AIC 1206

1859

No. 2923

Air Exchange Rate Measurements of the National Archives Building

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ABSTRACT

To aid in improving the performance of the heating, ventilating, and air-conditioning (HVAC) system of the National Archives Building so that it can better protect paper-based records of the United States, the National Bureau of Standards (NBS) measured air exchange rates under various combinations of temperature and wind speed. The average air exchange rate under normal operation of the HVAC system was 0.9 h^{-1} for an average temperature difference of 20.3°F (11.3°C) and an average wind speed of 6.0 mph (2.7 m/s). This rate is approximately twice those for new General Services Administration (GSA) office buildings. No clear dependence of air exchange rate on temperature differences up to 30°F (17°C) or wind speeds up to 11 mph (5 m/s) was found.

With outdoor air dampers closed and fans operating, the average air exchange rate was 1.2 h^{-1} for an average temperature difference of 14.8°F (8.2°C) and an average wind speed of 3.8 mph (1.7 m/s).

A test of interzone air movement showed that air migrates rapidly from nonstack to stack areas with fans operating normally.

The building could not be pressurized beyond an indoor-outdoor pressure difference of 0.06 in H_2O (14 Pa). At this pressure difference, the air exchange rate was 1.5 h^{-1}. As in the case of normal operation of the HVAC system, this rate is also approximately twice those for new GSA office buildings.

INTRODUCTION

The National Archives Building in Washington, D. C. (Figure 1), which houses many of the nation's records intended for permanent preservation, was constructed in the early 1930's. It was one of the first buildings in Washington, D. C., to provide all-season environmental control. The controlled environment was prescribed in order to protect the nation's valuable records from the effects of extreme temperature, high and low relative humidity excursions, and attack from acid gases such as those resulting from sulfur dioxide. The original heating, ventilating, and air-conditioning (HVAC) system was designed to meet these objectives, but it has since been modified a number of times and has had a history of less than satisfactory performance (General Services Administration 1983).

To aid in improving the performance of the HVAC systems at the National Archives Building, the Public Buildings Service of the General Services Administration (GSA) and the National Archives and Records Service (NARS) requested the National Bureau of Standards' (NBS) Center for Building Technology to provide criteria for environmental conditions for the storage and preservation of paper-based archival records. The study included a literature search on factors affecting the deterioration of paper-based records, an NBS Workshop on

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Environmental Conditions for Archival Storage, measurements of temperature, relative humidity, air exchange rate, and gaseous contaminant concentrations in the National Archives Building, and comparison of these measurements with similar measurments made in other buildings having controlled environments. Criteria were proposed for temperature, relative humidity, and gaseous and particulate contaminant concentrations. A detailed description of the study and its results, available as a report entitled "Air Quality Criteria for Storage of Paper-Based Archival Records" (Mathey et al. 1983), may also be useful in the design and modification of other archival storage facilities.

The present report describes air exchange rate and some temperature measurements made during March and April 1983 as part of the above study. The tests performed by NBS were as follows: (1) The air exchange rate of the building was measured under normal operation of the HVAC system. (2) The air exchange rate was measured with outdoor air dampers closed in order to determine how much air leakage there was through dampers. (3) Air leakage from the office and public areas to the stack areas was measured. (4) Fan pressurization measurements were performed in order to measure the intrinsic weather-independent envelope tightness of the building.

METHODS

The National Archives Building

The National Archives Building, located between Pennsylvania and Constitution Avenues, and between 7th and 9th Streets, in downtown Washington, is pictured in Figure 1. Its volume is 10,815,240 ft^3 (306,253.5 m^3) according to GSA. A schematic diagram of the building is shown in Figure 2. The northern side of the building, bordering on Pennsylvania Avenue, is composed of ten stories of offices. Each of these stories is subdivided in the center of the building into from one to three floors of stacks where records are stored. In addition, there are offices located on several of the stack floors. Nine air-handling systems serve the building (other than the garage). Each system, except for systems 2 and 4, is composed of two supply fans and a return fan; systems 2 and 4 are composed of one supply and return fan each. All fans in each system operate simultaneously. Figure 2 shows the areas served by each system, from information supplied by GSA. There are uncertainties as to the exact areas served by the various air-handling systems.

Installation of Automated Tracer Gas Equipment

One set of tubes and wires was connected from each air-handling system to a computer and electron-capture gas chromatography detector located in the basement. Each set of tubes and wires consists of 1/16-inch (3-mm) inner diameter (id) plastic tubing for injecting tracer gas into the supply fans, 1/4-inch (6-mm) id plastic tubing for sampling return air, wiring connected to a thermistor to measure return air temperature, and wiring connected to relays to determine whether fans were operating. In addition, a thermistor was placed outside the air intake of fan 1 to measure outdoor temperature, and a weather station was installed on the roof to measure wind speed and direction. All temperature and wind measurements were taken once a minute and the results averaged each hour. In all tests other than those for which fans were manually shut off, all fans operated continuously. Outdoor air dampers were automatically modulated by the building HVAC system and no record was kept of their status.

Automated Tracer Gas Equipment Used for All Tests

The automated tracer gas system developed at NBS and described elsewhere (Grot et al. 1980) was used to measure sulfur hexafluoride concentration and calculate hourly air exchange rates for each of the nine zones by the tracer-decay technique. The instrument was calibrated against samples containing known concentrations of sulfur hexafluoride. At 50 minutes past the hour, the system injected sulfur hexafluoride tracer gas for up to ten minutes. The maximal flow rate per zone was 170 cfm (80 L/s). Concentrations at each location were measured by a gas chromatograph, electron capture detector at 10-minute intervals thereafter and the results recorded on a floppy disk. The last four concentrations were fit by regression analysis to an equation of the form:

$$C = C_o\, e^{-I \cdot t} \qquad (1)$$

where

I = air exchange rate, h^{-1}
t = time after injection, h
C = concentration, ppb
C_o = initial concentration, ppb

A weighted average of the nine air exchange rates was calculated and called the air exchange rate of the building. The weighting factors were closely related to the flow rates of the air-handling systems. It would have been preferable to weight air exchange rates by relative zone volumes, but these data were unavailable. Table 1 shows these flow rates and the weighting factors. Average indoor temperature was calculated from the nine return air temperatures. Because these temperatures were always very close to each other, they were not weighted. Regression analysis of air exchange rate vs. indoor-outdoor temperature difference (always positive in these tests) was done essentially as described elsewhere (Silberstein 1980). Standard errors were also calculated as described in reference 2.

In the first tests, tracer gas was injected into each of the nine zones each hour and its concentration permitted to decay. It was found that gas was not always completely mixed within the first half-hour. It was also found that tracer gas often migrated into zones 1-5. Therefore, the system was reprogrammed to inject gas once every three hours for the full 10-minute injection period into zones 6-9 only. As a result, the tendency for gas to accumulate in zones 1-5 was no longer noted. Tracer gas was permitted to thoroughly mix during the first hour. During the third hour, concentrations were low. Consequently only data collected during the second hour were used. Figure 3 shows that there is little difference between earlier and later data.

Test 1. Normal Operation of the HVAC System. No modifications of the HVAC system were required for tests conducted under normal HVAC operation.

Test 2. Outdoor Air Dampers Closed. To determine how much air leakage was through dampers, air exchange rates were measured one weekend after the Archives maintenance staff shut all outdoor air dampers.

Test 3. Air Leakage from the Office and Public Areas to the Stack Areas. To determine whether air leaks into areas where archives are stored (stacks) from other areas (nonstack areas), gas was injected only into zones 1-5. Unlike during the earlier tests, it mixed evenly throughout the building. (These data were also used as normal fan-operation data.)

Test 4. Fan Pressurization Measurements. To measure the intrinsic weather-independent envelope tightness of the building, a fan pressurization test was conducted in the evening. Sampling tubes leading from systems 8 and 9 were rerouted to sample air in stack areas 7W-1 and 14W-1, both served by air-handling system 6, as seen in Figure 1. Just prior to pressurizing the building, it was determined that tracer-gas concentrations in these two stack areas were nearly equal to that in return fan 6, suggesting that tracer gas was uniformly distributed in that zone.

The maintenance staff shut off all the return air fans, closed the exhaust air dampers, and fully opened the supply air dampers (including dampers and fans serving the garage) prior to tracer gas injection. Tracer gas was manually injected for 30 minutes at a flow rate of 0.5 cfm (0.25 L/s) in order to maintain a high enough concentration for the high air exchange rates anticipated during the test. Differential pressure gauges were installed across the entrance doorways on Pennsylvania and Constitution Avenues. Since the concentrations in the two stack areas (and in fact in the remaining seven air-handling systems) were all nearly constant during tracer gas injection at about 200 ppb, the air exchange rate was calculated by the equation:

$$I = F/C \cdot V \qquad (2)$$

where

F = tracer gas flow rate, m^3/h
V = building volume, m^3

RESULTS

Test 1. Normal Operation of the HVAC System. Air exchange rates obtained under normal HVAC-system operation (Mathey et al. 1983; Silberstein et al. 1983) are shown in Figure 3 plotted against temperature difference, with wind speeds indicated next to the points. Curves representing one standard error unit about the line are also shown. The average air exchange rate was $0.9 \pm 0.3\ h^{-1}$, corresponding to an average temperature difference (ΔT) of 20.3°F (11.3°C) and an average wind speed of 6.0 mph (2.7 m/s). During normal operation of the HVAC system, the average indoor temperature of the Archives Building remained nearly constant at 73.0 ± 1.0°F (22.8 ± 0.5°C) (standard deviation or sd). The best-fit regression line is given by the equation:

$$I = 0.5 + 0.4(\Delta T) \tag{3}$$

where

$\Delta T = T_{in} - T_{out}$, °C

T_{in} = average indoor temperature, °C

T_{out} = outdoor temperature, °C

The correlation coefficient, R^2, is 0.23, reflecting the large amount of data scatter. The uncertainty of the first coefficient, as measured by the standard error, is 97%; the uncertainty of the second coefficient is 21%. It can be seen in Figure 3 that a linear relationship between I and ΔT going through the origin cannot be excluded. Neither can the possibility that I is independent of ΔT for ΔT below 30°F (17°C) be excluded.

At constant ΔT (this can be visualized, for example, by going up any corridor 2°F (1°C) wide in Figure 3), air exchange rate does not increase with increasing wind speed; if anything, it decreases. In fact, there is no apparent relationship between air exchange rate and wind speeds of 1.3-11 mph (0.6-5 m/s) encountered during the study.

Test 2. Outdoor Air Dampers Closed. In order to determine how much air leakage was through outdoor air dampers, a tracer-gas study was performed with outdoor dampers closed. Figure 3 shows the results of this experiment (Mathey et al. 1983; Silberstein et al. 1983) compared with the results of the previous study. The average air exchange rate was $1.2\ h^{-1}$ at an average temperature difference of 14.8°F (8.2°C) and an average wind speed of 3.8 mph (1.7 m/s). Two distinct temperature difference regimes make up this study: 1) small ΔT (4 data points below 36°F (2°C)), and 2) large ΔT (6 data points between 52°F (11°C) and 63°F (17°C). There are no data directly comparable to the first regime in the study under normal fan operation, but there are 20 points in the large ΔT region. The two large ΔT results are nearly identical: an air exchange rate of $1.1 \pm 0.2\ h^{-1}$ at a temperature difference of 24.1°F (13.4°C) and wind speed of 3.6 mph (1.6 m/s) with dampers closed, compared with an air exchange rate of $1.0 \pm 0.3\ h^{-1}$ at a temperature difference of 24.3°F (13.5°C) and wind speed of 6.3 mph (2.8 m/s).

As in the case of normal HVAC-system operation, the large amount of data scatter makes it difficult to assign a definite relationship between ΔT and I. In the present instance, neither a direct nor inverse dependence, nor independence of ΔT and I can be excluded. The standard error bands are not drawn, but are so wide that they encompass the origin and most of the normal HVAC-system operation data. The combined normal HVAC-system operation and damper-closed data are about as well fit by $I = 1\ h^{-1}$ as by any other relationship.

Test 3. Air Leakage from the Office and Public Areas to the Stack Areas. It was determined from information supplied by GSA that air-handling systems 6-9 serve mainly the stacks, while systems 1-5 serve mainly the remainder of the building (Figure 2). Therefore, tracer gas was injected only into zones 1 to 5 in order to test whether there was significant air leakage into the stack areas from the rest of the building. It was found (Mathey et al. 1983; Silberstein et al. 1983) that there was immediate, thorough mixing between the stack and nonstack areas. The tracer gas concentrations in the nine zones were so uniform during the test, in fact, that it was possible to calculate an air exchange rate for the building (see Figure 3).

Test 4. Fan Pressurization Measurements. Fan pressurization measurements were performed in order to measure the intrinsic weather-independent envelope tightness of the building. The building was pressurized by closing off all exhaust air dampers and return fans, including those serving the garage, and opening all supply air dampers and fans. Concentration measurements were made in two stack areas on the 7th and 14th stack floors. (There are 21 stack floors.) The building could be pressurized to maximum pressure differences of only 0.06 inch H_2O (14 Pa), measured at the Constitution Avenue entrance on the ground floor (corresponding to the fifth stack floor) and 0.04 inch H_2O (10 Pa) at the Pennsylvania Avenue entrance on the main floor (corresponding to the third stack floor). It was noticed during the test that there were strong drafts from the garage through two doorways into the main body of the building. The average temperature difference during the test was 10.6°F (5.9°C) and the average wind speed was 3.4 mph (1.5 m/s).

The air exchange rate calculated by the constant concentration method (Equation 2) was 1.5 h^{-1}.

SUMMARY AND CONCLUSIONS

Air exchange measurements were taken under various combinations of temperature and wind speed. The average air exchange rate was 0.9 h^{-1} for an average temperature difference of 20.3°F (11.3°C) and an average wind speed of 6.0 mph (2.7 m/s). The indoor temperature was very nearly constant at around 73°F (23°C) and the outdoor temperature was always lower than the indoor temperature. No clear dependence of air exchange rate on temperature differences up to 30°F (17°C) or wind speeds up to 11 mph (5 m/s) was found.

The test done with air dampers closed and fans operating showed that at a temperature difference between 20°F (11°C) and 30°F (17°C), the air exchange rate was the same as that when dampers were operating automatically. This may be because under normal operation of the HVAC system, dampers would be closed at these outdoor temperatures.

A test of interzone air movement showed that air migrates rapidly from nonstack to stack areas with fans operating normally.

The building could not be pressurized beyond an indoor-outdoor pressure difference of 0.06 inch H_2O (14 Pa). An air exchange rate of 1.5 h^{-1} was obtained by the constant concentration method at this pressure difference.

A similar study of eight new GSA buildings in various parts of the United States (Grot and Persily 1983) shows that the Archives Building is about twice as leaky as new office buildings, both under normal operation of the HVAC system and under pressurization. Their air exchange rates under normal operation of the HVAC systems vary from 0.2 to 0.6 h^{-1} for outdoor temperatures of 40-50°F (4-10°C) and wind speeds under 2.9 mph (1.3 m/s). Their air exchange rates at a pressure difference of 0.06 inch H_2O (14 Pa) were 0.5 to 0.9 h^{-1}.

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ACKNOWLEDGMENT

The report was sponsored by the Public Buildings Service of the General Services Administration, and the National Archives and Records Service, Washington, DC.

We wish to thank Ron Diggs, Lewis Johnson, Louis Olsen, Dan Poyner, and Joe Schaefer of GSA for their invaluable assistance in carrying out the tests.

TABLE 1

Air Handling System Flow Rates and Air Exchange Rate Weighting Factors

System	Flow rate 10^3 cfm	m^3/s	Air exchange rate weighting factor
1	69	33	1
2	5.9	2.8	0.09
3	62	29	1
4	5.9	2.8	0.09
5	40	19	0.6
6	70	33	1
7	65	31	1
8	66	31	1
9	66	31	1

Figure 1. The National Archives Building, located between Pennsylvania and Constitution Avenues, and between 7th and 9th Streets, in downtown Washington

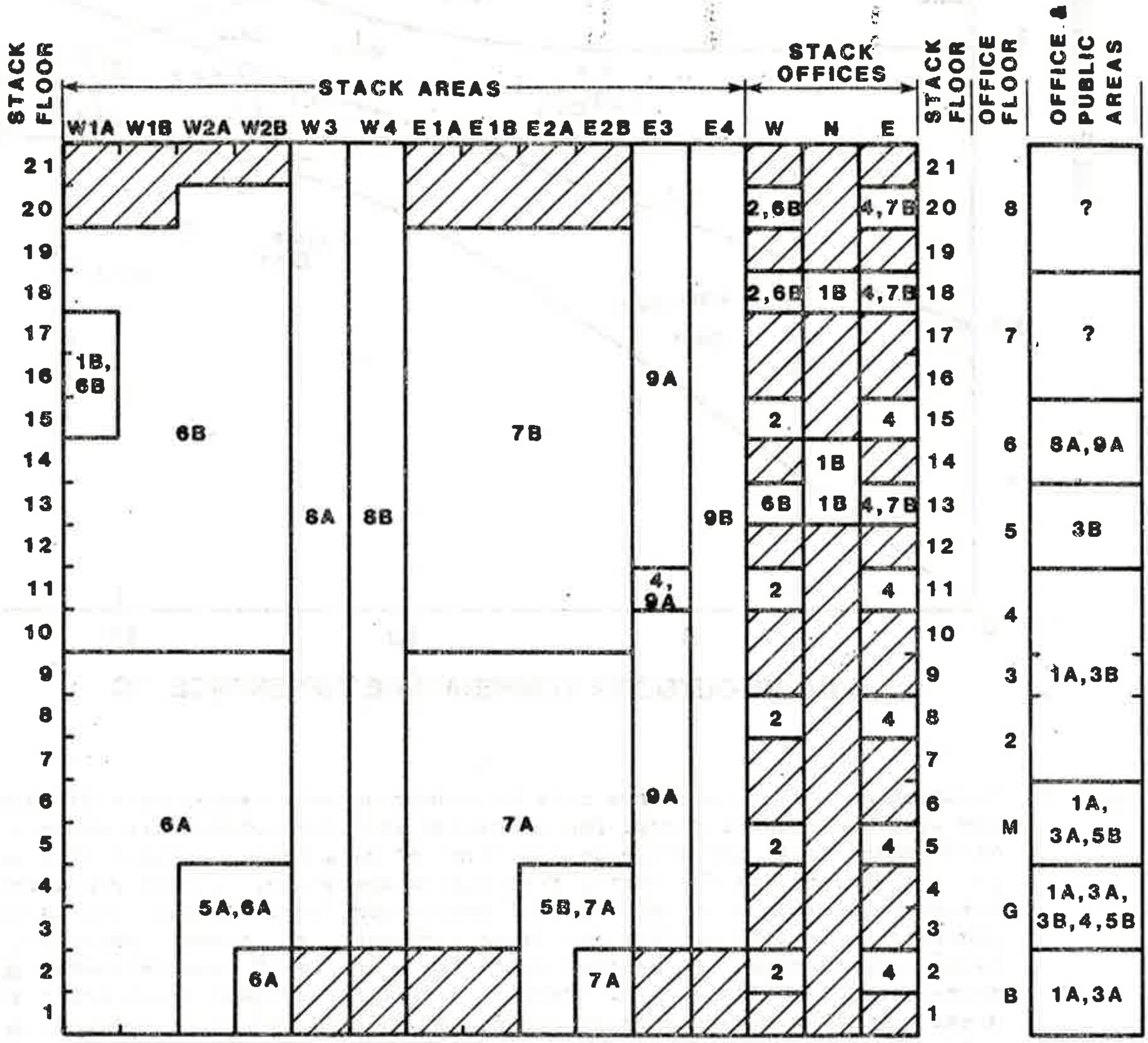

Figure 2. Schematic side view of National Archives Building, showing areas served by air-handling systems, from information supplied by GSA. Each of the nine air-handling systems of the building except 2 and 4 has two supply air fans labeled "A" and "B", and one return air fan; systems 2 and 4 have one supply and return fan each. All fans in each system operate simultaneously. The numbers in the figure above refer to supply fans.

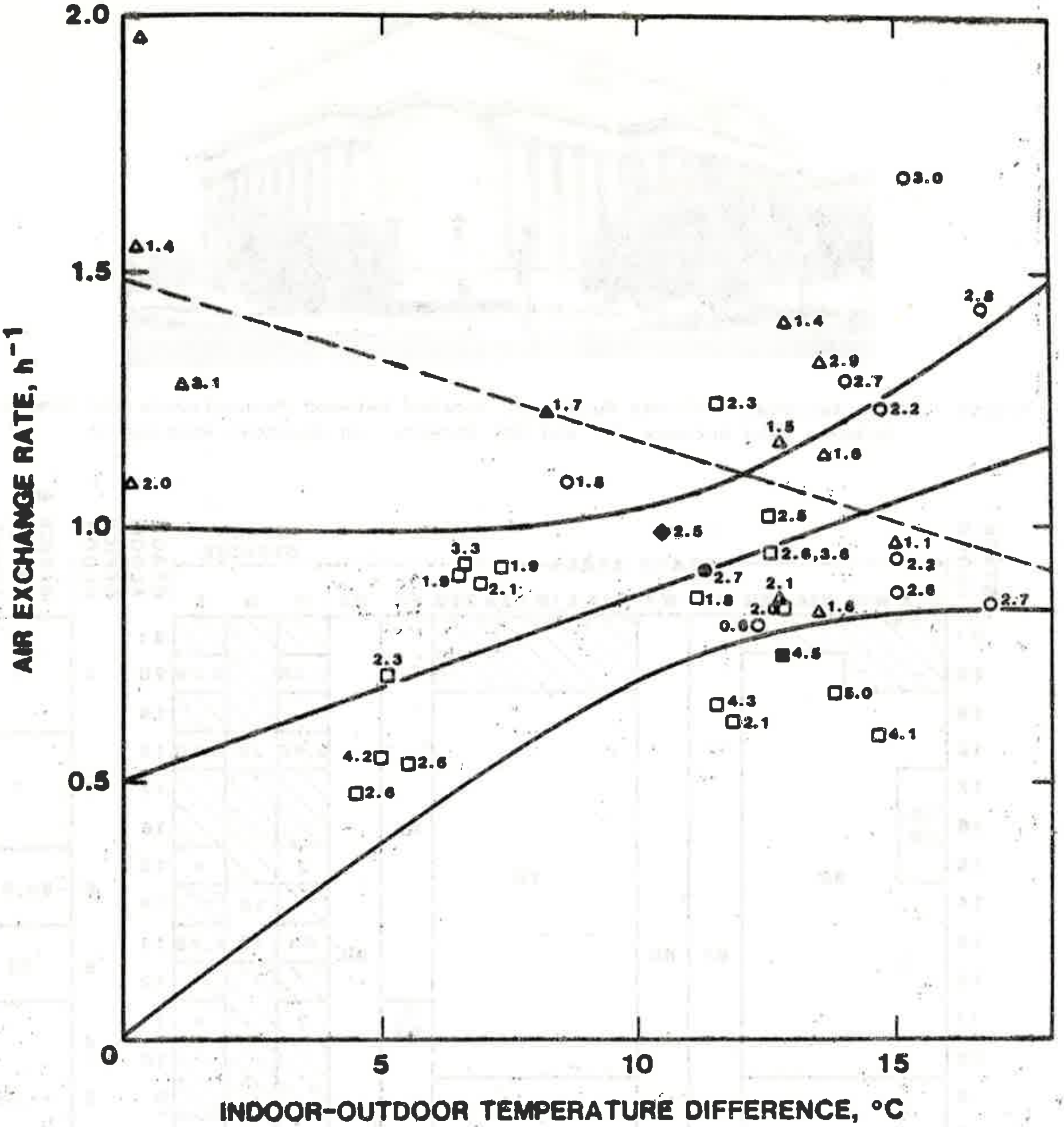

Figure 3. Relationship of air exchange rate to indoor-outdoor temperature difference and wind speed under normal fan operation and with outdoor air dampers closed. Wind speeds (m/s) are shown to the right of data points. Solid line is best-fit regression line for normal HVAC-system operation. Curves represent one standard error unit on each side of regression line. Dotted line is best fit regression line for outdoor air dampers closed. ○, normal operation, early tests (see Methods); □, normal operation, late tests (see Methods); ■, normal operation (late test), test of air mixing between stack areas and other areas; △, outdoor air dampers closed; ●, normal operation average; ▲, outdoor air dampers closed average; ◆, overall average