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DYNAMIC CHARACTERISTICS OF AIR INFILTRATION

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In the design of a building, the heating and cooling load should be calculated accurately in order to properly size the heating and cooling system and to make a suitable prediction of the seasonal energy requirements.

Energy is added to or taken from a structure in a variety of ways: conduction of heat through the solid portion of the structure; thermal radiation through transparent surfaces such as windows; the addition of energy from people and equipment inside; and finally the energy associated with the air that is either introduced through the ventilation system or continually infiltrating into and exfiltrating out of the structure. Of all these factors, infiltration is perhaps the most difficult to predict and can be as much as 1/3 of the heating load and even a larger percentage of the cooling load.

The ASHRAE HANDBOOK OF FUNDAMENTALS (1) describes the two basic techniques used in predicting air infiltration rates. One method-the air change method consists simply of assuming a certain number of air changes per hour for each room. The number depends upon the relative location of the room inside the structure, as well as the number of windows and doors in the room. The second method is based upon measured leakage characteristics of the building structure. Since cracks around windows and doors are usually the main source of air infiltration, it is known as the crack method. It is usually regarded as more accurate as long as the leakage characteristics can be evaluated properly.

In this second method, the air flow can be expressed:

$$Q = C\ \Delta P^n \tag{1}$$

where:

- Q = volumetric flow rate of air
- C = proportionality constant
- n = exponent between 1/2 and 1
- ΔP = pressure difference across the window

C and n must be determined for the structural component in question and the pressure difference must be known. This pressure difference, exerted on an enclosure, is the result of wind blowing over and around the building as well as the interior configuration and characteristics of the air handling equipment. In addition, infiltration can result from a difference in density between the inside and outside air.

Much research has been done to refine the design calculations of heating and cooling loads, and in particular, the infiltration portion as it applied to complex buildings and structures. Among some of the recent contributions are papers by Svetlov (2), Jackman and den Ouden (3), Gabrielsson and Porra (4), and Tamura (5). In all of these cases, some form of Eq (1) has been applied to all of the rooms within the structure, with a pressure difference used that is calculated from assumed velocity and temperature profiles both inside and out. This general approach has been used for some time and in "Procedure for Determining Heating and Cooling Loads for Computerized Energy Calculations" (6). Of course, since all of these procedures are

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based on the crack method and Eq (1), they assume a steady flow situation with a constant pressure drop across the crack, thus implying a constant wind velocity on the outside of the building. This rarely, if ever, happens. The purpose of this study was to determine, experimentally, if meaningful infiltration data could be obtained from observing this fluctuating wind speed and pressure difference exerted on an enclosure. In addition, an attempt was made to evaluate the correlation between these two dynamic variables.

EXPERIMENTAL INVESTIGATION

The Center for Building Technology office building located on the grounds of the National Bureau of Standards in Gaithersburg, Maryland is Building 226, Fig. 1. Two separate offices (A331 and B322) approximately 10 ft (3 m) high by 10 ft (3 m) wide by 16 ft (5 m) long were retrofitted and used as test rooms for this study. As shown, one of the rooms was on the north side of the building and the other was on the south. Both were on the third floor, and each contained one window approximately 5 ft (1 1/2 m) wide x 8 ft (2 1/2 m) high and one door facing a corridor. The interior walls of these rooms were metal partition walls, 3 in. (7.6 cm) thick having a sound transmission of STC-40. The partitions were joined every 4 ft (1.3 m) with metal post caps. The normal office windows were removed and replaced with experimental plastic windows containing adjustable cracks as shown in Fig. 2 and 3. The adjustable braces could be loosened so that the two center pieces would slide about, thus enabling one to change the width of the test crack. The test crack refers to the complete U-shaped opening shown. The remainder of the opening was always sealed with a special fiber-reinforced tape.

Before putting the experimental plastic or test windows in place, they were calibrated in a temporary structure (Fig. 4). A blower was used to pull air through the test crack, then into a polyethylene enclosure around the blower that pumped air back into the room for recirculation. An adjustable damper on the blower was used to obtain several flow rates through the window. A pitot tube mounted in the 3 in. (7.6 cm) suction pipe was used to determine the air flow rate. The pressures were measured with a Hook gage manometer. The manometer was also used to measure the pressure drop across the window by opening one side to the room and connecting the other to the inside of the enclosure, using 1/4 in. (0.63 cm) id plastic tubing. The two windows were calibrated at crack widths of .05 in. (0.126 cm) and .025 in. (0.063 cm). Several different damper positions on the blower were used to determine the calibration curve at steady flow conditions (Fig. 5).

Once the test windows were placed in the offices, the test equipment was arranged as shown in Fig. 6. A differential pressure transducer, having a range of $\pm$ 0.01 psi (68.95 N/m^2) difference, was located in each room, one side connected to the outside through a small hole in the test window and the other side open to the room. Three transducers are shown on the chair in Fig. 7. The transducers measured the instantaneous pressure drop across the windows. The transducer outputs were fed by way of shielded cable down the hall to an amplifier in the instrumentation room. The amplified signals were in turn sent to a two pen chart recorder and an analog tape recorder located on the first floor of the building.

CO_2 was released into the test rooms, and the CO_2 content of the air was continually analyzed to determine the air change rate for the rooms. This "tracer gas" technique has been used successfully in previous inventigations (7, 8, 9, 10, 11, 12, 13). The air change rate is defined as the ratio of the hourly rate at which air enters (or leaves) the enclosure to the volume of the enclosure. The amount of decay in CO_2 concentration in the test space per unit time is numerically equal to the amount of CO_2 leaving the space with the outlet air in the same unit time. This can be expressed:

$$-VdC = NVCdt \qquad (2)$$

where:

- V = volume of the space, ft^3 (or m^3)
- C = concentration of CO_2 at time t
- N = number of air changes per hour
- t = time, hours

(C for concentration is not to be confused with the proportionality constant of Eq (1)).

With $C = C_o$ at time t = 0, the solution to Eq (2) is:

$$N = (\ln[C_o/C])/t \qquad (3)$$

Eq (3) states that the number of air changes occurring during time (t) is equal to the natural logarithm of the ratio of the initial CO_2 concentration to the concentration at the end of the time interval.

In order to determine the CO_2 content of the air, an air pump circulated the mixture through 1/4 in. (0.63 cm) id plastic tubing from one or the other of the test rooms (depending on the position of the two-way valve) through a CO_2 analyzer and back into the rooms. A large fan was used in the room for a short period of time at the beginning of each test to insure a uniformly mixed atmosphere. The CO_2 transducers were located in the center of the room (Fig. 7). Since the fan was not run continuously throughout the test, it cannot be said for certain that the decay rate of CO_2 gave an accurate indication of the air movement occurring at the window. The analyzer output was displayed and recorded as a function of time on a pen chart recorder. During all tests, the initial concentration of CO_2 in the test rooms was 1% or less. Since the output of the analyzer was linear in this range, the voltage readings displayed on the pen chart recorder could be used directly for calculation of the air change rate. The result of a typical test recording of CO_2 decay is shown in Fig. 8. Since the slope was used to determine the equation of the straight line passing through the data with the "least error". The slope or air change rate was thus determined.

The wind velocity and direction were determined by anemometers located on a tower 300 ft (92 m) directly north of the building. They were approximately 30 ft (9 m) above the ground, which corresponded approximately to the height above the ground to the center of the windows. The total wind speed was measured by a cup-type anemometer, which is essentially a d c permanent magnet generator with the output voltage directly proportional to the speed of rotation of the 3-cup rotor attached to its shaft. Two propeller-type anemometers were also mounted on the tower to measure the north-south and east-west component of the wind velocity. These also were miniature d c generators providing an analog voltage output proportional to the wind speed. They responded only to that component of the wind which has parallel to the axis of rotation and indicated forward and reverse air flow by a reversal of signal polarity at the generator. All three indicators were calibrated so that 100 mV output represented 10 mph (4.47 m/s) of wind speed. These voltage signals were recorded simultaneously with the two pressure difference signals on 5 channels of the analog tape recorder located in Room B150 of the building.

During each test, the entire room, with the exception of the test window, was sealed as completely as possible. The ventilation system serving the room was shut off and the registers where air normally enters the room were also sealed. Polyethylene was taped over the door and all other noticeable cracks inside the room were taped. Nine separate one hour tests were conducted during the summer of 1970, and typical results are shown in Fig. 9 - 12 (for test No. 3).

DISCUSSION AND ANALYSIS OF EXPERIMENTAL RESULTS

Room A and Room B on the pressure difference plots signify data for Room A331 and Room B322, respectively. A positive ΔP signifies a larger pressure outside compared to inside the room. In addition, the wind velocity components were combined to compute a wind direction as shown. As noted previously, these data were taken from anemometers located approximately 300 feet (92 m) north of the building and 30 feet (9 m) above ground. Therefore, they represent undisturbed conditions and would be different from what is occurring at the building surface.

By observing the plots, it can be seen that the wind velocity and pressure differences were far from steady. Table 1 shows a summary of the infiltration studies. Indicated in this table are the observed wind data at the NBS site together with similar data obtained at Dulles International Airport, approximately 20 miles southwest of NBS. Columns 9 and 15 show the actual air change rate (AC_{act}) as measured by the CO_2 "tracer gas" technique. Temperatures were measured inside the room and on or around the test windows in addition to the temperature outside. During the summer period when these tests were being conducted, the temperature difference seldom exceeded 20 deg F (11.1 deg C), making the driving force due to temperature difference insignificant compared to the driving force due to the wind.

Preliminary tests were run on each of the test rooms in the sealed configuration and also with the window crack sealed with fiber-reinforced tape. A small amount of leakage still occurred, so the uncertainty associated with the actual air change rates is approximately 0.05 per hour.

The steady flow characteristics of the two test windows, as displayed in Fig. 5, were analyzed by use of the least squares method to give the coefficient (C) and exponent (n) tabluated in columns 6, 7, 12, and 13 respectively. An air change rate (AC_{sf}) was calculated for each test, using these constants and the time average of the measured pressure fluctuations (columns 8 and 14) in conjunction with Eq (1).

A third air change rate is tabulated in columns 11 and 17 and is labeled AC_{ASHRAE}, to signify a calculation done according to recommended procedures in the ASHRAE HANDBOOK OF FUNDAMENTALS (1).

ASHRAE recommends the use of Eq (1) calculating infiltration rates as a result of wind forces, provided that the leakage characteristics of the window (C and n) are known. The only difficulty arises in the choice of a ΔP. The velocity head equivalent to a given wind speed as specified in (Ref 1) is:

$$P_v = 0.000482\ V_w^2 \tag{4}$$

where:

P_v = velocity head, inches of H_2O

and:

V_w = wind speed, miles per hour

Ref 1 recommends for design purposes: "To account for the buildup of pressure inside the building, it is common practice to take 0.64 P_v as the pressure difference across the windward wall".

Consequently, the air change rates tabulated in columns 11 and 17 of Table 1 (AC_{ASHRAE}) were determined by using Eq (1) with:

$$\Delta P = .000308\ V_w^2 \tag{5}$$

where: V_w was taken as the wind speed measured at the NBS site, averaged over the duration of the test. Due to the unique configuration of the experimental setup described in this paper, one should really not expect there to be much correlation between AC_{ACT} and AC_{ASHRAE}, which is used for design purposes under a more realistic situation–where air flow through the building occurs. At the beginning of this project, it was intended that the two test rooms be connected by flexible ducts to ascertain any differences due to this "through-flow". However, that phase of the project was never completed.

The various air change rates of Table 1 are plotted in Fig. 13 - 16. As can be seen from Fig. 13 for Room A331 and a crack width of 0.05 in. (0.126 cm), there is very little correlation among the three differently determined rates. For Room B322 and a crack width of 0.05 in. (0.126 cm) (Fig. 14), there is relatively good correlation between the measured and steady flow calculation (using the average of the measured ΔP's) at the higher wind velocities. For all tests involving the smaller crack (.025 in. (0.063 cm), the correlation between the actual rate and steady state calculation is moderate to good (Fig. 15 and 16).

For all tests where the average wind velocity was larger than approximately 5 mph (2.2 m/s), the ASHRAE calculation gave a much higher air change rate than actually occurred. As mentioned above, this could be expected. Since little or no "through-flow" was allowed, the pressure buildup inside the room was such that the ΔP at any instant was considerably less than 0.64 P_v.

Elkins and Wensman (10) recently reported on an air infiltration study in which two residences in Canton, Ohio were instrumented to measure infiltration rates. Measurements were taken for a period of almost one year. Since these were single story dwellings, the results indicated infiltration rates almost solely a function of wind speed and direction.

It is often postulated and has been verified by several tests (7, 9) that the infiltration rate is a linear function of wind speed. This linearity arises because the infiltration rate is proportional to the wind pressure to approximately the one-half power while the wind pressure is proportional to the square of the wind speed. Observing this, Elkins and Wensman (10) divided their experimentally measured infiltration rates by the wind speed and plotted the new factor against wind direction. The resulting curve had a clearly defined peak, thus showing the separate effect of wind speed and direction. A similar plot was attempted for the data of this study (Fig. 17). There is no definite trend in the data, indicating, perhaps, localized processes at the windows unrelated to the wind velocity and direction measured 300 ft (92 m) north of the building.

Very recently H. K. Malinowski (14) presented a discussion of the wind effect on air movement inside buildings. His observations were that air exchange is a result of four factors:

1. air flow through a space
2. pulsating flow
3. the penetration of eddies (turbulence)
4. static or molecular diffusion

The air exchange by through-flow is depicted in A of Fig. 18 and occurs when openings are located in areas of different pressure. As noted previously, this type of flow was practically eliminated in the present study as a result of completely sealing the room except for the test window.

Pulsating flow occurs when all the openings are located in an area of the same external pressure, or when the pressure difference is very small, but the variation of the pressure in time predominates. This process is demonstrated in B of Fig. 18 and, as already noted, was perhaps the predominate factor in the experiments conducted in this study.

Another type of pulsation flow exists when the external pressure changes between two or more openings in such a way that the flow periodically changes direction (C of Fig. 18). Because of the basic configuration of the test crack, this latter process could very well have occurred during the tests and would help explain why the infiltration rate, calculated using the steady flow equation, and measured ΔP gave values smaller rather than larger than actually measured during 60% of the tests. Unfortunately only one location in the center of the window was chosen for a pressure difference measurement and no quantitative data exists to verify the occurrence of this phenomena.

If the external flow is turbulent or if potential turbulence is created in the vicinity of the opening, eddies, by penetration into the building, are carrier vehicles for the conveyance of external air into the building and the removal of the internal mixture of air to the outside. This process is illustrated in D of Fig. 18. It is felt that openings much larger than those which existed in the present tests are required before this process becomes significant.

SPECTRUM ANALYSIS

If any meaningful simulation is to be made of the dynamic infiltration process, then the frequency of the wind and/or pressure difference oscillations must be known. The range of frequencies that are predominant have been determined by a spectrum analysis of the measured data. The details of this kind of analysis are given in the Appendix and in more detail in Ref 17.

A sequence of calculations, described in the Appendix, were applied to a 3 min segment of north-south and east-west velocity components of test No. 3. The results are shown in Fig. 19. The ordinate is a normalized "power", and the abscissa is the frequency in Hz. The time increment between data points was 0.5 seconds, which limits the highest possible frequency detectable by the analysis to 1 Hz. As can be seen, the highest significant frequency is on the order of 0.1 Hz with the maximum "power" occurring at frequencies in the range of 0.01 Hz. The data of other tests were analyzed, and similar results were obtained. It is felt that this specturm is accurate since the response curve for the propeller-type anemometers is rather flat out to 1 Hz.

Turbulence in a flow field is called isotropic if its statistical features have no preference for any direction (16). This condition simultaneously requires no average shear stress and no velocity gradient in the field. Even though it is a hypothetical situation, the majority of theoretical analyses on turbulence has been in this area, and a knowledge of its characteristics had formed a fundamental basis for the study of actual turbulent flows. One of the ranges of frequencies where an equation for the power specturm has been derived on a theoretical basis (assuming isotropic turbulence) is the so-called "inertial subrange". It can be shown that the "power" is equal to a constant times the frequency to the minus 5/3 power. It is interesting to note in Fig. 19 that the specturm obtained has this kind of dependence over a large portion of the range.

Fig. 20 shows the results of a similar analysis that was done on the pressure differences across the test windows during test No. 3. As with the velocity components, the significant frequencies were below 0.1 Hz with the maximum "power" occurring at frequencies below 0.01 Hz. However, one should be cautioned that no frequency response was determined for the transducer-tubing system, and the absence of high frequency components could very well be due to the response characteristics of the measuring system itself.

CONCLUSIONS

The most obvious conclusion to be drawn from the present study is that the infiltration process that actually occurs in and around window cracks is an extremely complex one. It is postulated that air change is primarily a result of a pulsation process at the window crack, and the result is complicated by the fact that air flow can occur into and out of the room simultaneously.

The design calculation, as recommended by ASHRAE, gave air change rates larger than those measured, particularly when the average wind speed was higher than approximately 5 mph (2.2 m/s). Of course, the design calculation is for the normal situation where the building space is unsealed and air moving in through a window is free to move out through another opening. The correlation between actual air change rates and ones calculated using the steady flow equation and a measured ΔP (averaged over the duration of the test) was moderate to good. The agreement was better at higher average wind velocities. The major reason that the agreement was not better between the actual flow rates and those calculated using the steady-flow assumption was assumed to be the simultaneous forward and reverse flow through the windows.

APPENDIX

Spectrum Analysis Calculations

Consider one of the velocity components of the wind. Over a certain length of time the average value of this component can be determined. The instantaneous value is then assumed to be composed of the time average value plus some time dependent fluctuation.

$$U_1 = \overline{U}_1 + u_1 \tag{6}$$

where:

U_1 = instantaneous velocity component

$\overline{U}_1$ = time average value

u_1 = instantaneous value of the fluctuating component

The kinetic energy of the turbulent fluctuations can be considered to consist of the sum of the contributions of all the frequencies (n). Let:

$$E(n)\ dn$$

be the contribution to u_1 of the frequencies between n and n + dn; the distribution function E (n) then has to satisfy the condition:

$$\int_0^\infty E(n)\ dn = \overline{u_1^{\,2}} \tag{7}$$

E (n) is called the power spectrum.

In the field of statistics, there are many types of correlation functions that have been defined. One such function involves the correlation between values of a fluctuating quantity at a fixed point in a flow field at two different instants t' and t'-t or t'+t. For the experiment being analyzed here, the quantity of interest is the fluctuating velocity component u_1. The correlation desired is then:

$$\overline{u_1(t')\ u_1\ (t'-t)}$$

or in terms of a coefficient:

$$R(t) = \frac{\overline{u_1\ (t')\ u_1\ (t'-t)}}{\overline{u_1^{\,\prime 2}}} \tag{8}$$

where the average is taken with respect to time t.

It can be shown (15, 16) that the time correlation coefficient defined above and the power spectrum are Fourier cosine transforms:

$$R(t) = \frac{1}{\overline{u_1^2}} \int_0^\infty dn \quad E(n) \cos 2\pi nt \tag{9}$$

and:

$$E(n) = 4 \, \overline{u_1^2} \int_0^\infty dt \; R(t) \cos 2\pi nt \tag{10}$$

Consequently, the power spectrum can be obtained by first computing the correlation coefficient and then obtaining the power spectrum. In the analysis of the discrete data obtained from the experiment, the following sequence of calculations was used:

$$\overline{X} = \frac{1}{n} \sum_{n=1}^{N} X(t_n) \tag{11}$$

$$X'(t_n) = (t_n) - \overline{X} \tag{12}$$

$$\sigma^2 = \frac{1}{N} \sum_{n=1}^{N} (X'(t_n))^2 \tag{13}$$

$$R(k) = \frac{1}{N-k} \sum_{n=1}^{N-k} X'(t_n) \, X'(t_{n+k}) \tag{14}$$

for $k = 0, 1, \ldots m$

$$P\left(\frac{\nu}{m} \frac{1}{2\Delta t}\right) = \Delta t \left\{ R(0) + 2 \sum_{k=1}^{m-1} R(k) \cos 2\pi \frac{\nu}{2m} k + (-1)^{\nu} R(m) \right\} \tag{15}$$

for $\nu = 0, 1, \ldots m$

$$P\left(\frac{-\nu}{m} \frac{1}{2\Delta t}\right) = P\left(\frac{\nu}{m} \frac{1}{2\Delta t}\right)$$

$$\overline{P}\left(\frac{\nu}{m} \frac{1}{2\Delta t}\right) = \sum_{n=-i}^{i} a_n \, P\left(\frac{\nu - n}{m} \frac{1}{2\Delta t}\right) \tag{16}$$

where:

$X(t_n)$ = value of the variable of interest at time t_n

σ^2 = variance

Δt = time increment between discrete data values

N = No. of data values chosen for the analysis

a_n = smoothing window

The purpose of the window is to smooth the distortion caused by the finite, discrete data.

The smoothing window chosen for the calculation in this study was:

$$a_0 = 0.6398 \qquad a_2 = -a_2 = -0.061$$
$$a_1 = -a_1 = 0.2401 \qquad a_4 = -a_4 = 0.00 \tag{17}$$

REFERENCES

1. 1972 ASHRAE HANDBOOK OF FUNDAMENTALS.

2. K. S. Svetlov, "Calibration of Air Exchange in Multi-storey Buildings Using Electronic Computers", Vodosnabzenie i sanitarna tekhnika, Vol. 11, pp. 28-31, 1966.
3. P. J. Jackman, and H. Ph. L. den Ouden, "The Natural Ventilation of Tall Office Buildings", London, 1968.
4. J. Gabrielsson, and P. Porra, "Calculation of Infiltration and Transmission Heat Loss in Residential Buildings by Digital Computer", Journal of Industrial Heating Ventilating and Engineering, pp. 357-368, March 1968.
5. G. T. Tamura, "Computer Analysis of Smoke Movement in Tall Buildings", ASHRAE TRANSACTIONS, Vol. 75, Part II, pp. 81-92, 1969.
6. "Procedure for Determining Heating and Cooling Loads for Computerized Energy Calculations", ASHRAE, 1971.
7. D. R. Bahnfleth, T. T. Moseley, and W. S. Harris, "Measurement of Infiltration in Two Residences Part I: Technique and Measured Infiltration, Part II: Comparison of Variables Affecting Infiltration", ASHRAE TRANSACTIONS, Vol. 63, pp. 453-476, 1957.

8. C. W. Coblentz, and P. R. Achenbach, "Design and Performance of a Portable Infiltration Meter", ASHRAE TRANSACTIONS, Vol. 69, pp. 358-365, 1963.
9. C. W. Coblentz, and P. R. Achenbach, "Field Measurements of Air Infiltration in Ten Electrically Heated Houses", ASHRAE TRANSACTIONS, Vol. 69, pp. 358-365, 1963.
10. R. H. Elkins, and C. W. Wensman, "Natural Ventilation of Modern Tightly Constructed Homes", Paper presented at the American Gas Association - Institute of Gas Technology Conference on Natural Gas Research and Technology, Chicago, Illinois, February 28 - March 3, 1971.
11. L. Rubin, and R. Gittins, "The Use of Portable Gas Chromatograph and Tracer Gas Rapid Determination of Air Ventilation Rate", Panametrics Company Report.
12. P. J. Drivas, P. G. Simmonds, and F. H. Shair, "Experimental Characterization of Ventilation Systems in Buildings", Environmental Science and Technology, Vol.6 (7), pp. 577-666, 1972.
13. C. M. Hunt and D. M. Burch, "Air Infiltration Measurements in a Four-Bedroom Townhouse Using Sulfur Hexafluoride as a Tracer Gas", ASHRAE TRANSACTIONS, Vol. 81, Part I, 1975.
14. H. K. Malinowski, "Wind Effect on the Air Movement Inside Buildings", Paper presented at Tokyo Conference on Wind Loads, Toyko, Japan, September 6, 1971.
15. G. I. Taylor, Proceedings of the Royal Society of London, 164A, 476, 1938.
16. J. O. Hinze, Turbulence, McGraw-Hill Book Company, 1959.
17. G. M. Jenkins, and D. G. Watts, Spectral Analysis and Its Application, Holden-Day Publishing Company, 1968.
18. T. Tsuchiya, "Modeling Criteria for the Room Air Motion", Ph.D. Thesis, Tokyo University, 1970.

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TABLE 1 Infiltration Results

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
					Room A331						Room B322					
Test No.	Crack Width inches	Average Wind Direction	Average Wind Velocity mph	Average Wind Velocity at Dulles mph	C	n	Average ΔP in. H_2O	AC_{act} #/hr	AC_{sf} #/hr	AC_{ASHRAE} #/hr	C	n	Average ΔP in. H_2O	AC_{act} #/hr	AC_{sf} #/hr	AC ASHRAE #/hr
1	0.05	W	9.5	10.0	369.5	.603	--	0.26	--	1.34	298.5	.537	-.0065	0.54	0.51	1.10
2	0.05	N	4.0	6.0	369.5	.603	-.0052	0.15	0.37	0.47	298.5	.537	-.0002	0.70	0.08	0.44
3	0.05	WNW	13.1	10.0	369.5	.603	.0029	0.62	0.26	1.96	298.5	.537	.0102	0.79	0.65	1.58
4	0.05	SW	2.5	6.0	369.5	.603	-.0008	0.12	0.12	0.27	298.5	.537	-.0024	0.15	0.30	0.27
5	0.05	SE	5.2	9.0	369.5	.603	-.0014	0.32	0.17	0.64	298.5	.537	-.0003	0.22	0.10	0.59
6	0.05	S	6.0	6.0	369.5	.603	.0000	0.36	0.0	0.78	298.5	.537	-.0066	0.63	0.51	0.68
7	0.025	NE	3.3	5.0	198.3	.620	-.0025	0.069	0.12	0.18	176.2	.615	.0005	0.10	0.044	0.14
8	0.025	SSW	5.4	7.0	198.3	.620	.0043	0.15	0.16	0.33	176.2	.615	-.0128	0.20	0.31	0.25
9	0.025	ENE	9.3	11.5	198.3	.620	-.0038	0.18	0.15	0.66	176.2	.615	.0027	0.08	0.12	0.49

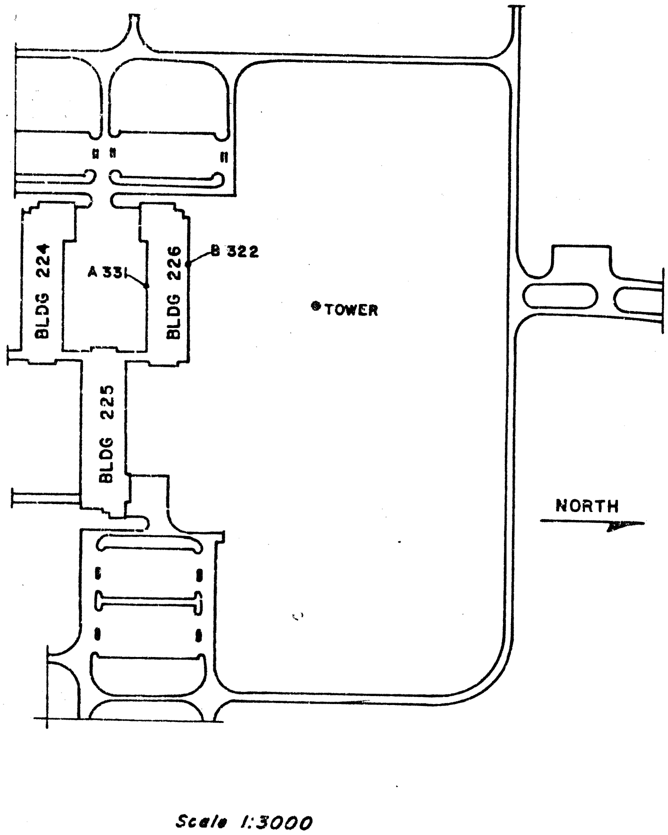


Fig. 1 Partial site plan of the National Bureau of Standards, Gaithersburg MD

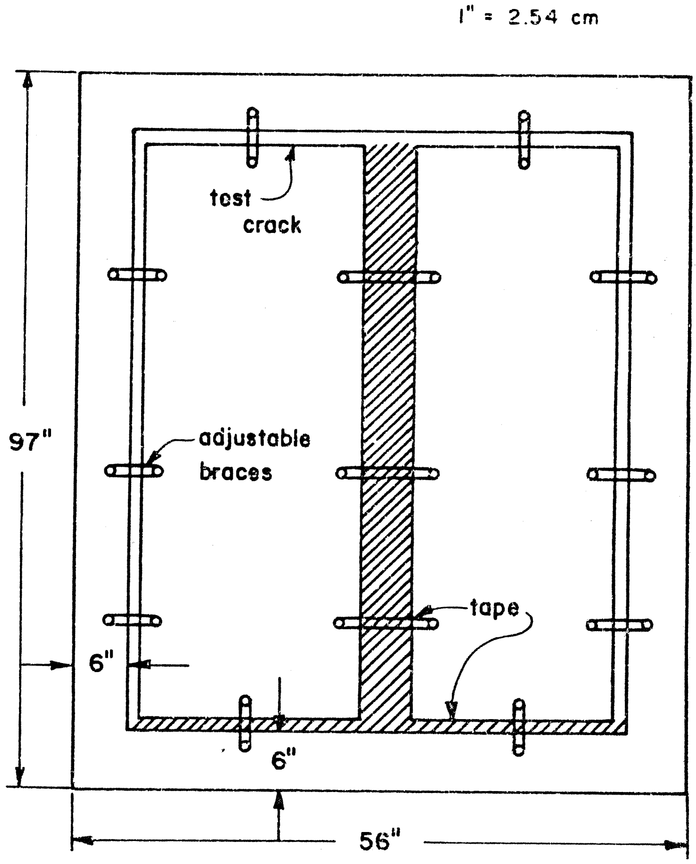


Fig. 2 Test window

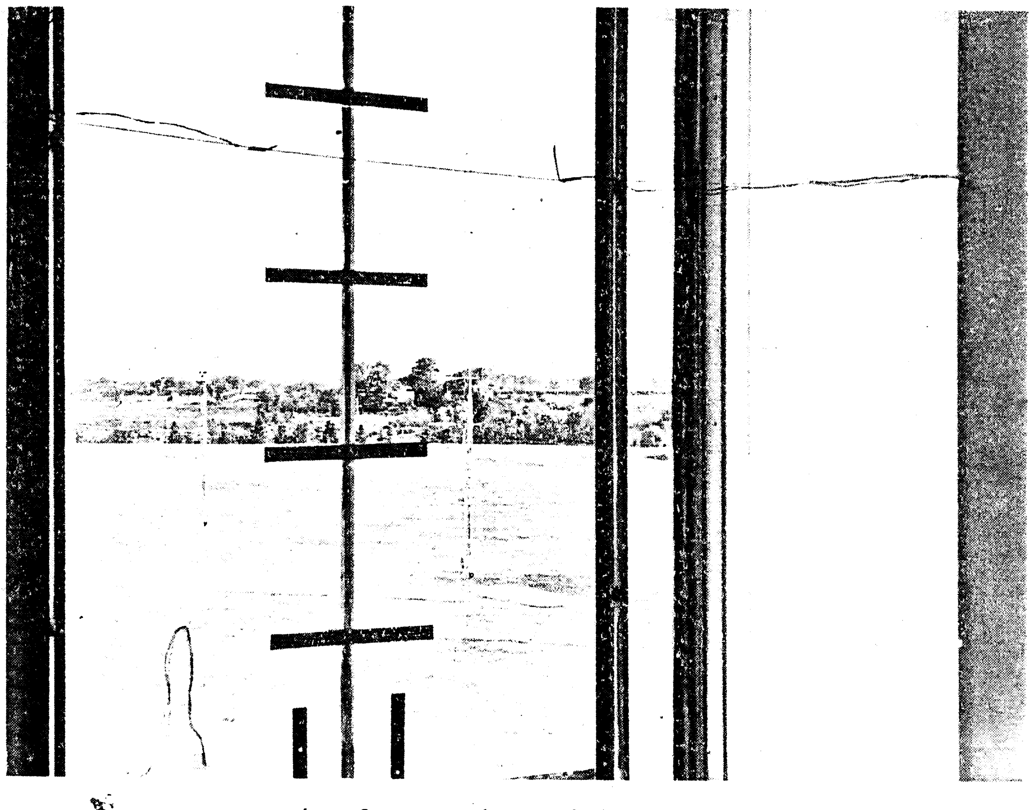


Fig. 3 Test window inserted in test room

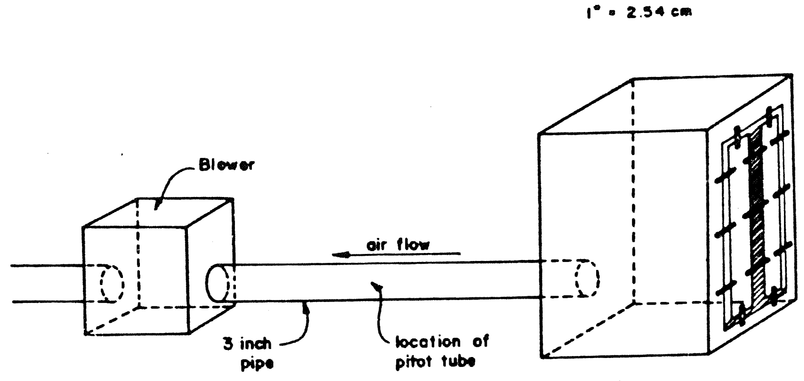


Fig. 4 Steady-state calibration apparatus for test windows

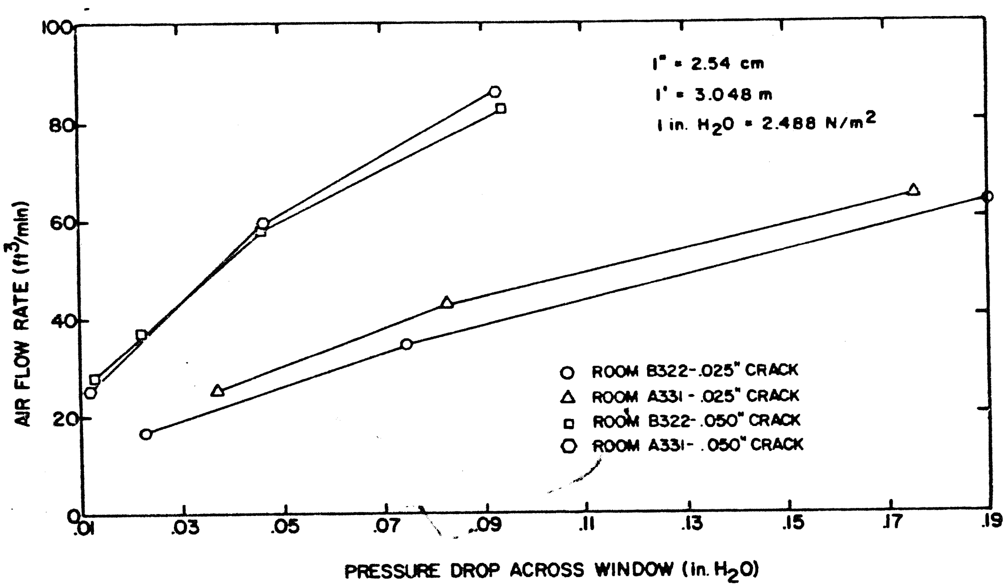


Fig. 5 Steady-state calibration curves for test window

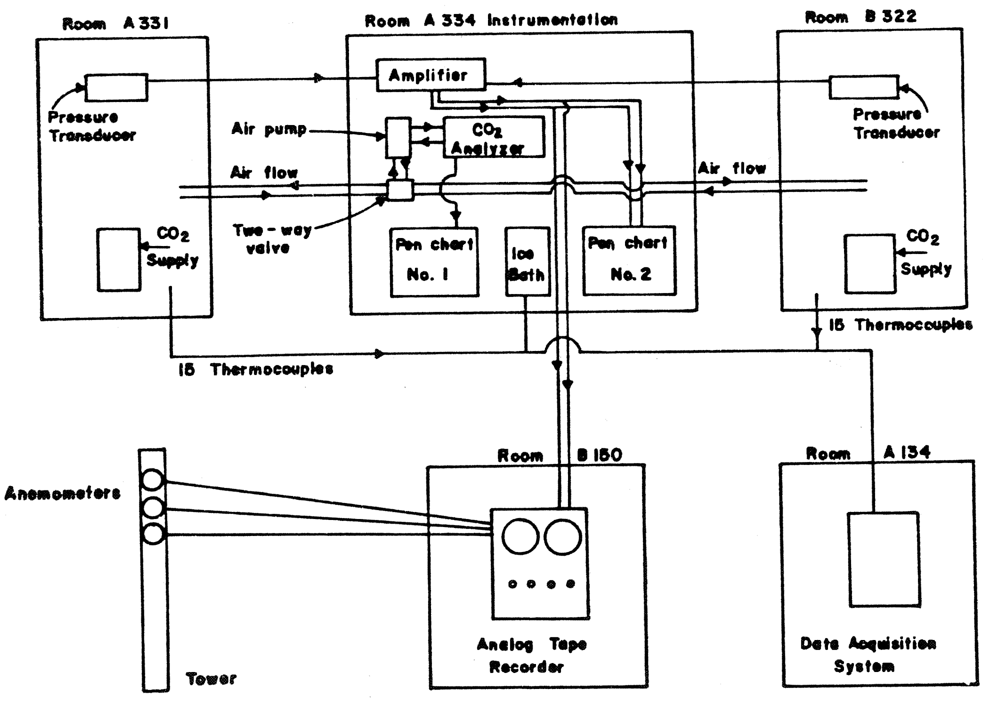


Fig. 6 Test equipment arrangement

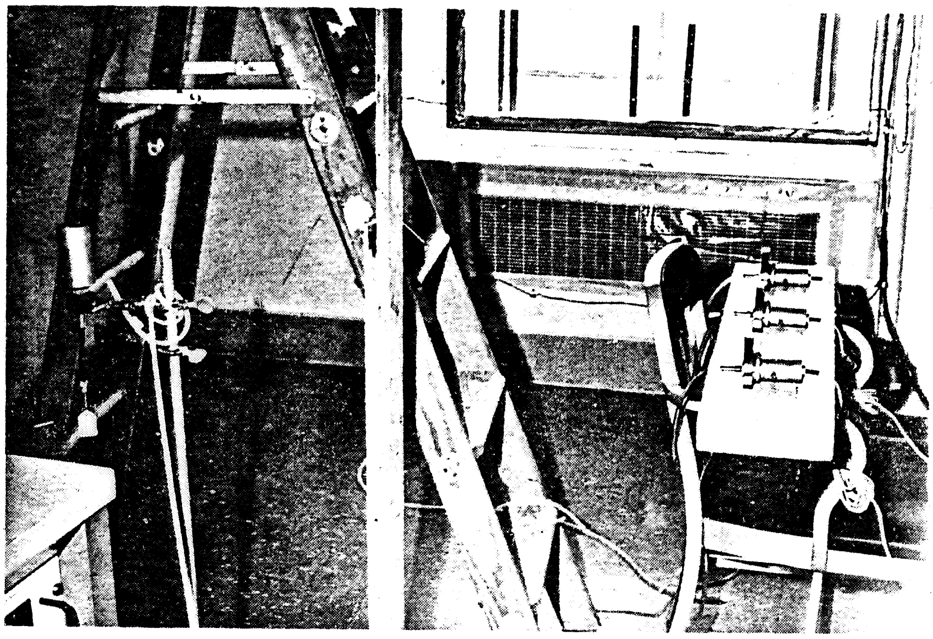


Fig. 7 Differential pressure transducers

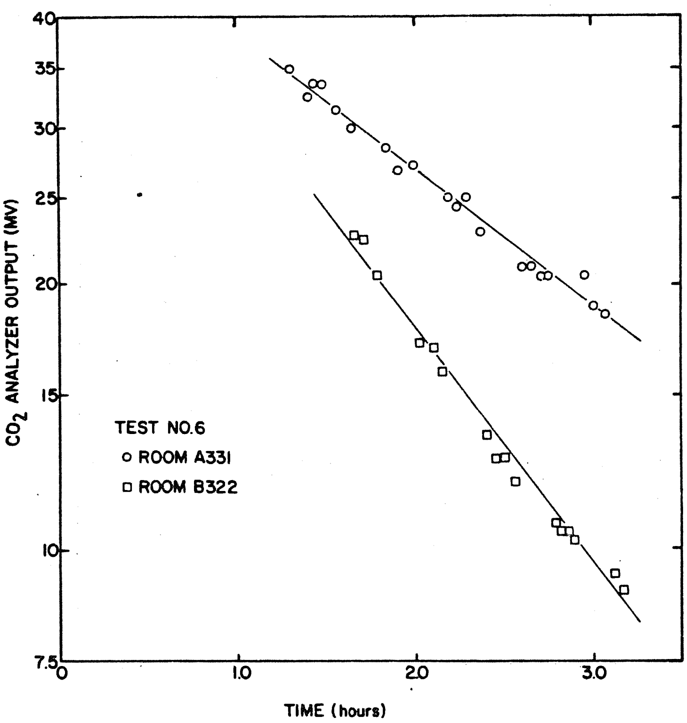


Fig. 8 Decay rate of CO_2 in test rooms for test no. 6

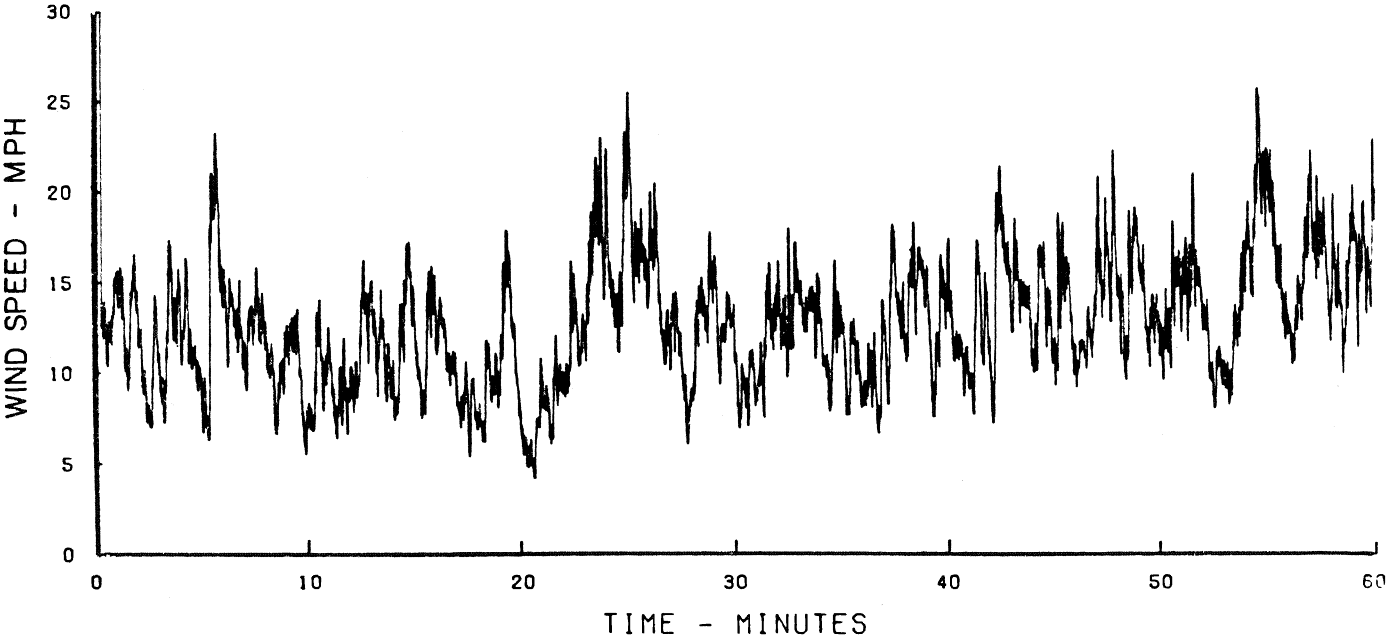


Fig. 9 Wind velocity for test no. 3

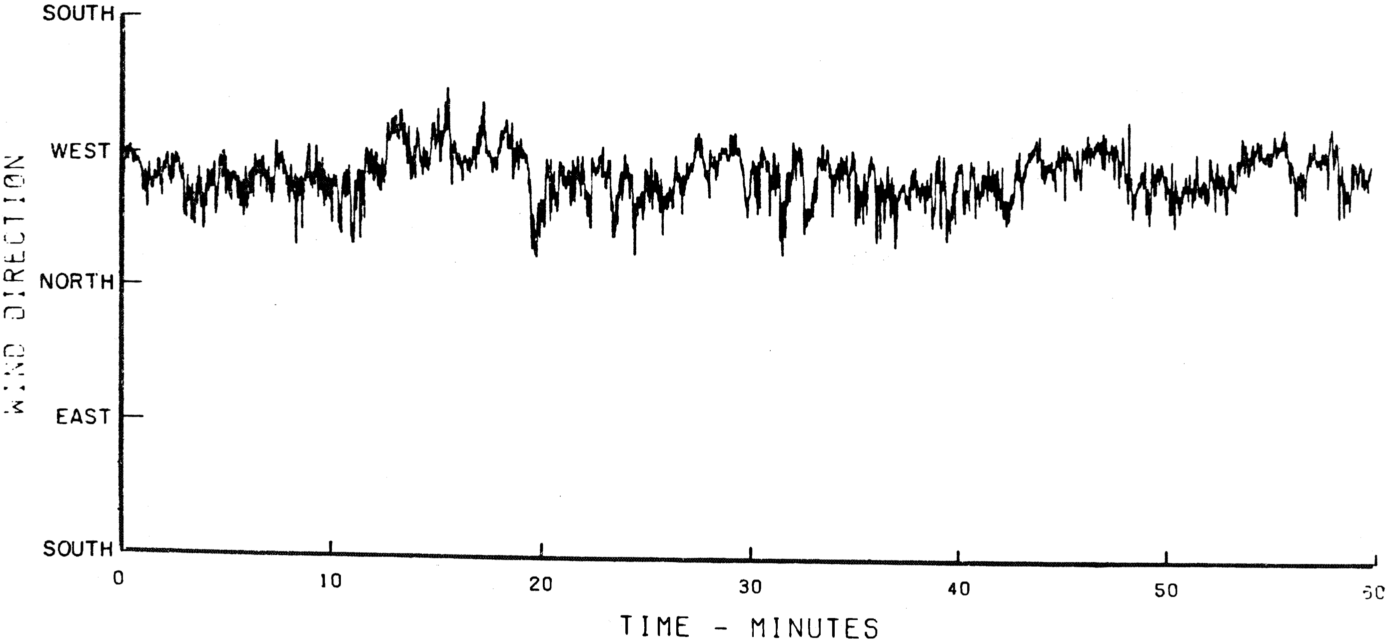


Fig. 10 Wind direction for test no. 3

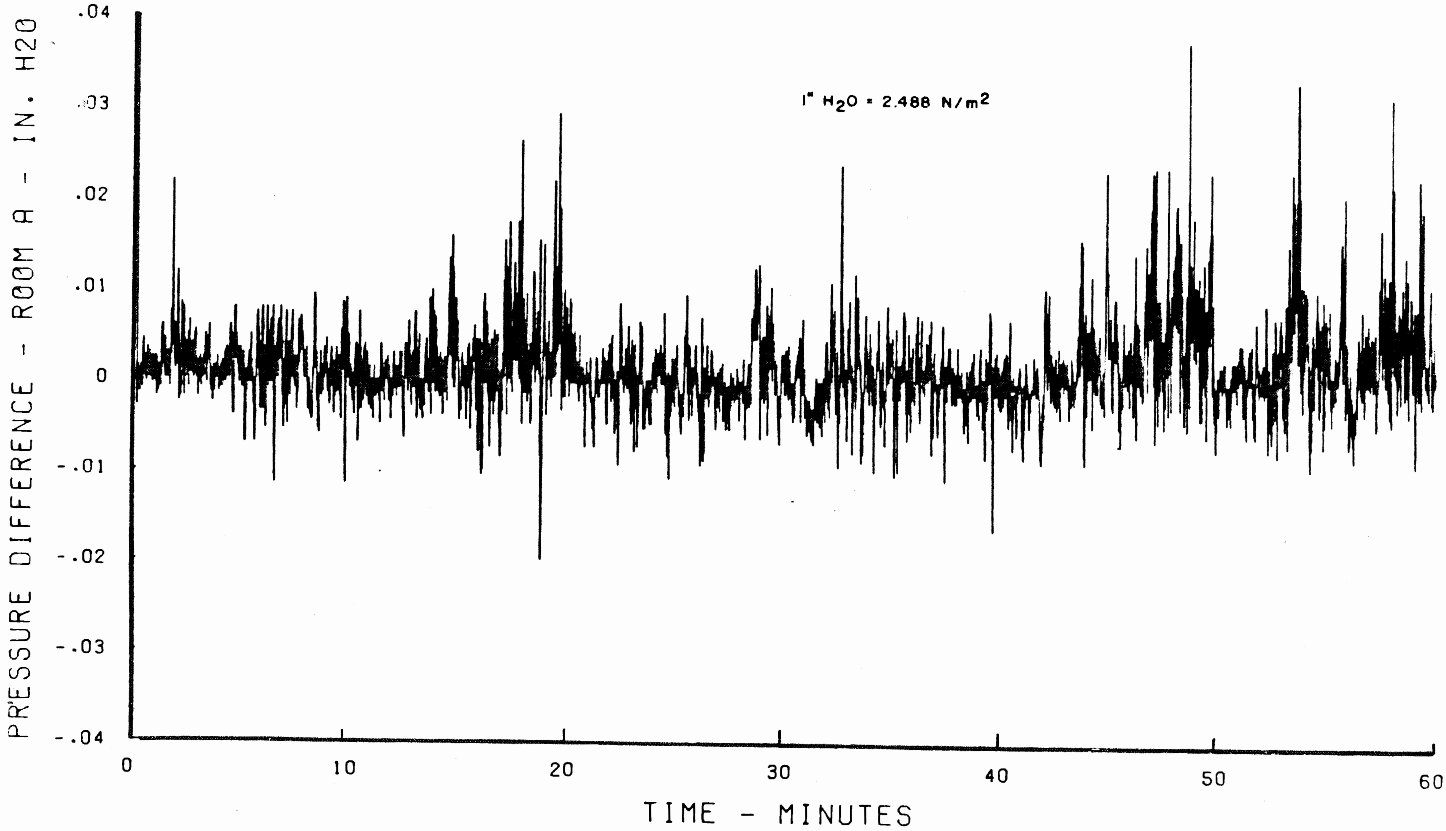


Fig. 11 Pressure difference across test window in room A331 for test no. 3

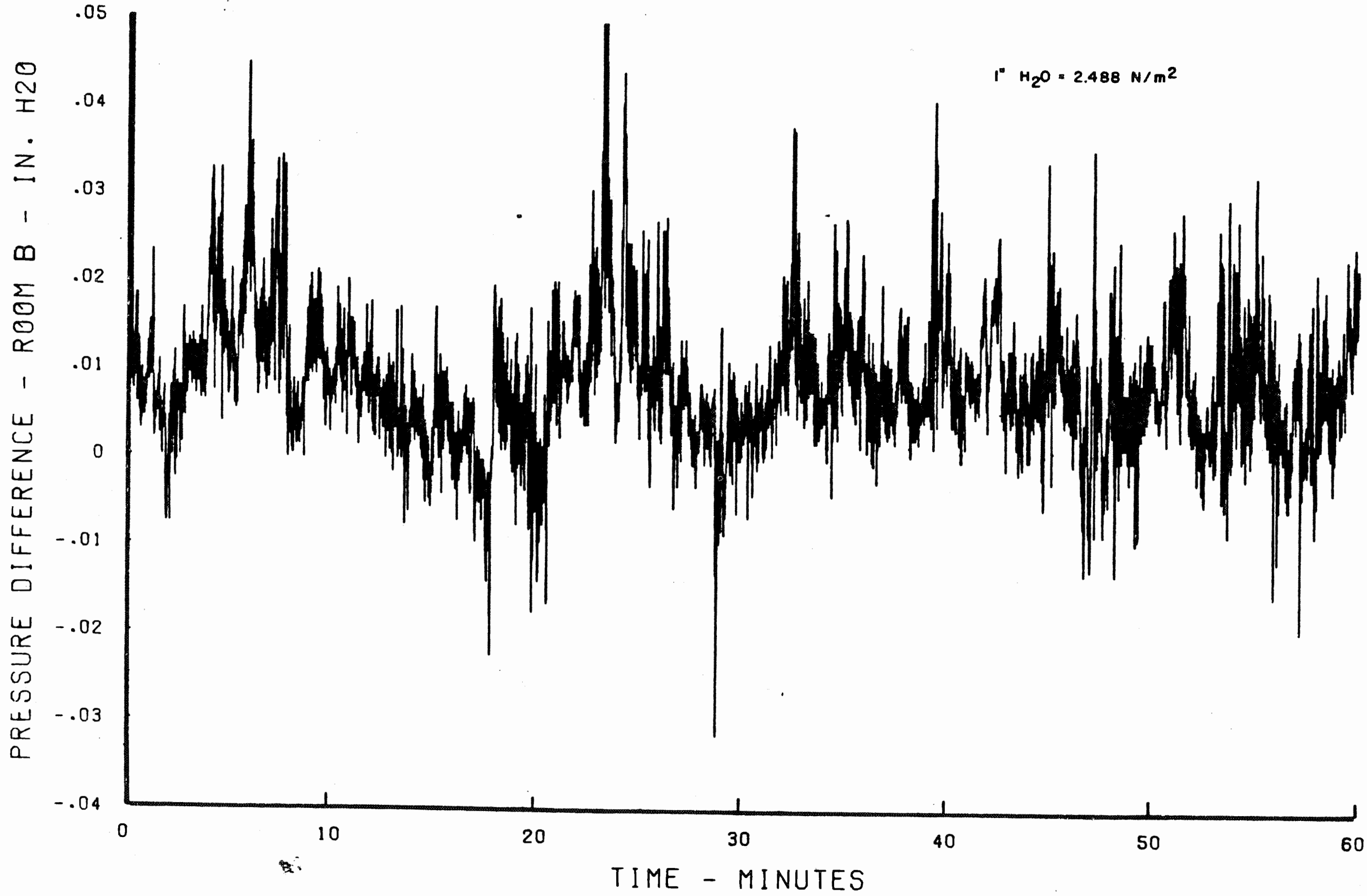


Fig. 12 Pressure difference across test window in room B322 for test no. 3

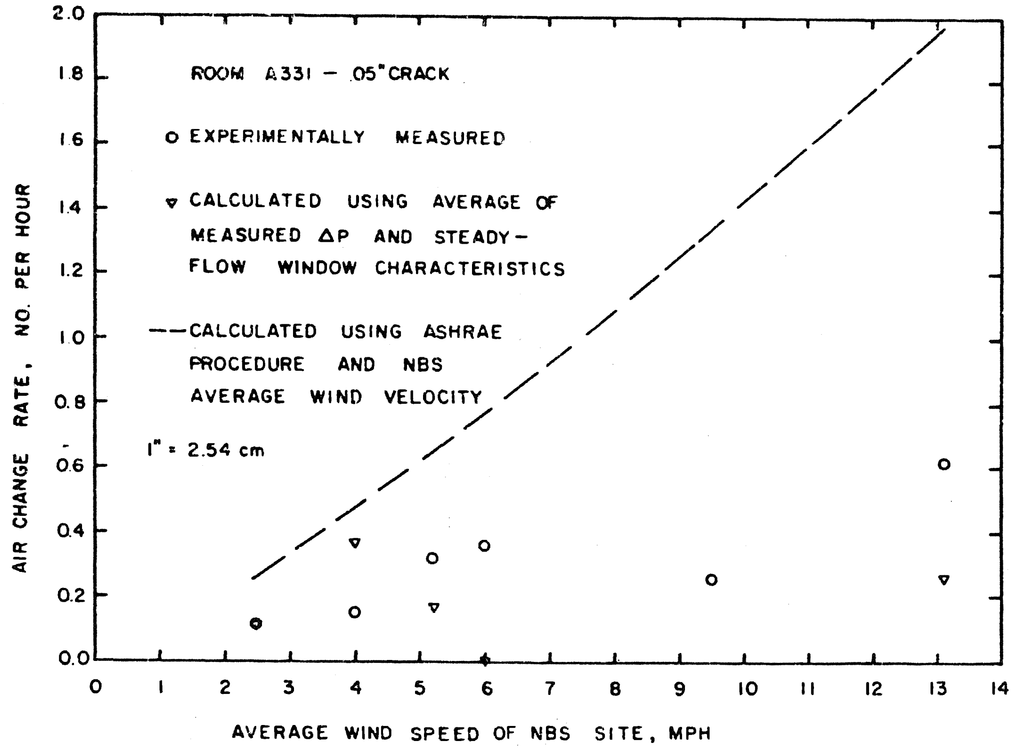


Fig. 13 Air change rate for room A331 with .05 inch crack in test window

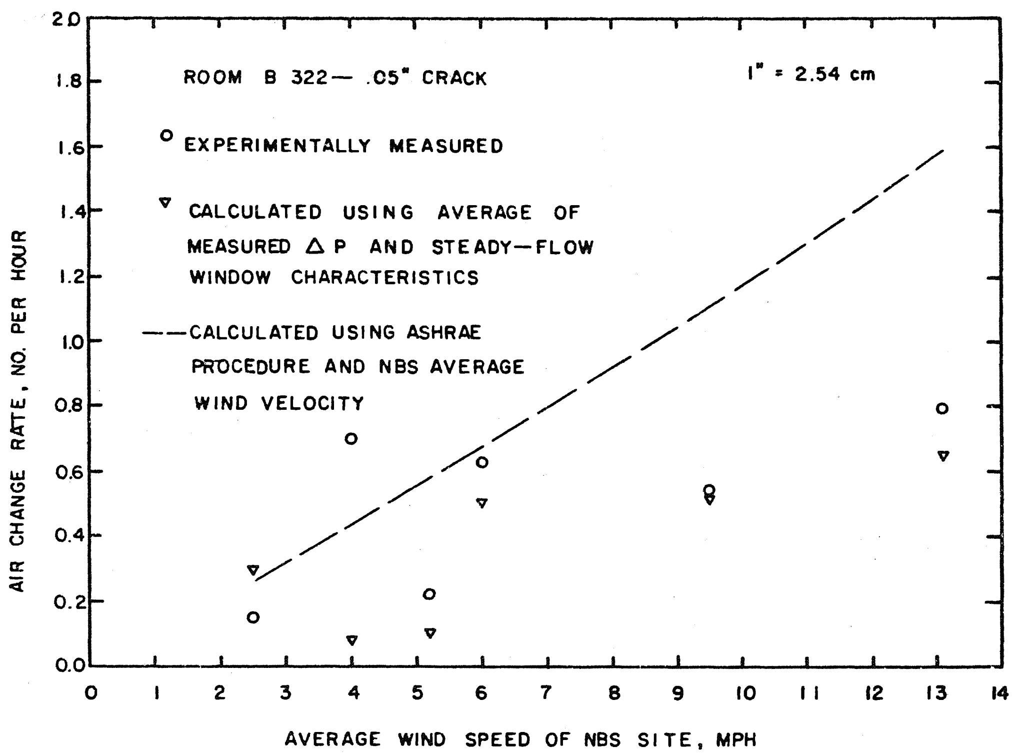


Fig. 14 Air change rate for room B322 with .05 inch crack in test window

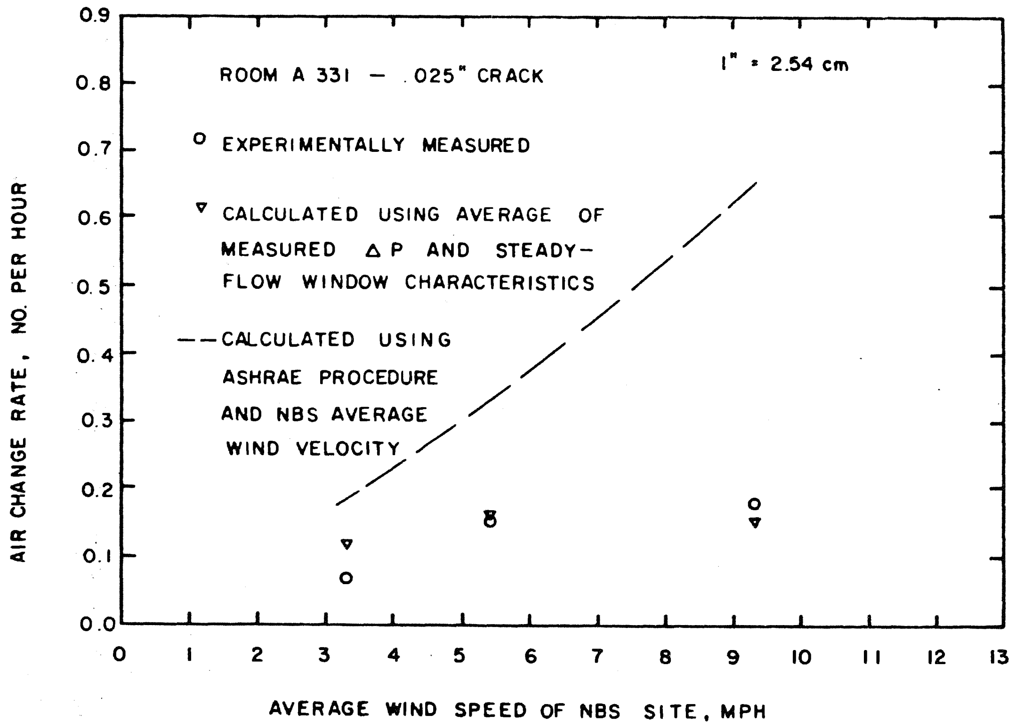


Fig. 15 Air change rate for room A331 with .025 inch crack in test window

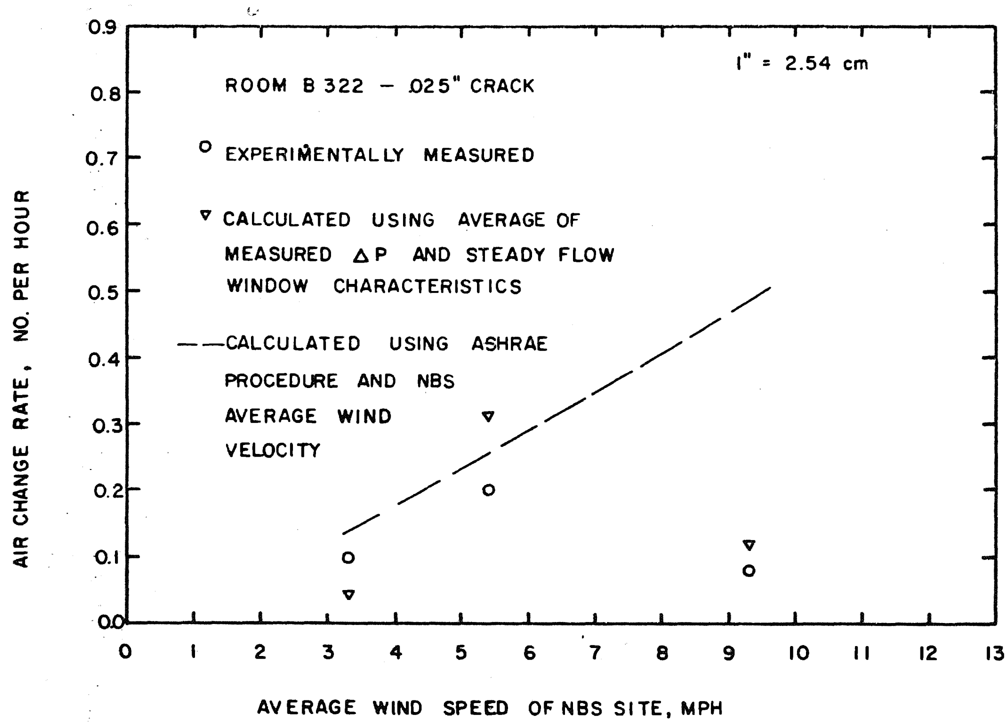


Fig. 16 Air change rate for room B322 with .025 inch crack in test window

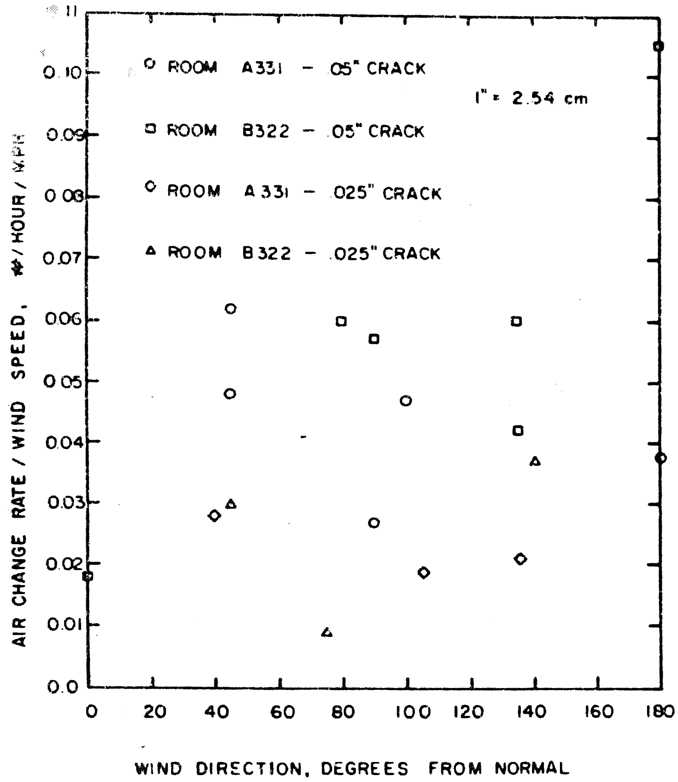
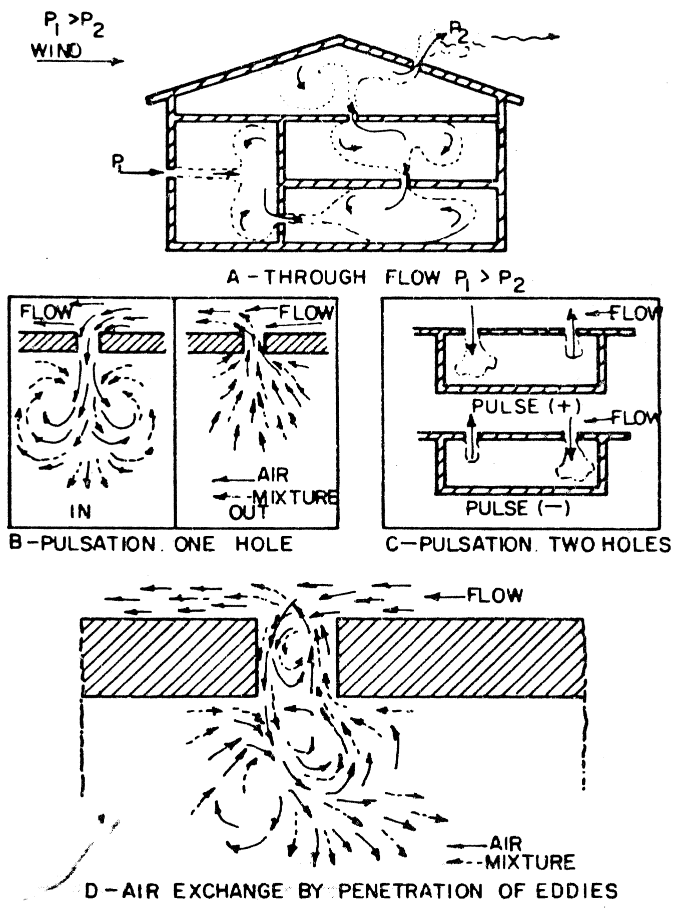


Fig. 17 Effect of wind speed and direction on air change rate



Adapted from reference [14]

Fig. 18 Conceptual view of air exchange process

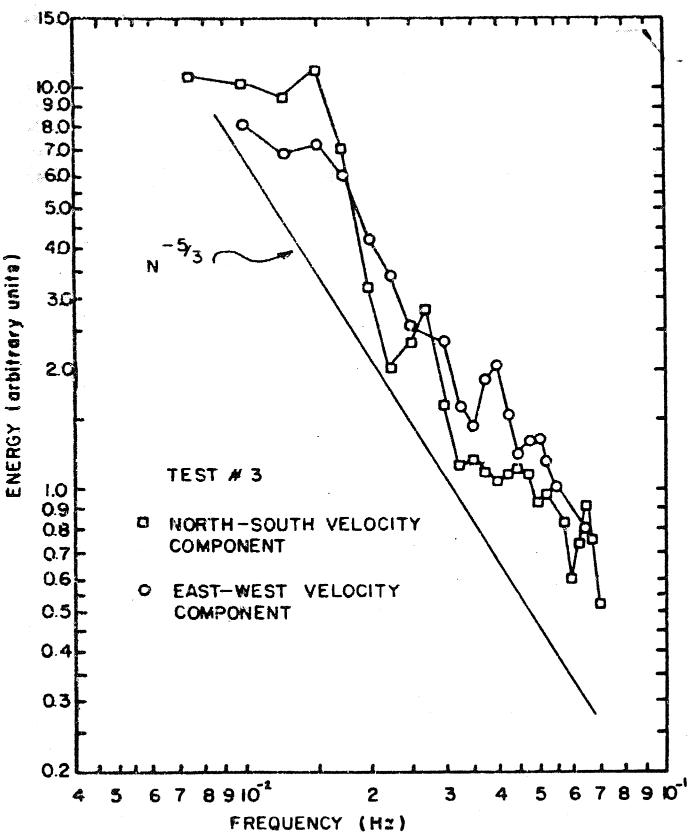


Fig. 19 Power spectrum for wind velocity components

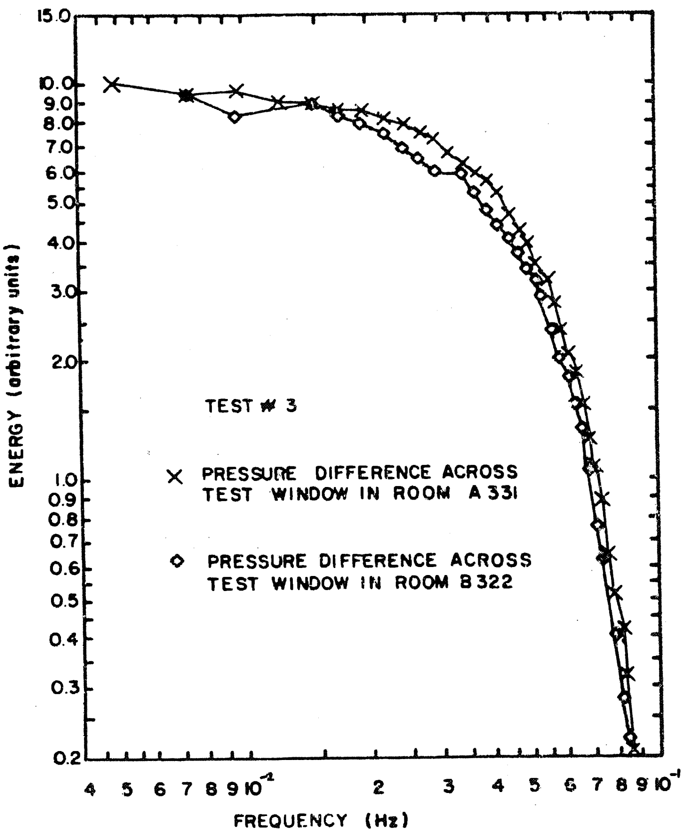


Fig. 20 Power spectrum for pressure differentials

DISCUSSION

ROBERT A. MACRISS (Institute of Gas Tech, Chicago IL): You showed that all your infiltration values were much lower than one would calculate by using the crack and ΔP method of ASHRAE at each windspeed level. Could the difference account in the fact that the sharp-edged, well-defined crack you created in the window does not approach the shape, roughness, etc., of actual cracks in houses in the field? Furthermore since the ASHRAE method has used data from actual field measurements, do you feel as I do that it represents more closely the level of infiltration in the field than your approach?

HILL: I think your observation is correct. Our enclosure was rather unrealistic in that no through flow was allowed to occur. However, our objective was not to validate the ASHRAE design method but rather to determine the relationship between the pulsations at the window cracks and the air movement through them.

PAUL R. ACHENBACH (National Bureau of Standards, Washington DC): This study essentially shows the effect of pulsating indoor-outdoor pressure difference caused by variable wind velocity on the air infiltration of an essentially air-tight room except for window cracks. The graphs show that there is an appreciable air exchange cause by pulsating pressure difference that increases with average wind velocity, but it is of a lower magnitude than would be determined by conventional calculation methods for a room having both interior and exterior cracks and openings.

HILL: I agree.

ARUN VOHRA (Fairfax Hospital, Falls Church VA): You have pointed out that the aerodynamics of air flow around a building is extremely complex and it is difficult to calculate the air leakage. Is infrared thermography a useful and practical tool to observe air leakage into and from a building?

HILL: It is a practical tool. We have used such equipment at the Bureau of Standards to find a significant leakage of hot air from one of our experimental residential buildings.