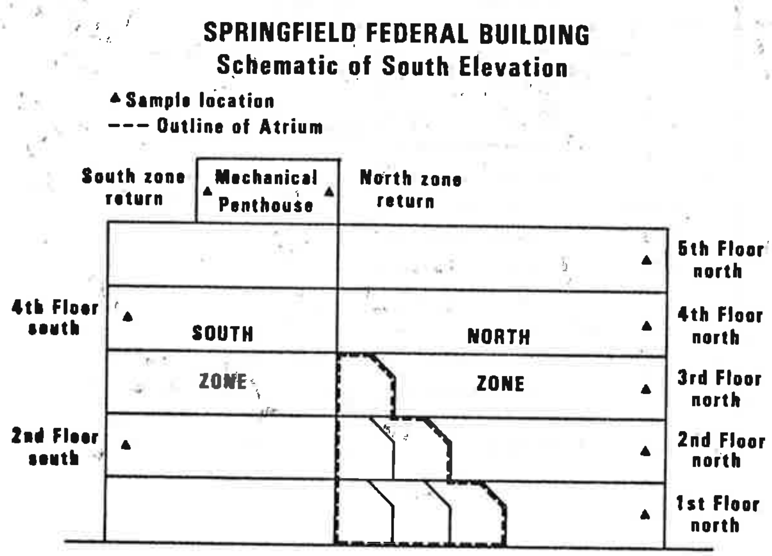


Figure 2. Schematic and Photograph of Federal Building in Anchorage, AK



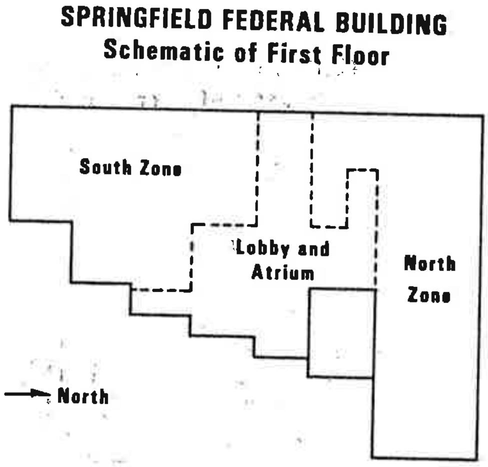
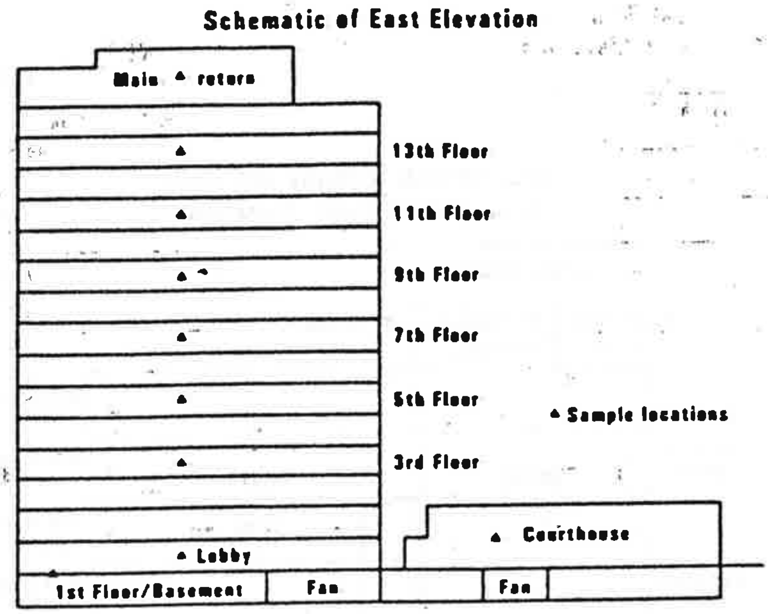


Figure 3. Schematic and Photograph of Federal Building in Springfield, MA



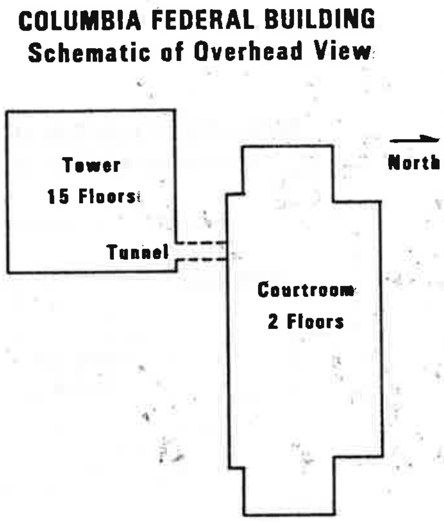
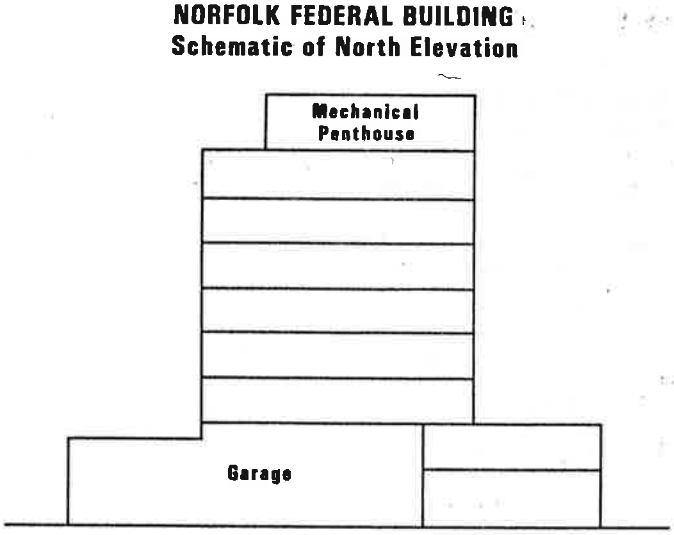


Figure 4. Schematic and Photograph of Federal Building in Columbia, SC



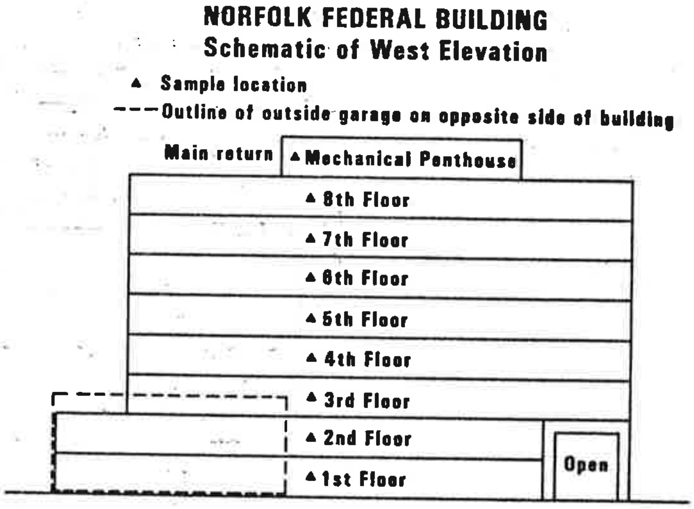
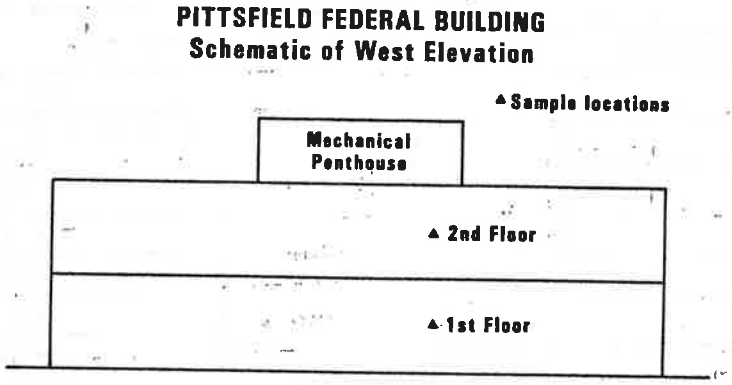
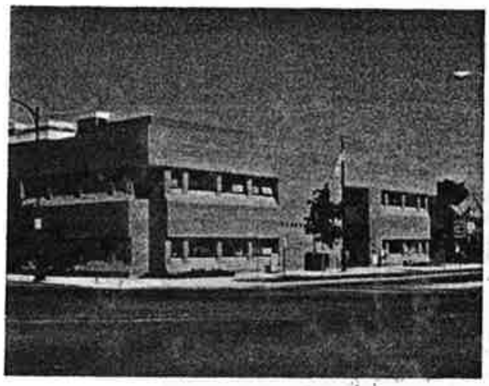


Figure 5. Schematic and Photograph of Federal Building in Norfolk, VA





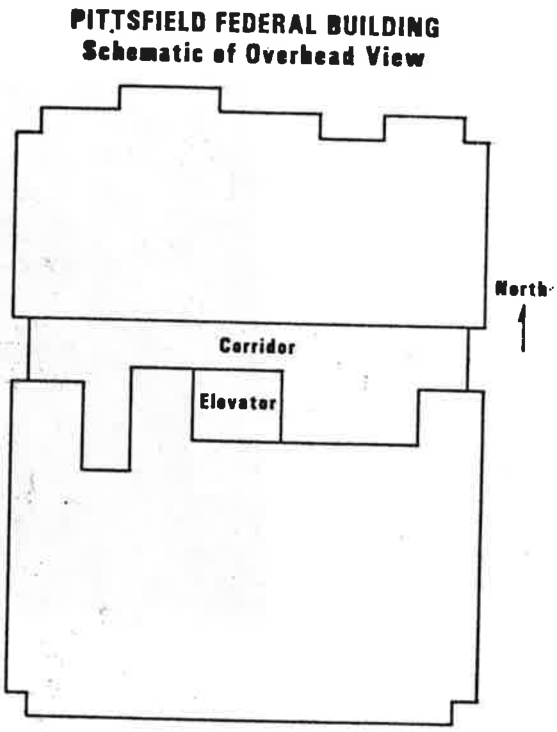
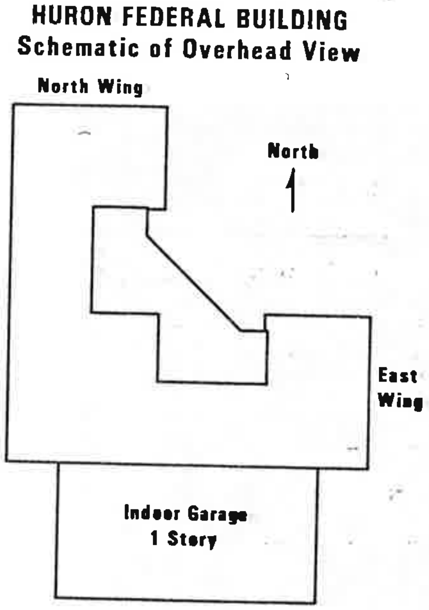


Figure 6. Schematic and Photograph of Federal Building in Pittsfield, MA



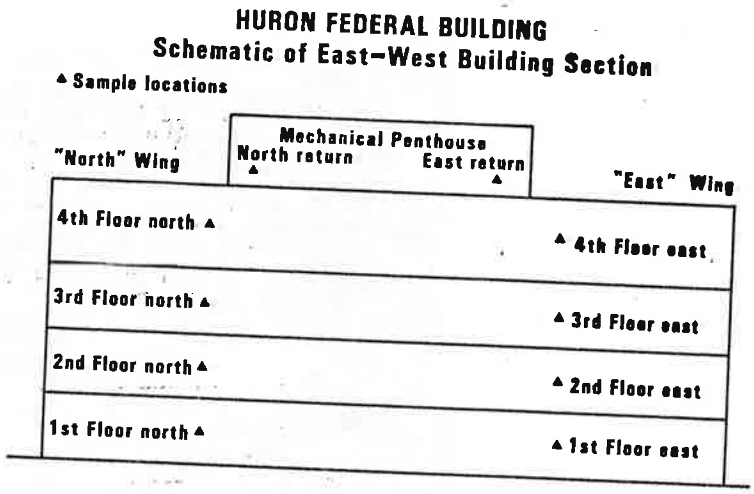
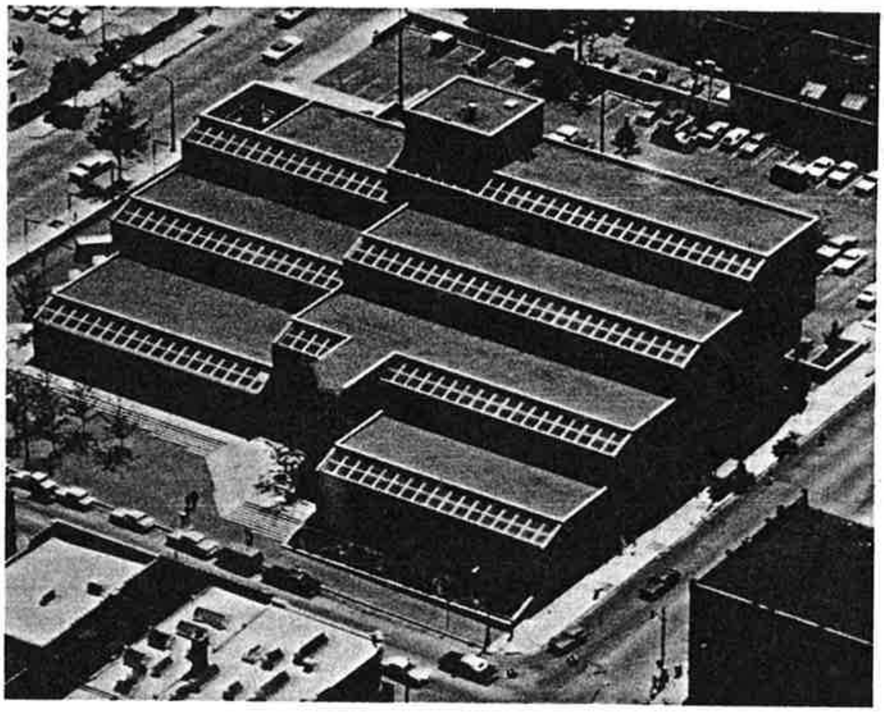
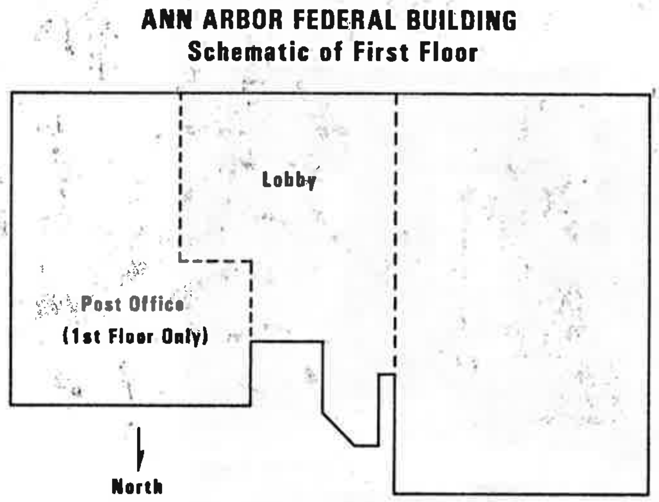


Figure 7. Schematic and Photograph of Federal Building in Huron, SD





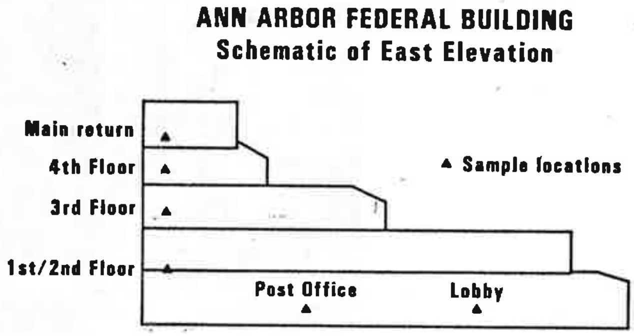
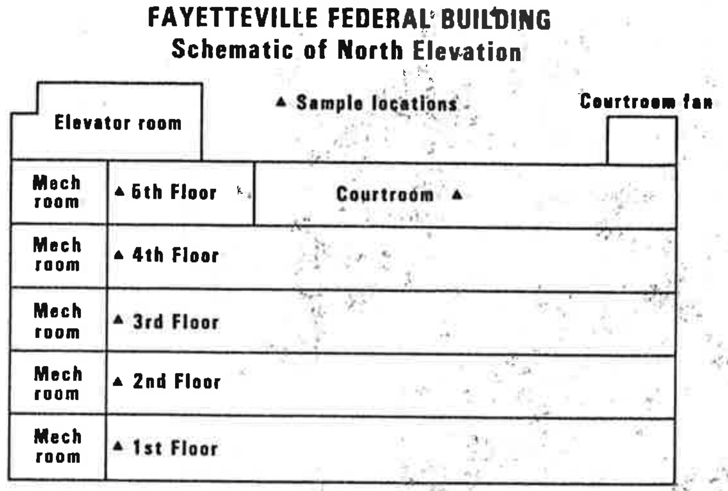
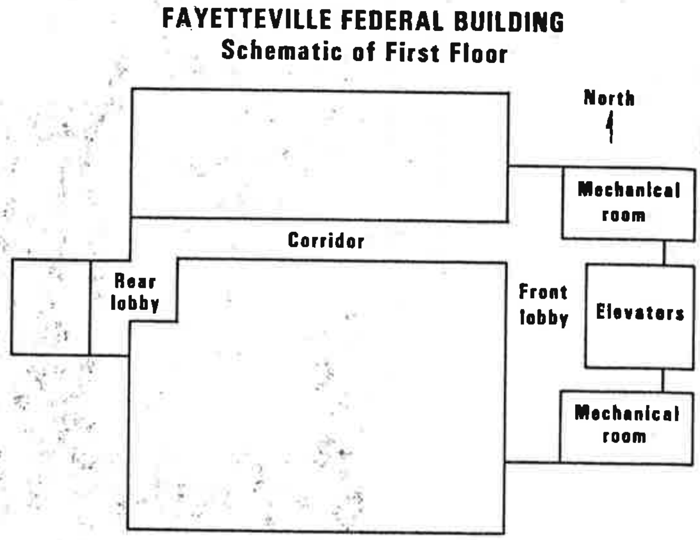


Figure 8. Schematic and Photograph of Federal Building in Ann Arbor, MI





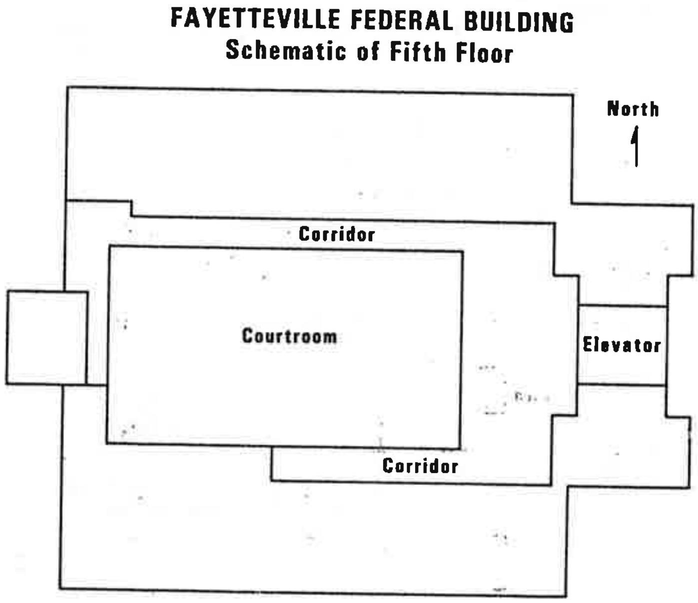


Figure 9. Schematic and Photograph of Federal Building in Fayetteville, AR

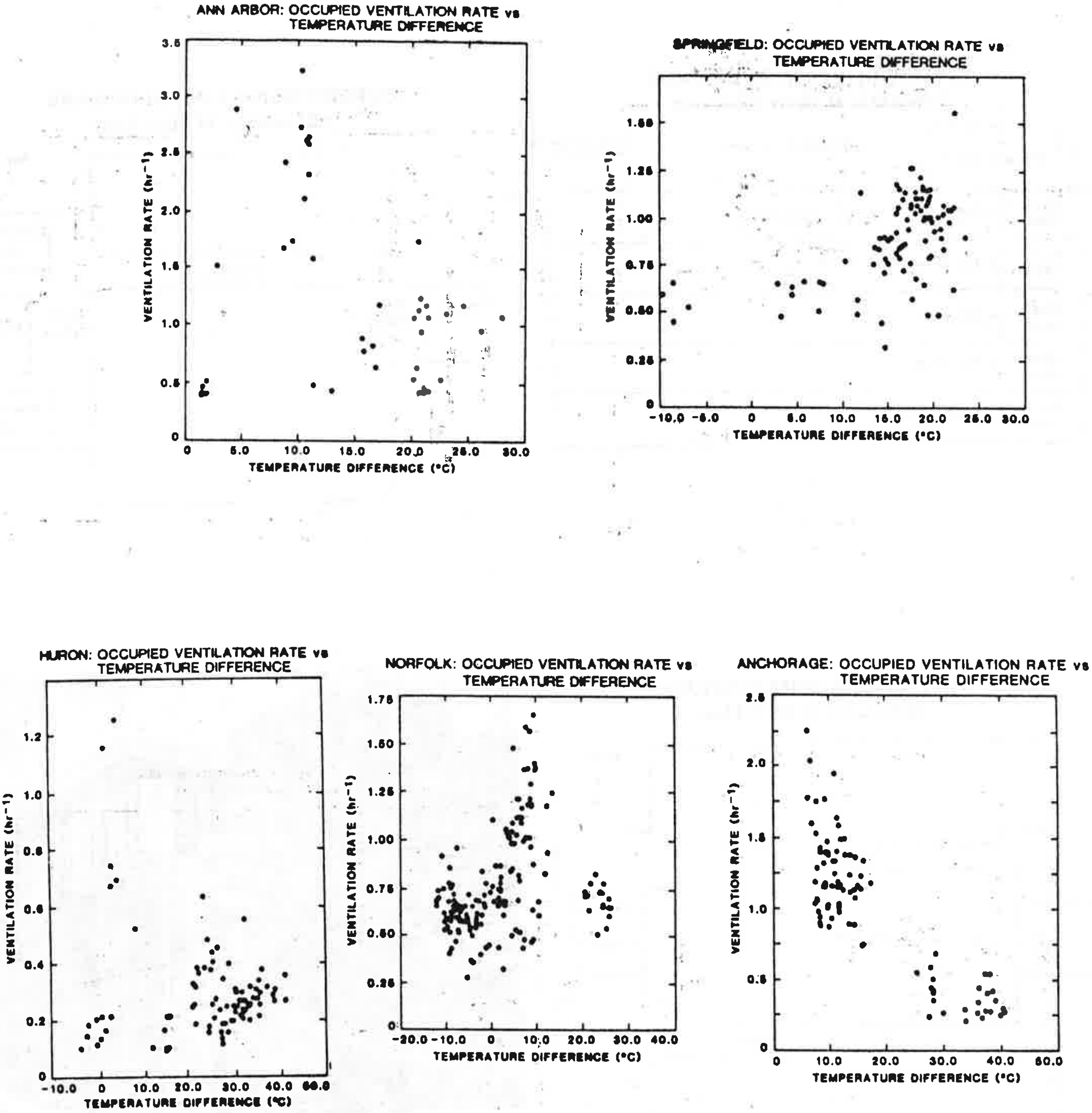


Figure 10. Ventilation Rates Versus Inside-Outside Temperature Difference for Various Office Buildings

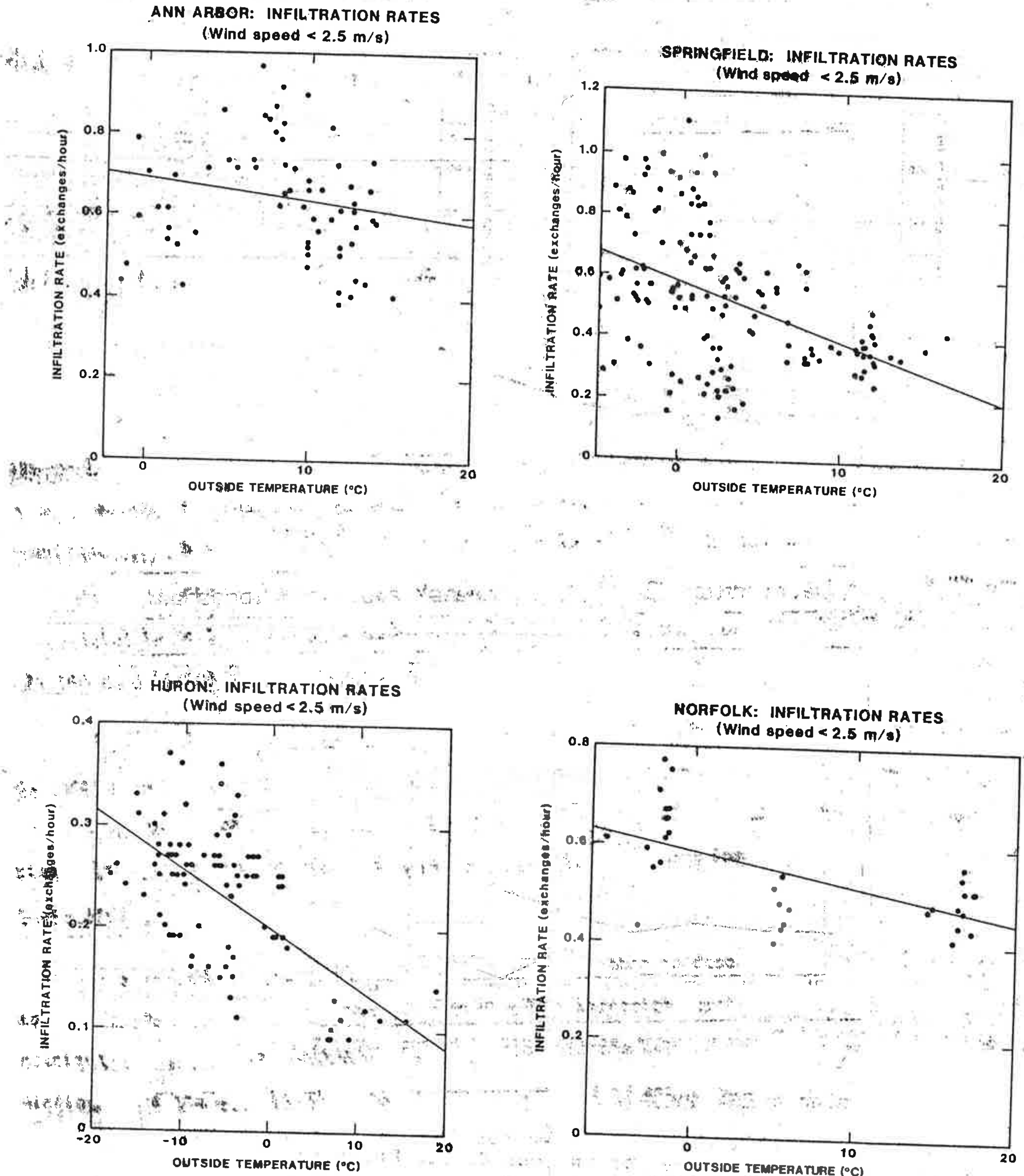
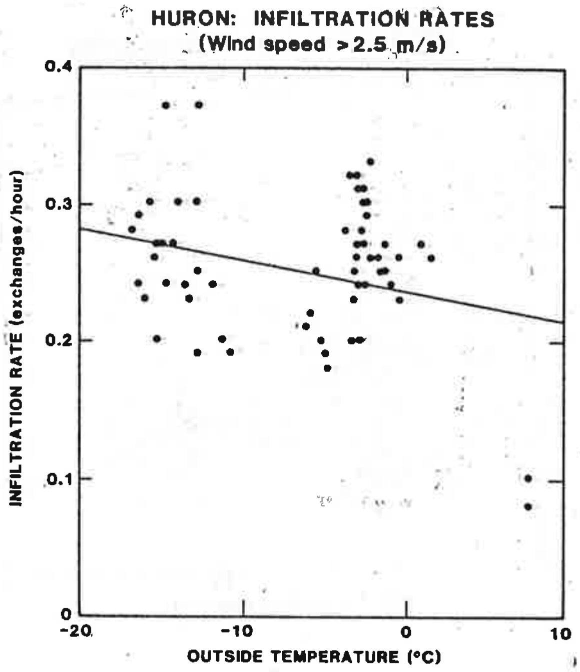
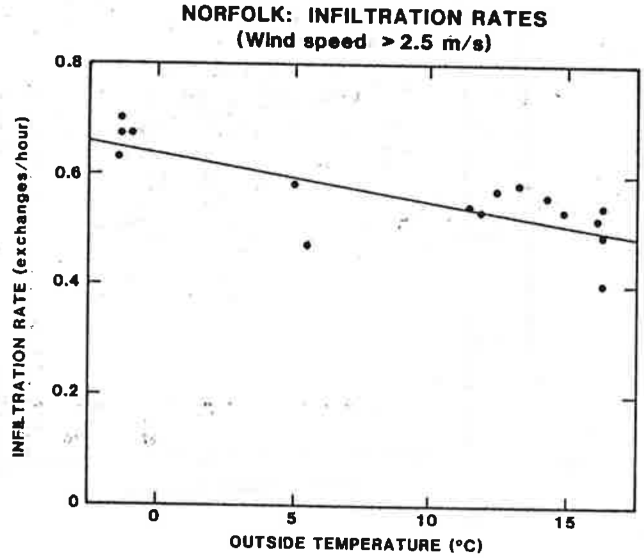


Figure 11. Infiltration Rates Versus Outdoor Temperature for Wind Speed Less Than 2.5 M/S (Solid lines are the regression lines of air infiltration vs temperature)





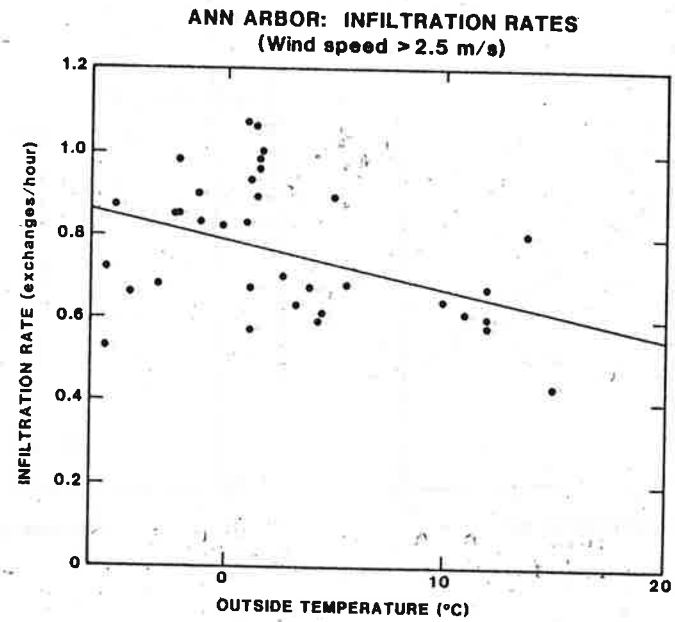


Figure 12. Infiltration Rates Versus outdoor Temperature for Speed Greater Than 2.5 M/S (Solid lines are the regression lines of air infiltration vs temperature)