Wind pressure measurements on the Post Office Building, Confederation Heights, Ottawa

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WIND PRESSURE MEASUREMENTS ON THE POST OFFICE BUILDING, CONFEDERATION HEIGHTS, OTTAWA

by
W. A. Dalgliesh

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PREFACE

Wind load design information comes to the structural designer essentially from two sources. The meteorologist provides estimates of design wind speeds, and the aerodynamicist, by carrying out wind tunnel tests on scale models, provides conversion factors known as pressure coefficients by which the design pressure for a given building surface can be calculated from the dynamic pressure (kinetic energy) of the design wind. Most of the wind tunnels and testing methods that have been applied to the study of bluff building models have been adapted to this work without much change from aeronautical work on streamlined shapes.

The working theories developed for airfoil shapes provide analytical results which are in remarkably close agreement with experimental model results over a reasonably wide range of working conditions. The same is not true, however, in the case of flow around bluff bodies for which the drag force is greatly influenced by flow separation, and the resulting wake. The assumption is made that scale effects do not occur in the case of sharp-edged structures for which the separation points are fixed by the sharp edges, and in the absence of analytical methods, wind tunnel results are applied directly in the design of full scale structures.

It is surprising to discover that very little published information exists to check the agreement between actual wind pressures on full scale structures with calculations based on wind tunnel tests on small scale models. The need is apparent for full scale wind pressure measurements on actual buildings, not only to substantiate and modify wind tunnel techniques presently employed but also to investigate in some detail the effects of the turbulence of natural wind on buildings.

With this need in mind, the Division of Building Research, initiated in 1962, a project to measure wind pressure on buildings, beginning with a pilot study on a nine-storey office building in Ottawa. It is expected that ultimately these experiments will lead to improved recommendations to designers in Supplement No. 3 to the National Building Code.

The work now recorded in this Progress Report was possible only through the active and willing cooperation of many from outside the Division mainly concerned with the building that was the subject of this pilot study. The Post Office Department and Mr. W. H. Wilson, Deputy Minister, who use the building in question, kindly granted every necessary facility. For this assistance the Division is most grateful.

The Report records yet another in the long-standing and steadily developing series of cooperative studies carried out by the Division in association with the Department of Public Works, Canada. It is a special pleasure for the writer to record his personal appreciation, and that of the Division, of the continuing interest in and assistance with all such projects by Mr. Lucien Lalonde, Deputy Minister, and Mr. G. B. Williams, Senior Assistant Deputy Minister, in addition to members of their staff.

The author of the Report is a Research Officer in the Building Structures Section of DBR/NRC who is making a special study of wind action on buildings.

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Director

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With one or two notable exceptions, the knowledge of designers and builders of the late nineteenth century of wind loads on structures was rather vague. For example, the designer of the first Firth of Tay Railway Bridge had used a wind pressure of 10 psf. Following the collapse of this bridge under the combined loads of the weight of a crowded passenger train and the force of a heavy gale, the recommended pressure was abruptly changed to 120 psf. Since few systematic observations of wind pressures or wind effects had been made up to that time, it is not surprising that the pendulum should swing that much.

The development of aerodynamics in the last half-century has brought to building construction, almost as a by-product, extremely valuable advances in theory and experimentation in fluid mechanics. The wind tunnel became the chief tool in dealing not only with aircraft but also with wind loading problems of buildings and other structures. In contrast with this, the development of ways and means for measuring actual wind effects in nature on full-scale buildings has not advanced so rapidly. Until quite recently, designers and builders have not had much actual verification of current ideas on wind effects on buildings.

This situation has begun to change rapidly in the last decade. Full-scale observations have been recognized as being of great importance in answering some of the questions that have been raised concerning the applicability of model test results to full-scale and particularly to tall structures. Work has begun, particularly in Britain and Denmark, to fill this need. In Canada, the Division of Building Research of the National Research Council has started a research project in this field.

The measurement of wind pressures on buildings was first considered by the Division five years ago when discussions were held about the possibility of instrumenting the 34-storey C. I. L. House in Montreal, then being designed. While negotiations were under way for the installation in Montreal, it was suggested that some pilot work be done on a building in Ottawa in order to gain experience and an awareness of the problems involved.

Permission was readily obtained from the Department of Public Works and the Post Office Department to take some wind pressure measurements on the Sir Alexander Campbell (or Post Office) Building at Confederation Heights in Ottawa. The first installation of equipment was made in September 1962. Shortly after that, the first good wind storm was experienced. During the following year, six storms occurred that had wind speeds considered worth recording.

The results of this work, the lessons learned, and some ideas concerning future work are discussed in this first progress report.

OBJECTIVES

The design and analysis of full-scale structures are based largely on information obtained from investigations of reduced scale models in wind tunnels. Except for the obvious requirement of geometrical similarity between model and prototype, the nature of the modelling laws that should be followed has not been clear. One reason for uncertainty about the parameters to be simulated in order to achieve valid results seems to be a lack of information about conditions for the prototype with which to check model results.

The basic objective of the full-scale wind pressure measurements was, therefore, to supply some of the information about the prototype that is essential for a proper evaluation of wind tunnel results for building aerodynamics problems, and if necessary, for a restatement of modelling requirements.

Specific Objectives

1. To measure pressure differentials caused by the wind, along with the corresponding wind speed and direction;

2. To attempt the calculation of pressure coefficients, i.e., to determine the functional relationship between the kinetic energy of the wind, $\frac{1}{2}\rho V^2$ and the pressure differentials measured on the building and to compare these coefficients with those commonly used in design;

3. To search for evidence of the relatively severe local suction maxima sometimes indicated by model tests as occurring near corners where streamlines of flow separate from the building; and

4. To investigate the effect of wind gusts on the pressures and suctions on the building by taking continuous and simultaneous records for analysis using spectral estimation techniques developed by Blackman and Tukey(1) and others.

THE BUILDING AND THE SITE

The Post Office Building is a 9-storey reinforced concrete building, approximately 275 ft long in the east-west direction and 80 ft wide in the north-south direction. The height to the main roof is 113 ft, and a penthouse, set back on the main roof, rises an additional 22 ft.

Only the long walls have windows; the short end walls are solid brick (Figure 1). There are two "annexes" at the eastern end, the 2-storey Financial Building on the south and a 1-storey Provision and Stores Building on the north. As shown in Figures 2 and 3, the vicinity is fairly open for several hundred feet in most directions. The terrain beyond the open area could be classified as "suburban."

EQUIPMENT AND INSTALLATION

Wind pressure measurements on the walls of a building are made either by measuring the force, inward or outward, on panels of known size arranged on the walls, or by providing small orifices in the wall through which the exterior pressure is picked up and then measured (in relation to a suitable interior reference pressure) by a transducer. Since the building has openable windows, it was concluded that the easiest way to measure the pressure would be to provide an orifice through suitable plexiglass panels fitted into a window opening and to mount a transducer on the inside of each panel (Figure 4).

The transducer, consisting essentially of a thin diaphragm, converts the difference in pressure between two tapping points (such as the pressures outside and inside the wall) into an electrical signal which is conveyed by cable to a common recording station with one channel of amplifying and recording equipment for each transducer. Initially two sets of four transducers each which measure differential pressures in the ranges 0 ± 10 psf and 0 ± 40 psf were purchased. Later, a third set of four was added in the range 0 ± 20 psf.

A continuously varying signal giving the variation of pressure difference with time is recorded, the usable frequency range being from 0 to 5 or 10 cycles per second. The upper limit on frequency response is governed by the speed of the recording chart rather than the transducer or the recording galvanometer, both of which have much higher capabilities in this regard.

In the Post Office Building all twelve transducer signals were recorded simultaneously on a single strip chart. The signals were traced by light beam galvanometers using an ultraviolet light source writing on direct-print photographic paper. Development and handling of the records are discussed in Appendix A.

Wind speed was also recorded on the same chart as a continuous signal voltage from a small 3-cup anemometer mounted on a 40-ft mast on the main roof of the building. Wind direction was not recorded continuously in this pilot study. The direction of the wind relative to the building was, however, checked periodically by the operator of the recording equipment.

The transducers were mounted on plexiglass panels that fitted into the opening of the lower half of any openable window in the building (Figure 4). The transducer panels were installed in various locations on each of the two long walls in whatever pattern was thought to be of the most interest and value for each run. In all, four distinct arrangements were used. In the fourth and fifth runs the panel arrangements were the same, but the wind directions were different.

Outside air pressure was brought to the transducer through an orifice (inside diameter 1/8 in.) in the plexiglass panel and short length of flexible plastic tubing. The reference pressure was that pressure which happened to exist in the room where the particular transducer was located. A more detailed discussion of reference pressure will be given later in this report.

The equipment at the recording station included, in addition to the recorder, separate amplifiers for each transducer which provided an alternating current excitation at 5 volts and 3000 cycles per second to activate the transducer bridge and also contained balancing and calibrating potentiometers and resistors.

WIND STORMS

Of the records from the six wind storms during which useful observations were made, one set was unfortunately lost while attempting to process the record in "permanizing" chemical baths. The remaining sets of records are numbered as follows:

Run No.	Date	Average Wind Speed and Direction (Peak gust in brackets) Wind Speed	Wind Direction
1	28 Sept. 1962	38 (60)	Northeast
2	12 Oct. 1962	32 (56)	West-northwest
3	29 Dec. 1962	24 (42)	Northwest
4	30 Oct. 1963	24 (32)	Northwest
5	23 Nov. 1963	24 (58)*	Southwest

* On run No. 5, the anemometer at the Post Office Building was not functioning. The wind speeds and direction given here are from another anemometer located at the Division of Building Research about 7 miles away.

The procedure for taking wind pressure measurements required that an operator be ready to drive to the building and start the recording equipment whenever there was a good possibility of a wind storm. As the panels were already in place activating the equipment was all that was required at the time of recording, allowing 20 minutes for the amplifiers to warm up. Between storms panel positions were usually changed and made ready for the next storm. Visits between storms permitted the checking of each channel and transducer to verify proper balancing and calibration after the previous storm.

The maximum hourly wind speed recorded during the one year that readings were taken was about 38 mph. This compares favourably with the modal value for extreme annual hourly windspeed, which is 37 mph for Ottawa.

DETERMINATION OF WIND SPEED AND DIRECTION

Measurements of wind speed and direction are an indispensable part of a program to evaluate wind action on buildings. In model tunnel tests, it is usual to measure velocity at one point in the undisturbed flow, and to establish the direction by changing the orientation of the model. Every effort is made to have a uniform distribution of velocity horizontally and the vertical profile either is also constant or is plotted beforehand and assumed to be known. One reading each of speed and direction is normally sufficient to determine the wind characteristics for the usual purposes of model work.

The problem is much more involved with field measurements. For measurements on buildings within a city, complete knowledge of wind flow on the building would, in principle, be desirable. This would be extremely difficult to obtain even if several anemometers could be employed at the desired locations, in view of the complications added to the flow by the proximity of other structures. One may in practice often be limited to one speed and direction measurement obtained from a single anemometer, not because it is sufficient, but because more extensive siting arrangements are impractical.

A second major change encountered in the field is the difference in scale of turbulence compared with the turbulence in the wind tunnel which is normally on a much smaller scale with respect to building size. These difficulties can be partially countered by using statistical methods to correlate wind speeds and pressures.

The anemometer should preferably be as close to the building as possible, yet not close enough to it or to any other structure to have the readings systematically altered by the flow disturbance of the structure. The anemometer is often set up on a mast above the building itself. It may be advisable to take into account the time lag between the recorded wind speed and the various pressures in order to achieve the best correlation results.

ESTABLISHMENT OF AN INTERNAL REFERENCE PRESSURE

Wind pressure measurements on buildings are not absolute or barometric pressure measurements. In absolute terms, the conversion of the kinetic energy of strong winds to pressure amounts to less than 1 or 2 per cent of the total barometric pressure. The external pressures at various points on the Post Office Building were measured as differential pressures relative to the internal pressures at their respective locations. The chief merit of such measurements is that it gives directly the net wind pressure at each measuring point, which is of interest in determining net wind loads on windows or wall elements.

In scale model tests in the wind tunnel, external pressures on the model are all measured relative to a common reference pressure, the barometric pressure in the undisturbed airflow upstream of the model. Although this gives no information about internal pressures or the net load on individual wall or roof elements, it establishes the distribution of external pressures and gives the total external effect of the wind.

If the internal pressure could be considered uniform throughout a building, unaffected by heating, air conditioning or wind, and was approximately equal to the average barometric pressure in the undisturbed wind upstream of the building, the two approaches to reference pressure just described would give the same results. This, however, is not the case. The internal building pressure often differs significantly from the outside barometric pressure because of the operation of the mechanical equipment for air conditioning or ventilating. Moreover, whenever there is a difference in temperature from inside to outside, pressure differences result, and for high buildings in winter there is a considerable gradient in differential pressure with height between inside and outside pressures, due to the "chimney effect." These variations of internal pressure are being studied by the Building Services Section and are reported elsewhere (2). Finally, wind also affects the internal pressure of a building even when windows and doors are closed.

Because of the variability of internal building pressures from one part of the building to another, the disadvantages of direct differential measurements of pressures at each transducer location outweigh the one major advantage -- the direct determination of net wind loading at a point. Unless all external pressures are measured relative to a common reference it becomes very difficult to correlate wind pressures to wind speed squared.

One result, therefore, of the preliminary work carried out on the Post Office Building was the decision to change to a single reference pressure that would be as little affected by wind action as possible for all external pressure measurements. In subsequent measurements at C. I. L. House in Montreal, the reference side of each transducer on both measurement levels was connected by flexible plastic tubing to a common reference internal pressure which was the pressure in the false ceiling space of the 9th floor near the centre of the building.

SUMMARY OF WIND SPEEDS AND PRESSURES MEASURED

Wind speeds and pressures must be summarized for presentation because records were taken simultaneously and continuously from all transducers and from the anemometer. The complete records total several hours of recording and over 100 ft of chart length. Figure 5 shows a typical chart record 45 seconds in length. The eight pressure records are channels 6 through 13 and the wind speed record is channel 14. The grid lines, 1/10 in. apart, represent 2 mph divisions for speed and 0.5 psf for pressure. The average speed shown is about 20 mph.

The diagrams in Figure 6 show the locations of the transducers for each of the five runs. Positions are designated by a letter for the bay and a number for the floor. For example, the third transducer from the east end on the north side for run No. 1 is called D7 because it is in the 4th bay on the 7th floor. Points on the south wall have in addition the letter S. The diagrams for points on the south wall are drawn looking south, so that the left end is still the east end of the building.

Measurements were summarized by taking one or more "records" from each of the five runs. A "record" consists of a number of digital values of pressure or speed taken at regular intervals from the original strip charts. Average values and peak values were then taken for each record; they are tabulated in the second and third columns opposite transducer location in Tables I through V. The table numbers correspond to the numbers of the runs. Records are designated by small Roman numerals, i through ii, iii, iv or v as the case may be.

Most of the records were sampled manually at intervals of one minute (every 4 in. on the chart) and were used in correlating pressures to wind speeds squared. A total of 25 other records were made with the help of a Benson-Lehner OSCAR (Oscillographic SCAnning and Readout) with decimal converter. This automated the scaling of the value from the chart, the conversion to digital values, and the punching of the values on IBM cards, requiring only manual positioning of the coordinate cross-hairs over the point on the chart. The time interval for these 25 records (constant for any given set of records) varied from 0.25 to 1 sec, an interval of 1/16 in. on the chart.

Average wind speeds and standard deviations of wind speeds are given at the top of each table opposite the record descriptions.

RELATION BETWEEN WIND SPEED AND PRESSURE

The relation between wind speed and the kinetic energy of the wind is given by the formula:

$$P_v = \tfrac{1}{2} \rho V^2 \qquad (1)$$

where

P_v = velocity pressure of the wind

ρ = mass density of the air

V = wind speed.

P_v has the dimensions of pressure (FL^{-2}) and is variously referred to as velocity pressure, stagnation pressure, or dynamic pressure. It represents the maximum excess of pressure over ambient (barometric) pressure that can be caused by the wind on an obstructing surface. Pressure differentials (with respect to ambient pressure) over a building, model or prototype, are usually expressed as a proportion of the velocity pressure as follows:

$$C_{pi} = \frac{P_i - P_a}{P_v} = \frac{P_i - P_a}{\frac{1}{2}\rho V^2}. \qquad (2)$$

C_{pi} is a non-dimensional ratio called a pressure coefficient, and refers to the pressure condition over a specific area, or at a specific point.

Pressure differentials measured in the wake of a building, i. e., where there is a separation of flow from the building, are negative, indicating a pressure below ambient pressure. The possible range of values for the pressure coefficient is, therefore, $C_p \leq 1.0$. Pressure coefficients as low as -5.0 or -6.0 over small areas have been found in model tests.

Pressure Coefficients

The calculation of pressure coefficients from model test information is relatively straightforward. Pressure differential with respect to ambient pressure (static load) upwind of the model can be measured directly with the velocity pressure. The intensity of turbulence in "conventional" constant velocity wind tunnel tests is so low that the readings are steady enough to be used directly to compute C_p.

On the other hand, calculation of pressure coefficients from measurements on prototype structures is much more involved. In the first place, pressures cannot usually be measured relative to the ambient pressure of the undisturbed flow. As mentioned under the heading Establishment of an Internal Reference Pressure (p. 7), each pressure measured at the Post Office Building had its own reference pressure, which was affected by building pressurization, chimney action, and even its location in the building. Secondly, wind speed measured at one location some 45 ft above the main roof is hardly adequate to describe the oncoming flow. Finally, the level of turbulence is about 10 times that experienced in the wind tunnel, necessitating a statistical approach for relating measured speeds to measured pressure differentials.

Two different approaches were tried in order to extract the best possible estimate of pressure coefficients from the records available from the Post Office Building measurements.

Method I for computing pressure coefficients

Method I is basically the same procedure used in calculating pressure coefficients from wind tunnel records, except that allowance is made for the random component in both wind speed and pressure measurements. It was assumed that large variations in wind speed will affect both the anemometer and the pressure transducers, i. e., that large gusts will envelope the whole structure and can thus be treated as a change in velocity pressure.

As there will be smaller gusts superimposed on the large variations, some randomness must be accounted for in the calculation of pressure coefficients. This is done by taking several sets of readings, each giving a somewhat different value of pressure coefficient, and then determining the "best" value by a linear regression analysis of the records.

In the process of linear regression a linear function of the independent variable is found that fits a straight line to the data by minimizing the squared deviations of the dependent variable from the "regression" line. The equation of the line is:

$$P_i - P_{ri} = P_c + C_{pi} \cdot P_v \,. \qquad (3)$$

The dependent variable $(P_i - P_{ri})$ is the pressure at point i minus the reference pressure at point i(i. e., the internal pressure at that point). P_c is a constant pressure differential which represents the difference between the reference pressure at point i and the "true" reference pressure which is the static pressure in the undisturbed flow. C_{pi} is the pressure coefficient for point i and P_v is the velocity pressure.

Strictly speaking, C_{pi} should be written as the product of two factors, $C_h \cdot C_{pi}$, since the velocity pressure when averaged over a long enough interval increases considerably with increase of height above ground. This increase is less significant, however, as the averaging time decreases, and is true only on the average not at any particular instant. It was decided not to attempt to separate the height factor effect in the analysis because a whole range of gust sizes is involved in the regression and, therefore, no accurate estimate of the rate of increase of speed with height could be made (see Appendix B).

Linear regression analysis is widely used as a means for indicating whether there is a significant correlation between two variables. The measure of correlation normally used is the correlation coefficient, r. The square of r is the proportion of the total variance in the dependent variable that is assigned to, or "explainable by," the variance in the independent variable; significance levels can be established (depending on the number of sets of samples) for deciding whether r is large enough to indicate a real relation between the variables.

The object of linear regression analysis in computing pressure coefficients is somewhat different. The assumption in this case is that not only is there a significant correlation, but that the correlation is good enough to give a useful estimate of the actual parameters, P_c and C_{pi}. The correlation coefficient r is still a useful indication, however, as to how well this assumption fits the data.

The results of the Method I analysis are given in the appropriately headed columns of Tables I through IV. In some cases, correlation is nonexistent from a statistical point of view. In 80 per cent of the calculated values the correlation coefficient is less than 0.6. The correlation coefficient should probably be at least 0.8 and preferably greater than 0.9 before much confidence can be placed in the pressure coefficients so derived. Thus the necessity for an alternate approach.

<u>Method II for computing pressure coefficients</u>

Method II has essentially the same basic assumption, i.e., that the pressure at any instant is related to the velocity at that same instant and location by the equation:

$$P(t) = \tfrac{1}{2}\rho\, C_p^{*}\,(V(t))^2. \qquad (4)$$

P(t) indicates that the pressure differential is a function of time t and similarly the wind velocity V is a function of time. The pressure coefficient has an asterisk (C_p*) to distinguish it from the pressure coefficient derived by Method I.

The difference between Method I and Method II lies mainly in the way in which the data are handled to give the pressure coefficient. In Method II stress is laid on a correspondence between the total variance of wind speed and the total variance of pressure rather than a point-to-point correlation of the records. The following derivation of a formula for C_p* is based on the assumption that C_p* for point pressures is independent (or nearly so) of gust size. More will be said of this under the heading Relation Between Wind Pressure Spectra and Wind Speed Spectra (p. 24).

Derivation of C_p*

For convenience, substitute in Equation (4)

$$\tfrac{1}{2}\rho\, C_p^{*} = K. \tag{5}$$

Let V be the average velocity over a record length T

$$V = \frac{1}{T}\int_0^T V(t)\,dt. \tag{6}$$

Let the fluctuating component of velocity be v(t)

$$v(t) = V(t) - V \tag{7}$$

and for convenience,

$$v(t) = v.$$

Then the average pressure P is given by:

$$P = \frac{K}{T}\int_0^T (V + v)^2\,dt. \tag{8}$$

Note that V is independent of t whereas v is still a function of t.

Then

$$P = K\left(V^2 + \frac{2V}{T}\int_0^T v\,dt + \frac{1}{T}\int_0^T v^2\,dt\right). \tag{9}$$

By definition, the second term is zero, and the third term is the variance, σ_V^2, of the velocity. The coefficient of variance, $C = \sigma_V/V$, will be used as well to simplify the notation:

$$P = KV^2(1 + C^2). \tag{10}$$

Next, form the expression for the variance of the pressure, σ_p^2, in terms of K, v, V and C:

$$P(t) - P = KV^2\left(1 + \frac{2v}{V} + \left(\frac{v}{V}\right)^2 - 1 - C^2\right) \tag{11}$$

$$= KV^2\left(\frac{2v}{V} + \left(\frac{v}{V}\right)^2 - C^2\right) \tag{11a}$$

$$(P(t) - P)^2 = K^2V^4\left(4\left(\frac{v}{V}\right)^2 + \left(\frac{v}{V}\right)^4 + C^4 + 4\left(\frac{v}{V}\right)^3 - 4C^2\left(\frac{v}{V}\right) - 2C^2\left(\frac{v}{V}\right)^2\right) \tag{11b}$$

Pressure variance is given by:

$$\sigma_p^2 = \frac{1}{T}\int_0^T (P(t) - P)^2\,dt$$

$$= \frac{K^2V^4}{T}\int_0^T\left[C^4 - 4C^2\left(\frac{v}{V}\right) + \left(4 - 2C^2\right)\left(\frac{v}{V}\right)^2 + 4\left(\frac{v}{V}\right)^3 + \left(\frac{v}{V}\right)^4\right]dt. \tag{12}$$

This can be simplified by introducing the terms

$$m_3 = \frac{1}{T}\int_0^T v^3\,dt \tag{13}$$

$$m_4 = \frac{1}{T}\int_0^T v^4\,dt. \tag{14}$$

These are the third and fourth moments about the mean of the velocity.

Then substituting from (13) and (14) into (12) and regrouping:

$$\sigma_p^{\ 2} = 4C^2K^2V^2\left[1 - \frac{C^2}{4} + \frac{1}{C^2}\left(\frac{m_4}{4V^4} + \frac{m_3}{V^3}\right)\right]. \tag{15}$$

It is shown in Appendix C that the following algebraic identity is true:

$$\frac{m_4}{4V^4} + \frac{m_3}{V^3} = \frac{C^4}{4} + C^2\left(\frac{\sigma^2_{\ V^2}}{4V^2\sigma_V^{\ 2}} - 1\right) \tag{16}$$

in which $\sigma^2_{\ V^2}$ is the variance of the velocity squared, i.e.,

$$\sigma^2_{\ V^2} = \sigma_x^{\ 2}$$

where

$$x(t) = (V(t))^2.$$

Substituting in (15) from (16) the following is obtained:

$$\sigma_p^{\,2} = 4C^2 K^2 V^4 \left[\frac{\dfrac{\sigma^2}{V^2}}{4V^2 \sigma_V^{\,2}} \right] . \tag{17}$$

Set the quantity in brackets equal to a correction factor $\frac{1}{W^2}$:

$$\sigma_p^{\,2} = 4C^2 K^2 V^4 \left[\frac{1}{W^2} \right] \tag{17a}$$

$$= 4C^2 \left(\tfrac{1}{2} \rho \, C_p^{\,*} \right)^2 V^4 \left[\frac{1}{W^2} \right] . \tag{17b}$$

Finally,

$$C_p^{\,*} = \pm \frac{\sigma_p W}{2C \, P_V} . \tag{18}$$

In this case P_V is the average velocity pressure for the whole record of length T, σ_p is the standard deviation of the pressure, and C is the coefficient of variation of the velocity.

<u>Correction factor W</u>

The correction factor W was found to be close to unity for all the wind speed records chosen for calculating $C_p^{\,*}$. The actual values found are given in column 8 of Tables I to IV.

The nature of the correction factor can be demonstrated by rewriting W^2 in terms of moments (about the origin) of the wind speed distribution.

By definition,

$$W^2 = \frac{4V^2 \sigma_V^{\ 2}}{\sigma^2_{V^2}}$$

where

$$V^2 = \left(\frac{1}{N} \sum_{i=1}^{N} v_i \right)^2 = m_1^{\ 2}$$ (first moment about the origin, squared).

$$\sigma_V^{\ 2} = \frac{1}{N} \sum_{i=1}^{N} v_i^{\ 2} - \left(\frac{1}{N} \sum_{i=1}^{N} v_i \right)^2 = m_2 - m_1^{\ 2}$$

$$\sigma^2_{V^2} = \frac{1}{N} \sum_{i=1}^{N} v_i^{\ 4} - \left(\frac{1}{N} \sum_{i=1}^{N} v_i^{\ 2} \right)^2 = m_4 - m_2^{\ 2} .$$

These moments all refer to the population of wind speeds v_i.

Therefore

$$W^2 = \frac{4m_1^{\ 2} (m_2 - m_1^{\ 2})}{m_4 - m_2^{\ 2}} \qquad (18a)$$

Before anything more can be said about the value of W^2, some assumption must be made about the nature of the frequency distribution of wind speeds. For the population of wind speeds sampled at intervals during a 1- or 2-hr period of strong winds (during which time the mean is relatively constant, i. e., no trend in the mean), the assumption of a normal distribution is probably justified as a first approximation.

The moment-generating function for moments about the origin of a normal distribution is given by $M_x(\theta) = e^{\mu\theta + \left(\frac{\sigma^2\theta^2}{2}\right)}$ (3, p. 85). The k^{th} moment about the origin is given by the coefficient of the term $\frac{\theta^R}{R!}$ in the series expansion of $M_x(\theta)$:

$$M_x(\theta) = 1 + \theta(\mu) + \frac{\theta^2}{2!}(\sigma^2 + \mu^2) + \frac{\theta^3}{3!}(3\mu\sigma^2 + \mu^3)$$

$$+ \frac{\theta^4}{4!}(3\sigma^4 + 6\mu^2\sigma^2 + \mu^4) + \dots \qquad (18b)$$

By substituting from (18b) into (18a) W^2 can be expressed in terms of only two parameters, μ and σ which are the mean and standard deviation of the assumed normal population of wind speeds:

$$W^2 = \frac{4\mu^2\sigma^2}{4\mu^2\sigma^2 + 2\sigma^4}. \qquad (18c)$$

Recall the definition of coefficient of variation, i.e.,

$$C = \frac{\sigma}{\mu} \quad \text{or,} \quad C = \frac{\sigma_V}{V}.$$

Then W^2 can be reduced to a function of a single parameter, coefficient of variation of the wind speed as follows:

$$W^2 = \frac{1}{1 + \frac{1}{2}\frac{\sigma^2}{\mu^2}} \qquad (18d)$$

$$W^2 = \frac{1}{1 + \frac{1}{2}C^2} \cdot \qquad (18e)$$

The average coefficient of variation for the wind speed records is 0.184, giving a value for W of 0.992. The actual average value for W turned out to be 0.996 with a standard deviation of 0.01, in good agreement with the theoretical value.

Other distributions were tried, for example a parabolic distribution, a uniform distribution, and a right triangular distribution sloping down to the right (all limited distributions). The expressions for W^2 for these three cases (in terms of C) are as follows:

1. Parabolic : $W^2 = \dfrac{1}{1 + \frac{2}{7}C^2}$

2. Uniform (rectangular) : $W^2 = \dfrac{1}{1 + \frac{1}{5}C^2}$

3. Triangular : $W^2 = \dfrac{1}{1 - \frac{2\sqrt{2}C}{5} - \frac{7C^2}{20}}$

These examples suggest that in general W^2 has a limiting value of 1 as the variance goes to zero and that the convergence improves with symmetry and flatness of the distribution.

Explanation of Tables I to V

The results of pressure coefficient calculations by both Methods I and II are given for each of the first four runs in Tables I to IV. Table V contains only average and maximum pressures measured, as no wind speed record was taken at the Post Office Building during the fifth run.

The symbols heading Tables I to IV are the same as given in the derivation of the equations. Four figures of decimal precision are reported for ease in following the calculations made but they are not meant to imply 4-figure accuracy in the results. The close correspondence between the correlation coefficient r of Method I and the ratio C_p / C_p^* forms a check on the calculations and confirms the algebraic identities used in deriving the equation for Method II.

SPECTRAL ANALYSIS OF WIND SPEED AND PRESSURE RECORDS

Since "maximum calculated gust speeds" are used in design calculations, structures are usually designed to withstand a static load larger than the load that would result from the mean speed. The design static loading is considered to be equivalent in its effect on the structure to the effect of the actual fluctuating wind speed, which may be viewed as a steady component (mean speed) with a superimposed varying component.

The "equivalent static load" is usually thought of as resulting from a particular gust speed higher than the mean speed by an appropriate "gust factor." Choosing a gust factor also implies choosing a certain gust magnitude because gust speed increases as the averaging period decreases.

The choice of an appropriate gust factor is necessarily rather arbitrary without a knowledge of how gusts affect structures or what sort of gustiness makes up the varying component of the wind. In the past the gust factor selected has often been based on the "shortest" gust recorded by the particular anemometer used. Obviously this is not the best way of expressing gust speeds.

Spectral analysis is one way of investigating gustiness in the wind. Assumptions must be made that gusts occur randomly, that their statistical properties, if determined over a suitable time interval, are constant, and that these properties are independent of translations in time of the record origin. The methods of spectral analysis can then be used to give estimates of the amount of variance each gust size contributes to the total variance of the wind record, whether it be a record of speed or pressure.

Gust magnitude is most conveniently specified in terms of the "wave number," which may be thought of as the number of gusts occurring per unit length along the wind direction.

Another way of considering spectral analysis is to realize that it redefines the variable of interest (in this case, wind speed or wind pressure) and makes it a function of frequency instead of time. Wave number is the frequency divided by the mean wind speed.

The computational techniques used in doing spectral analysis on the wind records taken at the Post Office Building are those described by R. B. Blackman and J. W. Tukey (1). These or similar techniques have been used previously by many investigators working with wind records e.g., Panofsky and McCormick (4) and A. G. Davenport (5, 6).

Spectral density estimates based on records from each of the five runs made on five different dates are shown in Figures 7 to 11. Spectra for wind speeds and wind pressures recorded at the same time are shown together on all but the last of these figures. Figure 11, (run No. 5), also shows one spectrum of speed and one spectrum of pressure but in this case the speed record was taken at the Division of Building Research about 7 miles to the northeast because the anemometer at the Post Office Building had been damaged in an earlier storm.

The horizontal axis of each figure represents wave number in waves (gusts) per foot. The vertical axis represents the proportion of variance attributable to any particular "bandwidth" of frequency, or in the limit as the bandwidth becomes infinitesimally small, the "spectral density." In the case of plots of spectral density on a logarithmic frequency scale, it is necessary to multiply the ordinates (the spectral density) by their central frequencies to preserve the analogy between area under the spectral curve and proportion of variance attributable to gusts of a given size range.

Except for this proviso about the logarithmic scale, the ordinate scale in Figures 7 to 11 has been made nondimensional. All the spectral estimates were normalized by dividing by the total variance.

As "best fit" Davenport (5) has given an empirical curve having the following equation:

$$f(n/\bar{V}) = \frac{k(Cn/\bar{V})^2}{\left(1 + \left(Cn/\bar{V}\right)^2\right)^{4/3}}$$

where

> $n/\bar{V}$ is the wave number
>
> C is a constant (4,000 for $\bar{V}$ in ft/sec)
>
> k is another constant set by Davenport at 4.0.

This curve has a "cocked-hat" shape, and Davenport suggests that this is the shape of the spectral curve of horizontal gustiness near the ground in high winds. He has shown that spectra of wind records taken from different locations and having different total variances can all be reduced to a common vertical scale by a normalization procedure involving two parameters, a ground roughness parameter and the mean wind speed.

The reduced logarithmic spectral density according to Davenport is: $\dfrac{nS(n)}{k_z \bar{V}_z^2}$

where

> k_z is the roughness parameter for height z above ground,
>
> $\bar{V}_z$ is the mean wind speed at height z,

or, combining the two parameters into a single term called the friction velocity squared, the reduced spectrum is:

$$\frac{nS(n)}{k_z \bar{V}_z^2} = \frac{nS(n)}{V_*^2}.$$

These two parameters, k_z and V_*, are discussed further in Appendix B, where it is also pointed out that there are insufficient data to establish either k_z or V_* for any of the Post Office Building records except by judicious guessing.

It is of interest to compare the shapes of the spectral curves with Davenport's empirical curve, but in the absence of values for k_z or V_*, it seems appropriate in this instance to modify the empirical curve rather than to reduce the spectral density curves. This affects only the factor k of the empirical curve and is accomplished by equating the area under the empirical curve to unity.

The area under the experimental curves should also be unity, since all the estimates of density were divided by the total variance. The experimental curves will then have an ordinate scale comparable to Davenport's empirical curve:

$$\int_o^\infty \frac{nS(n)}{\sigma_V^2} d(\log n/\bar{V}) = \frac{1}{\sigma_V^2} \int_o^\infty S(n)\,dn = \frac{\sigma_V^2}{\sigma_V^2} = 1 \qquad (19)$$

$$\int_o^\infty \frac{k(Cn/\bar{V})^2}{\left(1 + (Cn/\bar{V})^2\right)^{4/3}} d(\log n/\bar{V}) = \frac{kC^2}{\bar{V}^2} \int_o^\infty \frac{n\,dn}{\left(1 + (Cn/\bar{V})^2\right)^{4/3}} = 1 \qquad (20)$$

Solve equation (20) for k: let $w = 1 + (Cn/\bar{V})^2$

$$\frac{k}{2} \int_1^\infty w^{-4/3}\,dw = 1 \qquad (21)$$

$$\frac{k}{2} \left[\frac{-3}{w^{1/3}}\right]_1^\infty = \frac{3k}{2} = 1 \qquad (22)$$

$$k = 2/3.$$

RELATION BETWEEN WIND PRESSURE SPECTRA AND WIND SPEED SPECTRA

The relation between the total variances of pressure and of speed was used to make estimates about pressure coefficients as previously described. It has been implied that the pressure coefficient is constant and does not depend on the wind speed or on the frequency of fluctuation of the wind speed. If this is so, then the ratio of spectral density for pressure to spectral density for speed should be approximately the same for all values of wave number (gust frequency).

Davenport calls this ratio, suitably normalized, the aerodynamic admittance when applied to force spectra and speed spectra, when force represents the wind pressure "drag" integrated over the area of a particular structure. He suggests that $|X(n/\bar{V})|^2$, aerodynamic admittance, is a decreasing function of wave number. Gust energy at higher wave numbers would be less effective because of reduced correlation over the whole surface of the structure. Davenport also suggests that this tendency might be opposed by an increase in the value of the pressure coefficient with wave number. Such an increase (with frequency) in the drag coefficient has been observed for truss members tested in wind tunnels and seems to be related to additional forces imposed by acceleration and deceleration of air masses (gusts) striking the structure.

The loss in correlation at high wave numbers could not, of course, be noticed in spectra of point pressures, but it is possible that the counter-tendency of increasing the pressure coefficient might occur.

Davenport (6) suggested normalizing force spectra by dividing by the average force as in the following equation:

$$\frac{n\,Sp(n)}{\bar{p}^{\,2}} = \left| X(n/\bar{V}) \right|^2 \cdot \frac{4n\,SV(n)}{\bar{V}^{\,2}} \cdot \qquad (23)$$

As has been mentioned in the section on spectral analysis, both pressure spectra and speed spectra in this report were normalized by dividing by the total variance.

For the "quasi-steady" case, $\left|X(n/\bar{V})\right|^2$ is unity, and equation (23) is equivalent to the expression derived for C_p^*:

$$C_p^* = \frac{\sigma_p}{\rho \bar{V} \sigma_V}$$

or,

$$\frac{\sigma_p}{(\frac{1}{2}\rho \bar{V}^2)} = \frac{4\sigma_V}{\bar{V}^2} .$$

(In this case, σ_p and σ_V, the total variances, represent the values of $nSp(n)$ and $nSV(n)$, respectively, integrated over the whole spectrum.)

The graphs plotted in Figure 12 on logarithmic paper are the ratios of pressure spectra to speed spectra for the six pairs of records from the Post Office Building. These ratios are functions of wave number described by:

$$f(n/\bar{V}) = \frac{nSp(n)}{nSV(n)} \left[\frac{\sigma_V^2}{\sigma_p^2}\right] . \tag{24}$$

The aerodynamic admittance is related to this function as follows:

$$\left|X(n/\bar{V})\right|^2 = f(n/\bar{V}) \left[\frac{\sigma_p^2}{\sigma_V^2}\right] \left[\frac{1}{\rho C_{p_o} \bar{V}}\right]^2 . \tag{25}$$

C_{p_o} here means the value of the pressure coefficient for steady wind, and so the terms in the square brackets can be considered a "scale factor" constant for all values of n/V (wave number). In fact, this scale factor is precisely the expression that was used to determine C_p^* and has been assumed approximately equal to unity!

Figure 12 appears to show a definite upward trend with increasing wave number in three of the six curves. At the low frequency end, since $|X(o)|^2 = 1$ by definition, f(n/V) should approach unity if the scale factor is in fact 1. Figure 12 indicates that, if anything, the scale factor should be somewhat less than 1, perhaps 0.7 or 0.8 to make the curves approach 1 for slowly varying gusts. This would mean an increase in C_p^* of about 10 or 15 per cent over the values already calculated.

CROSS-CORRELATION OF PRESSURES AT VARIOUS POINTS ON A BUILDING

Wind speed and pressure measured at a given point fluctuate because parcels of air (gusts) of various sizes are travelling at speeds different from the surrounding flow. Some gusts may be large enough to engulf a whole building whereas others are so small that when they strike one part of the structure their effect on the rest of the building is negligible.

Cross-correlation spectra were computed to determine the degree of correlation between pairs of pressures recorded at various separations as a function of wave number. Positively and negatively lagged products were computed for a range of lags, then treated with cosine and sine transforms, respectively, to give co-spectral and quadrature spectral estimates.

A measure of the cross-correlation as a function of wave number is given by the coherence, which is the sum of the squares of the co-spectral and the quadrature spectral densities. Figure 13 is a sample plot of the square root of coherence versus reduced frequency $nd/\bar{V}$, where d is the separation in feet of the two transducer locations.

Davenport has shown that the fall-off of correlation with reduced frequency can be approximated in the region of good cross-correlation by an exponential curve of the form:

$$\left| R(\Delta x) \right| = e^{\frac{-\Delta x}{C}} \qquad (26)$$

where x is the distance between the two points and $C = \bar{V}/kn$.

The term C is suggested by Davenport as a scale of turbulence, or an "effective gust width," and he points out that it is the distance to the centre of gravity of the correlation diagram. Reduced frequency, it should be noted, is the ratio of separation to gust wavelength.

Values for the factor k in the definition of the vertical scale of turbulence were determined from the cross-correlation spectra for the Post Office Building records. The results are given in Table VI. The column headed, $nd/\bar{V}$ or reduced frequency, indicates the cut-off point beyond which the cross-spectral densities were not included in the calculation of k.

The items in Table VI with an asterisk are those values of k for which the separation was vertical and for which the correlation between coherence and reduced frequency was 90 per cent or better. The average value of k for these selected points was 5.9, indicating a vertical scale of turbulence of approximately $1/6\ (\bar{V}/n)$, i.e., one sixth of the gust wavelength.

DISCUSSION OF RESULTS

(a) Wind Speeds and Pressures

The maximum mean speed that was measured occurred in run No. 1 (see summary on page 5). This value, 38 mph, is approximately the mode for annual maximum mean speed for the Ottawa area. The velocity pressure for a 38-mph wind is about 4 psf. It is not surprising, therefore, that the mean pressures measured at various points on the building were generally in the range 0 ± 2 psf. Attention should be drawn also to the fact that the mean pressures registered do not necessarily represent the full effect of the wind in view of the significance of reference pressure variations.

The velocity pressure for the peak gusts of 55 to 60 mph is about 10 psf; the highest gust pressure registered was about 7 to 8 psf. The same proviso that applies to internal or reference pressure also applies to registered gust pressures.

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These results may appear disappointing as an indication of what can be achieved by the relatively costly and difficult business of full-scale wind pressure measurements. The low "signal levels" and the difficulties of obtaining a satisfactory reference pressure are serious problems but not insurmountable. A realistic assessment can now be made of the degree of accuracy and/or precision possible and desirable in instrumentation, and methods have been devised to extract useful information from the records.

Record handling turned out to be a major problem. Once procedures have been established to obtain desired information and to handle observations, automatic recording on magnetic tape is recommended.

(b) Calculation of Pressure Coefficients

The results of the pressure coefficient calculations by the two methods can be compared in Tables I to IV. On the surface it may seem remarkable that the ratios of the values calculated by linear regression, compared with the corresponding values from Method II, are precisely the same as the correlation coefficients in each case. This is mainly a consequence of the relations used to define the two versions of pressure coefficient so that the agreement demonstrated is simply a cross-check on the calculations.

Under certain assumptions, however, this relation between C_p and C_p^* can be given a physical interpretation. If it is assumed that fluctuations in pressure are caused by wind and nothing else, and if pressure on the building and velocity pressure of the wind are assumed to be linearly related over the whole range of gust sizes, then there should in fact be 100 per cent correlation between simultaneous readings of building pressure and velocity pressure. Then the two methods of calculating pressure coefficient would yield the same result, but Method II would be considerably easier to use because no cross-products would need to be calculated. If these two assumptions are true, how can the low correlation be explained? Loss of correlation can be partly explained by the spatial separation between the wind sensor and the various pressure sensors. That is, even though the pairs of readings are recorded simultaneously, the readings are <u>not</u> simultaneous in the sense of registering the same wind effect. The same gusts do not reach all points at the same time, or even to the same degree. Some gusts are larger and some smaller than those required to be registered simultaneously, and in every case there will be some time lag or displacement if the wind sensor and the pressure sensor are not in the same vertical plane normal to wind direction.

Of course, this is not the only possible explanation for poor correlation. It evidently accounts for a large portion of it, however, as correlation in general improves as the pressure sensors are located nearer and nearer to the wind sensor, taking into account wind direction. Correlation could certainly be improved, in some cases, by shifting the records with respect to the wind speed record. This is apparent from cross-correlation diagrams, which all peak at some distance in time away from zero lag.

The application of Method II to the Post Office Building rests on an assumption that is open to question. It was assumed that the variance and speed at the wind sensor height are a close approximation to the variance and speed some 50 or 60 ft lower, at the heights of the pressure sensors. This is certainly not absolutely true, and the approximation is worse as the difference in height increases. It is suggested that the calculation of such "factors" or pressure coefficients does provide a useful and instructive comparison of the relative effect of a gusty wind over the face of the building. As pressure coefficients, the values will be artificially enlarged by any component of pressure fluctuation due to sources of disturbance other than the turbulence of the wind itself. If such disturbances are applied selectively to some areas and not to others, even the comparative value of the coefficients is impaired. In general, however, where other sources of pressure fluctuation are not apparent, or can be eliminated, Method II does provide a ready and more simple comparison than the linear regression analysis. Another consideration not to be overlooked is the possibility of non-linearities in the relationship of building pressure to velocity pressure as short gusts are considered.

Such a comparative study of pressure coefficients is shown in Figure 14 where the average values of C_p^* are given near the points of the building to which they apply.

(c) Spectral Analysis and Magnitude of Gusts

The spectral analyses of speeds and pressures appear to be in general agreement with Davenport's curve insofar as there is a fairly rapid decrease in energy from 5×10^{-4} to 5×10^{-2} waves/ft. The records were not long enough, however, to provide much information on the low frequency side of the spectral peak. It will be of considerable interest to define the low frequency side of the spectral curve. When and if suitable records can be taken, this will certainly be tried.

The purpose of cross-correlation spectral analysis is to find out something about the dimensions of gusts of various wave numbers. Davenport (7) has suggested that horizontal lateral correlation of the longitudinal velocity has a semi-scale of approximately $1/25(\bar{V}/n)$ and that the vertical lateral correlation has a semi-scale of $1/6(\bar{V}/n)$ to $1/8(\bar{V}/n)$.

The results of the cross-correlation of pressures measured for points arranged vertically in line on the Post Office Building appear to indicate a lateral scale in the vertical direction of about $1/6(\bar{V}/n)$. This is in agreement with Davenport's findings for velocity records.

Cross-correlations for points separated by a horizontal distance in most cases did not give a good "fit" to the exponential form of curve. This was particularly the case for large separations. In the case of run No. 1 where the horizontal separation was approximately 40 ft, the lateral scale of turbulence in one record was about $1/3(\bar{V}/n)$ and in the other, $1/6(\bar{V}/n)$. There is some difficulty in defining the separation in the case of horizontal separations when the wind direction is not perpendicular to the line joining the two points, and this may explain the large difference between the two results. In no case was the wind perpendicular to the windward wall so no useful comparison of semi-scales for horizontal lateral correlation can be made with Davenport's figure of $1/25(\bar{V}/n)$ for velocity.

CONCLUSIONS

Assessment of Results

The experiments in wind pressure measurements conducted at the Post Office Building and described in this report, have made it possible to establish basic procedures for verifying model test results obtained in wind tunnels aimed at providing wind load design criteria. The need for careful and rather involved measuring, recording, and analysing techniques, the importance of proper handling of reference pressure, and above all a recognition of the complete dependence on the weather were all clearly brought out.

The method of determining pressure coefficients presented in this report does not yet allow any definite conclusions in the comparison of field results with model results, but it does indicate that it may be possible to set up model experiments that will reproduce field conditions, based on the measurements taken on actual buildings. In other words, instead of going into the field and attempting to confirm or modify model results, the reverse and more logical procedure should be used - namely, selecting a model environment to simulate field results as closely as possible.

Recommendations

On the basis of the present results the following recommendations for further DBR work in this project can be made:

1. There should be a common reference pressure for all pressure transducers which should be vented in an area affected by the wind as little as possible. If the vertical connecting links are not kept at outside air temperature, corrections must be made for chimney effect (i. e., if inside and outside air temperatures differ when inside lines are used).

2. Every effort should be made to record wind pressure and direction, preferably at more than one height, and as close as is reasonably possible to the building being instrumented. Even if the velocity measurements are not absolutely satisfactory, they will be better than no wind measurements at all.

3. Continuous or frequently sampled records are important in order to extract the maximum possible amount of information from the measurements. Automatic recording in a computer-compatible format i. e., punched paper tape or magnetic tape, should be considered.

4. There are some indications that small orifice taps of pressure are satisfactory but further work should be done to determine what effect wall roughnesses such as mullions and louvres will have on the pressure patterns.

5. Some thought should be given to the instrumentation of flat and low-slope roofs which often show evidence of high local suctions, both in field experience and in model tests. The instrumentation has so far been confined to walls, and although pressure variance is appreciably greater near corners and on the windward sides, no strong evidence of extreme local suctions on walls has been found.

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TABLE I

WIND PRESSURE MEASUREMENTS AT POST OFFICE BUILDING

RUN # 1 DATE 28 Sept. 62

RECORD #	TIME	To	SAMPLING INT.	WIND (MPH)	σ	DIR.
i)	11:48	12:30	1 min.	32.2	5.2	N.E.
ii)	12:30	13:15	1 min.	34.4	5.7	N.E.
iii)	12:30	12:36	0.25 sec.	33.8	5.8	N.E.
iv)	12:36	13:15	1 sec.	38.5	8.1	N.E.
v)	____	____	____	____	____	____

Location	Rec. No.	Max. Press. psf	Ave. Press. psf	Method I P_c psf	Method I C_p	Method I r	Method II w	Method II σ_p psf	Method II C_p^*/w	Method II C_p^*	C_p/C_p^*	C_p^* Ave.
A7	i	+1.8 -1.3	-0.38	-0.45	+0.024	.0226	1.0294	0.8761	1.0142	1.0440	0.0230	
	ii	+1.5 -2.0	-0.77	-0.74	-0.0080	.0123	0.9754	0.6698	0.6652	0.6488	0.0123	
	iii	-2.6	-1.15	-0.43	-0.2331	.5075	1.0289	0.4477	0.4464	0.4593	0.5073	
	iv	-3.4	-0.71	-0.47	-0.0621	.1418	1.0069	0.6185	0.4335	0.4365	0.1423	.6472
B7	i	+1.7 -1.9	+0.17	-0.09	+0.094	.0920	1.0294	0.8581	0.9934	1.0226	0.0919	
	ii	+1.8 -1.6	+0.02	+0.11	-0.0281	.0412	0.9754	0.7052	0.7004	0.6832	0.0411	
	iii	-2.2	-0.55	-0.08	-0.1539	.2161	1.0289	0.6939	0.6918	0.7118	0.2163	
	iv	-3.1	-0.08	-0.12	+0.0117	.0204	1.0069	0.8113	0.5686	0.5725	0.0204	.7475
D7	i	+2.0	+0.24	-0.01	+0.094	.200	1.0294	0.3953	0.4576	0.4711	0.1995	
	ii	+0.8	+0.06	+0.03	+0.0098	.0346	0.9754	0.2848	0.2829	0.2759	0.0355	.3735
F7	i	+1.9	+0.17	-0.10	+0.101	.187	1.0294	0.4517	0.5229	0.5383	0.1876	
	ii	+0.7	+0.11	+0.11	+0.0019	.0106	0.9754	0.1849	0.1836	0.1791	0.0106	.3587
H7	i	+1.3	+0.12	+0.00	+0.043	.108	1.0294	0.3366	0.3897	0.4012	0.1072	
	ii	+0.4	+0.08	+0.19	-0.0366	.2258	0.9754	0.1667	0.1656	0.1615	0.2266	.2814
K7	i	+1.3	+0.08	-0.03	+0.041	.123	1.0294	.2816	.3260	.3356	.1222	
	ii	+0.6	+0.05	+0.24	-0.0618	.3436	0.9754	0.1855	0.1842	0.1797	.3429	.2576
L7	i	+1.3	+0.60	+0.19	+0.147	.455	1.0294	0.2717	0.3145	0.3237	0.4541	
	ii	+1.6	+0.65	+0.30	+0.1126	.4209	0.9754	0.2759	0.2740	0.2673	0.4212	.2955
A7S	i	-1.0	-0.60	-0.59	-0.004	.022	1.0294	0.1649	0.1909	0.1965	0.0204	
	ii	-1.0	-0.62	-0.46	-0.0518	.2981	0.9754	0.1792	0.1780	0.1736	0.2984	.1851

TABLE II

WIND PRESSURE MEASUREMENTS AT POST OFFICE BUILDING

RUN # 2 DATE 12 Oct. 62

RECORD #	TIME	To	SAMPLING INT.	WIND	MPH, σ	DIR.
i)	12:17	12:32	30 sec.	30.8	6.2	W.N.W.
ii)	12:42	12:58	25 sec.	31.7	5.6	W.N.W.
iii)						
iv)						
v)						

Location	Rec. No.	Max. Press. psf	Ave. Press. psf	Method I			Method II				C_p/C_p^*	C_p^* Ave.
				P_c psf	C_p	r	w	σ_p psf	C_p^*/w	C_p^*		
A7	i	-1.3	-0.84	-0.40	+0.1725	.6059	0.9864	0.2865	0.2886	0.2847	0.6060	
	ii	-	+0.62	+0.39	+0.0895	.3767	1.0037	0.2331	0.2366	0.2375	0.3768	.2611
A5	i	-1.4	-0.66	-0.16	+0.2071	.4659	1.0145	0.3807	0.4383	0.4447	0.4657	
	ii	-	+0.56	+0.36	+0.0762	.4509	1.0037	0.1658	0.1683	0.1689	0.4512	.3068
L7	i	-1.8	-0.84	-0.07	+0.2960	.5473	0.9864	0.5442	0.5481	0.5407	0.5475	
	ii	-	+0.50	+0.48	+0.00439	.00875	1.0037	0.4928	0.5002	0.5021	0.00874	.5214
L5	i	-2.0	-0.82	+0.33	+0.4457	.6622	0.9864	0.6772	0.6821	0.6728	0.6625	
	ii	-	+0.52	+0.052	-0.0001616	.0003417	1.0037	0.4641	0.4711	0.4728	0.0003417	.5728
A9S	i	+0.6	+0.53	-0.027	-0.0173	.2411	0.9864	0.0711	0.0716	0.0706	0.2449	.0706
L9S	i	+0.6	+0.13	-0.097	-0.0866	.5536	0.9864	0.1574	0.1585	0.1563	0.5543	0.1563
L7S	i	+0.7	+0.53	+0.38	-0.0556	.6046	0.9864	0.0925	0.0912	0.0900	0.6177	0.0900
L5S	i	+0.1	+0.0067	-0.020	-0.0103	.3965	0.9864	0.0253	0.0255	0.0252	0.4079	.0252

TABLE III

WIND PRESSURE MEASUREMENTS AT POST OFFICE BUILDING

RUN # 3 DATE 29 Dec. 62

RECORD #	TIME	To	SAMPLING INT.	WIND (MPH)	σ	DIR.
i)	18:28	18:45	0.5 sec.	24.3	5.1	N.W.
ii)	18:53	19:03	0.5 sec.	22.5	4.7	N.W.
iii)	19:20	19:35	30 sec.	25.6	3.9	N.W.
iv)	19:35	19:50	30 sec.	22.3	5.1	N.W.
v)						

Location	Rec. No.	Max. Press. psf	Ave. Press. psf	Method I			Method II					
				P_c psf	C_p	r	w	σ_p psf	C_p^*/w	C_p^*	C_p/C_p^*	C_p^* Ave.
L7	i	-2.5	-0.49	-0.11	+0.2264	.2627	1.0052	0.5832	0.8572	0.8617	0.2627	
	ii	-1.87	-0.51	-0.33	+0.08709	.1252	0.9301	0.4317	0.7481	0.6958	0.1252	
	iii	+1.2	+0.54	-0.03	+0.318	.540	0.9966	0.3167	0.5891	0.5871	0.5416	
	iv	+1.4	+0.49	-0.20	+0.4917	.8885	1.0095	0.3319	0.5491	0.5543	0.8871	.6747
L6	i	-2.4	-0.51	-0.19	+0.1918	.2338	1.0052	0.5551	0.8159	0.8202	0.2338	
	ii	-2.1	-0.57	-0.50	+0.05021	.07514	0.9301	0.4146	0.7185	0.6682	0.07514	
	iii	+1.0	+0.44	-0.11	+0.307	.543	0.9966	0.3047	0.5667	0.5648	0.5436	
	iv	+1.4	+0.46	-0.15	+0.442	.6943	1.0095	0.3810	0.6303	0.6363	0.6946	.6724
L5	i	-1.9	-0.37	-0.17	+0.1178	.1955	1.0052	0.4077	0.5993	0.6024	0.1956	
	ii	-1.3	-0.28	-0.24	+0.03026	.06366	0.9301	0.2949	0.5111	0.4754	0.06364	
	iii	+0.7	+0.30	+0.03	+0.150	.389	0.9966	0.2076	0.3861	0.3848	0.3898	
	iv	+0.8	+0.33	+0.01	+0.229	.626	1.0095	0.2196	0.3633	0.3667	0.6245	.4573
L3	i	-4.8	+0.14	+0.57	+0.2539	.2741	1.0052	0.6270	0.9216	0.9264	0.2741	
	ii	-1.2	+0.20	+0.15	+0.03548	.05437	0.9301	0.4048	0.7015	0.6525	0.05437	
	iii	+1.8	+0.94	+0.70	+0.134	.233	0.9966	0.3080	0.5729	0.5710	0.2347	
	iv	+1.5	+0.90	+0.44	+0.324	.5509	1.0095	0.3528	0.5837	0.5892	0.5499	.6848
L9S	iii	-0.8	-0.53	-0.32	-0.119	.531	0.9966	0.1213	0.2256	0.2248	0.5294	
	iv	-0.7	-0.47	-0.21	-0.189	0.709	1.0095	0.1596	0.2640	0.2665	0.7092	.2456
L7S	iii	+0.4	+0.23	+0.44	-0.115	.348	0.9966	0.1784	0.3318	0.3307	0.3477	
	iv	+0.6	+0.28	+0.34	-0.043	0.164	1.0095	0.1569	0.2596	0.2621	0.1641	.2964
L5S	iii	-1.2	-0.69	-0.40	-0.157	.409	0.9966	0.2074	0.3858	0.3845	0.4083	
	iv	-0.8	-0.58	-0.37	-0.150	.597	1.0095	0.1511	0.2500	0.2524	0.5943	.3184
L3S	iii	-0.5	-0.02	+0.30	-0.174	.594	0.9966	0.1578	0.2935	0.2925	0.5949	
	iv	+0.3	+0.05	+0.13	-0.057	.417	1.0095	0.08197	0.1356	0.1369	0.4164	.2147

,E IV

WIND PRESSURE MEASUREMENTS AT POST OFFICE BUILDING

RUN # 4 DATE 30 Oct. 63

RECORD #	TIME	To	SAMPLING INT.	WIND MPH	σ	DIR.
i)	9:00	9:16	1 min.	23.7	3.5	N.W.
ii)	9:30	10:00	1 min.	21.3	3.0	N.W.
iii)	10:03	10:33	1 min.	17.3	3.8	N.W.
iv)						
v)						

Location	Rec. No.	Max. Press. psf	Ave. Press. psf	Method I: P_c psf	Method I: C_p	Method I: r	Method II: w	Method II: σ_p psf	Method II: C_p^*/w	Method II: C_p^*	C_p/C_p^*	C_p^* Ave.
A7	i	+1.3	+0.78	+0.23	+0.3377	.5946	1.0417	0.2857	0.5450	0.5677	0.5949	
	ii	+1.3	+0.82	+0.43	+0.319	.473	0.9485	0.2396	0.7105	0.6739	0.4734	
	iii	+0.8	+0.44	+0.23	+0.251	.3478	0.9832	0.2563	0.7340	0.7217	0.3478	0.6544
A5	i	+1.4	+0.65	+0.49	+0.1006	.1479	1.0417	0.3425	0.6533	0.6806	0.1479	
	ii	+1.1	+0.60	+0.20	+0.330	.587	0.9485	0.2000	0.5931	0.5625	0.5867	
	iii	+0.8	+0.44	+0.18	+0.3245	.4353	0.9832	0.2648	0.7583	0.7456	0.4345	0.6629
B9	i	+2.2	+1.40	+0.73	+0.4103	.5672	1.0417	0.3642	0.6947	0.7237	0.5669	
	ii	+2.0	+1.16	+0.76	+0.328	.397	0.9485	0.2934	0.8701	0.8253	0.3974	
	iii	+1.4	+0.74	+0.40	+0.411	.5929	0.9832	0.2462	0.7050	0.6931	0.5930	0.7474
C7	i	+1.3	+0.79	+0.29	+0.3071	.5318	1.0417	0.2909	0.5549	0.5781	0.5312	
	ii	+1.3	+0.78	+0.38	+0.326	.439	0.9485	0.2640	0.7829	0.7425	0.4391	
	iii	+0.8	+0.53	+0.32	+0.252	.4065	0.9832	0.2202	0.6306	0.6200	0.4065	0.6469
D5	i	+1.7	+1.06	+0.70	+0.2201	.3354	1.0417	0.3304	0.6302	0.6565	0.3353	
	ii	+1.5	+0.88	+0.24	+0.524	.776	0.9485	0.2400	0.7117	0.6750	0.7763	
	iii	+1.2	+0.72	+0.47	+0.2990	.5377	0.9832	0.1975	0.5657	0.5561	0.5377	0.6292
E9	i	+2.0	+1.46	+0.80	+0.4036	.6184	1.0417	0.3286	0.6268	0.6530	0.6181	
	ii	+1.8	+1.08	+0.53	+0.446	.603	0.9485	0.2627	0.7790	0.7389	0.6036	
	iii	+1.4	+0.81	+0.43	+0.465	.6382	0.9832	0.2588	0.7411	0.7286	0.6382	0.7068
F7	i											
	ii	+1.3	+0.92	+0.51	+0.334	.576	0.9485	0.2059	0.6106	0.5791	0.5768	
	iii	+1.4	+0.64	+0.21	+0.521	.5965	0.9832	0.3102	0.8883	0.8734	0.5965	0.7263

TABLE IV (CONTINUED)

WIND PRESSURE MEASUREMENTS AT POST OFFICE BUILDING

RUN # 4 Cont'd. DATE 30 Oct. 63

RECORD #	TIME	To	SAMPLING INT.	WIND MPH	σ	DIR.
i)	9:00	9:16	1 min.	23.7	3.5	N.W.
ii)	9:30	10:00	1 min.	21.3	3.0	N.W.
iii)	10:03	10:33	1 min.	17.3	3.8	N.W.
iv)	____	____	____	____	____	____
v)	____	____	____	____	____	____

Location	Rec. No.	Max. Press. psf	Ave. Press. psf	Method I			Method II				C_p / C_p^*	C_p^* Ave.
				P_c psf	C_p	r	w	σ_p psf	C_p^* / w	C_p^*		
F5	i	+2.0	+1.46	+0.68	+0.4775	.7655	1.0417	0.3140	0.5989	0.6239	0.7653	
	ii	+1.8	+1.26	+0.69	+0.4655	.662	0.9485	0.2500	0.7414	0.7032	0.6620	
	iii	+1.5	+1.03	+0.61	+0.509	.5976	0.9832	0.3025	0.8663	0.8517	0.5976	0.7263
J9	i	+2.2	+1.41	+0.31	+0.6784	.7666	1.0417	0.4455	0.8498	0.8853	0.7663	
	ii	+1.8	+1.12	+0.58	+0.444	.590	0.9485	0.2680	0.7947	0.7537	0.5891	
	iii	+1.5	+1.01	+0.49	+0.631	.6763	0.9832	0.3314	0.9490	0.9330	0.6763	0.8573
L5	i	+2.6	+1.87	+0.87	+0.6103	.7595	1.0417	0.4045	0.7716	0.8038	0.7593	
	ii	+2.2	+1.49	+0.99	+0.413	.526	0.9485	0.2789	0.8271	0.7845	0.5264	
	iii	+1.8	+1.28	+0.47	+0.616	.5928	0.9832	0.3691	1.0570	1.0392	0.5928	0.8758
L7	i	+1.7	+0.80	+0.33	+0.307	.6478	1.0224	0.2044	0.4668	0.4773	0.6433	
	ii	+2.2	+1.38	+0.57	+0.665	.716	0.9485	0.3306	0.9804	0.9299	0.7151	
	iii	+1.9	+1.08	+0.41	+0.822	.6180	0.9832	0.4724	1.3528	1.3300	0.6180	0.9124
L7S	i	-0.6	-0.29	+0.22	-0.2828	.5885	1.0417	0.2419	0.4614	0.4807	0.5883	
	ii	-0.5	-0.21	0	-0.206	.634	0.9485	0.1153	0.3419	0.3243	0.6352	
	iii	-0.4	-0.14	-0.05	-0.173	.4620	0.9832	0.1330	0.3809	0.3745	0.4619	0.3932
F-7S	i	-0.4	-0.29	-0.05	-0.1430	.7026	1.0417	0.1025	0.1954	0.2036	0.7024	
	ii	-0.4	-0.25	-0.08	-0.111	.405	0.9485	0.0975	0.2891	0.2742	0.4048	
	iii	-0.4	-0.19	0	-0.175	.5197	0.9832	0.1196	0.3425	0.3367	0.5198	0.2715

TABLE V

WIND PRESSURE MEASUREMENTS AT POST OFFICE BUILDING

RUN # 5 DATE 23 Nov. 63

RECORD #	TIME	To	SAMPLING INT.	WIND	MPH, σ	DIR.
i)	9:47	10:12	1 min. (1 sec.)	____	____	____
ii)	10:30	10:50	1 min. (1 sec.)	____	____	____
iii)	11:35	11:55	1 min. (1 sec.)	____	____	____
iv)	____	____	____	____	____	____
v)	____	____	____	____	____	____

Location	Rec. No.	Max. Press. psf	Ave. Press. psf	Location	Rec. No.	Max. Press. psf	Ave. Press. psf
A7	i	-2.0	-1.12	F5	i	-2.2	-1.58
	ii	-2.0	-1.31		ii	-3.0	-1.66
	iii	-1.0	- .51		iii	-1.7	-1.40
A5	i	-1.5	-1.02	J9	i	-1.9	-1.35
	ii	-2.0	-1.27		ii	-2.8	-1.64
	iii	- .9	- .43		iii	-2.9	-1.34
B9	i	-4.5	-1.97	L5	i	-2.0	-1.43
	ii	-2.2	-1.30		ii	-2.5	-1.52
	iii	-1.5	- .68		iii	-1.8	-1.12
C7	i	-2.0	-1.46	L7	i	-2.0	-1.44
	ii	-2.8	-1.64		ii	-2.8	-1.64
	iii	-1.8	-1.02		iii	-2.2	-1.45
D5	i	-1.9	-1.38				
	ii	-2.5	-1.46				
	iii	-1.4	- .80				
E9	i	-3.9	-2.13	L7S	i	+7.0	+1.84
	ii	-2.8	-1.60		ii		+1.78
	iii	-1.9	-1.15		iii		+2.45
F7	i	-2.0	-1.46	F7S	i	+6.4	+1.83
	ii	-2.8	-1.64		ii		+2.00
	iii	-2.0	-1.22		iii		+1.98

TABLE VI

LATERAL SCALE OF TURBULENCE k CALCULATED BY FITTING AN EXPONENTIAL CURVE TO CROSS CORRELATION SPECTRA

Time	Records Correlated X	Y	Separation	Max. Reduced Frequency nd/$\bar{V}$	k	Correlation Coefficient for the regression r
Run No. 1, 28 Sept. 1962						
1230	A7	B7	Horizontal	.35	-2.77	.80
1236	A7	B7	"	.34	-6.54	.91 *
Run No. 2, 12 Oct. 1962						
1242	A7	A5	Vertical	.55	-5.53	.85
	L7	L5	Vertical	.37	-7.10	.94 *
	L7	A5	H. & V	2.51	-0.66	.72
	L7	A7	Horizontal	1.46	-1.26	.79
	L5	A7	Vertical	3.48	-0.37	.60
	L5	A5	Horizontal	4.44	-0.22	.51
Run No. 3, 29 Dec. 1962						
1828	L7	L3	Vertical	.74	-3.59	.80
	L6	L5	"	.44	-5.71	.82
	L7	L5	"	.35	-5.81	.92 *
	L6	L3	"	.49	-5.55	.93 *
	L7	L6	"	.33	-8.06	.84
	L5	L3	"	.58	-4.09	.84
1853	L6	L5	Vertical	.60	-6.66	.88
	L7	L3	"	.50	-2.11	.72
	L7	L6	"	.36	-4.38	.71
	L5	L3	"	.39	-5.60	.91 *
	L7	L5	"	.32	-4.97	.88
	L6	L3	"	.39	-4.87	.91 *
Run No. 4, 30 Oct. 1962						
0900	L75	F75	Horizontal	.43	-2.61	.64

*Average of Values for Vertical Separations for which correlation coefficient >0.90 = -5.91

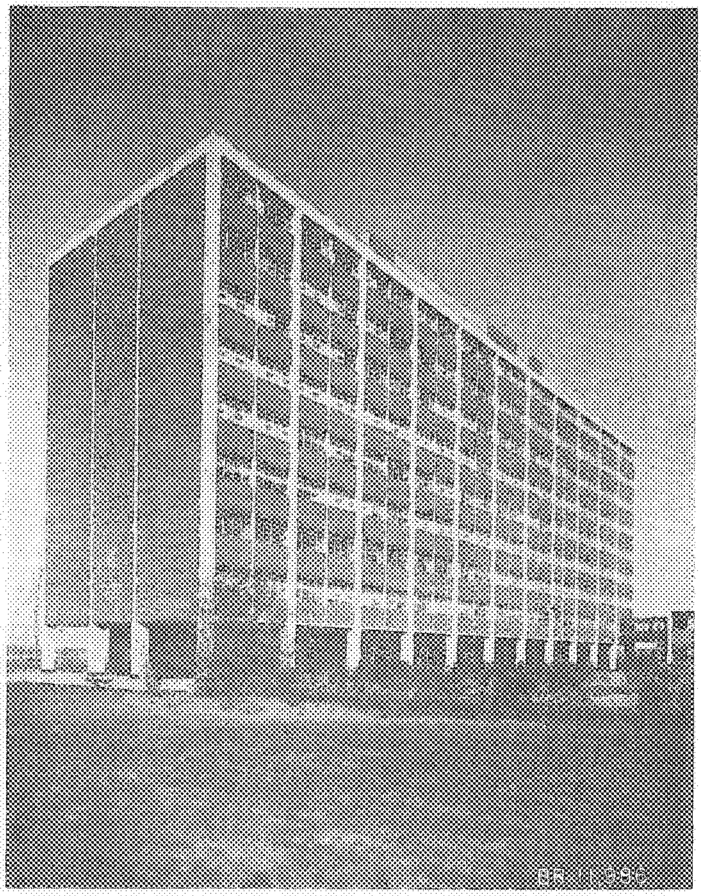

Figure 1 Post Office Building, Confederation Heights, Ottawa. View from southwest.

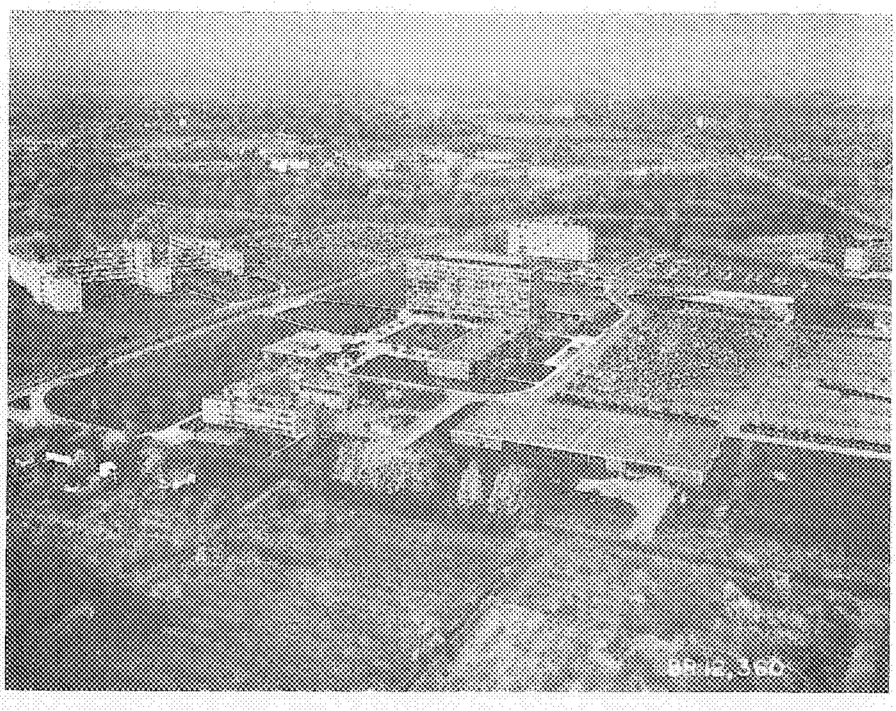

Figure 2 View from southeast showing suburban terrain upwind of Post Office Building (N. W. winds, Runs #2, 3, 4)

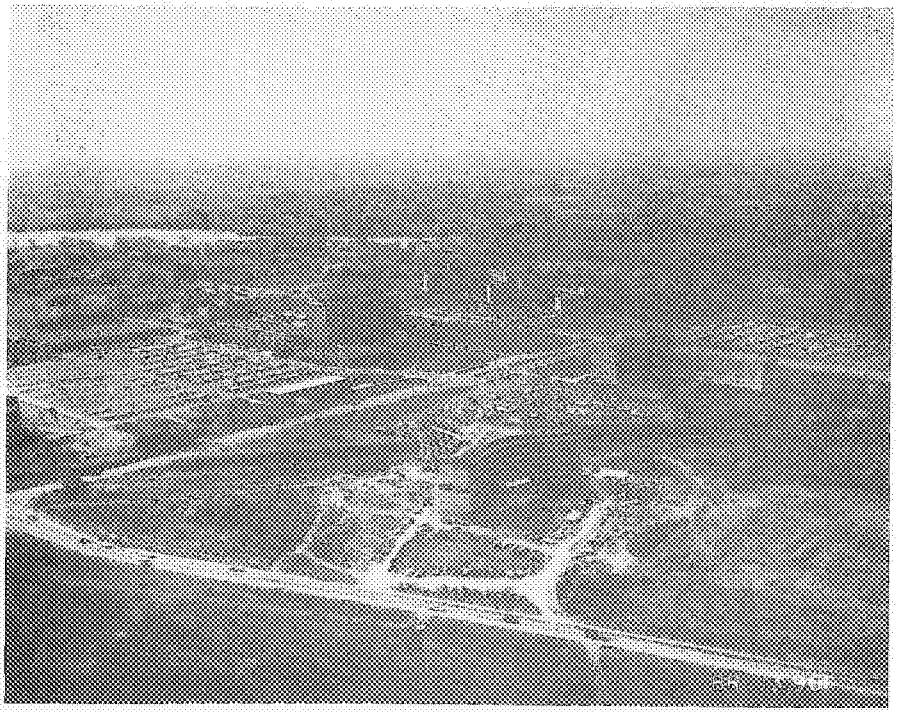

Figure 3 View from northeast showing suburban terrain upwind of Post Office Building (S. W. wind, Run #5)

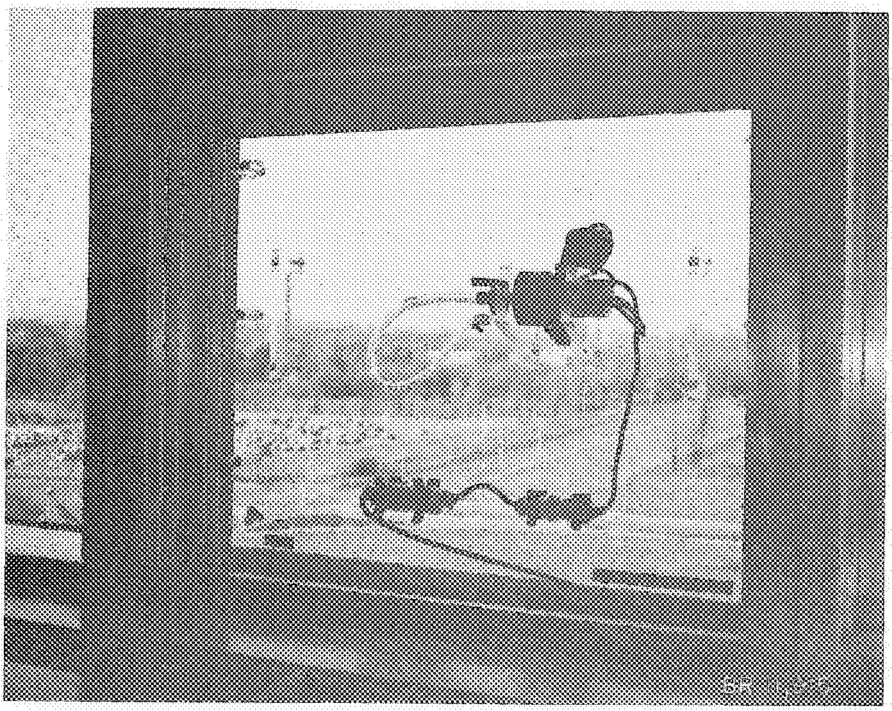

Figure 4 Pressure transducer mounted on transparent panel in window opening.

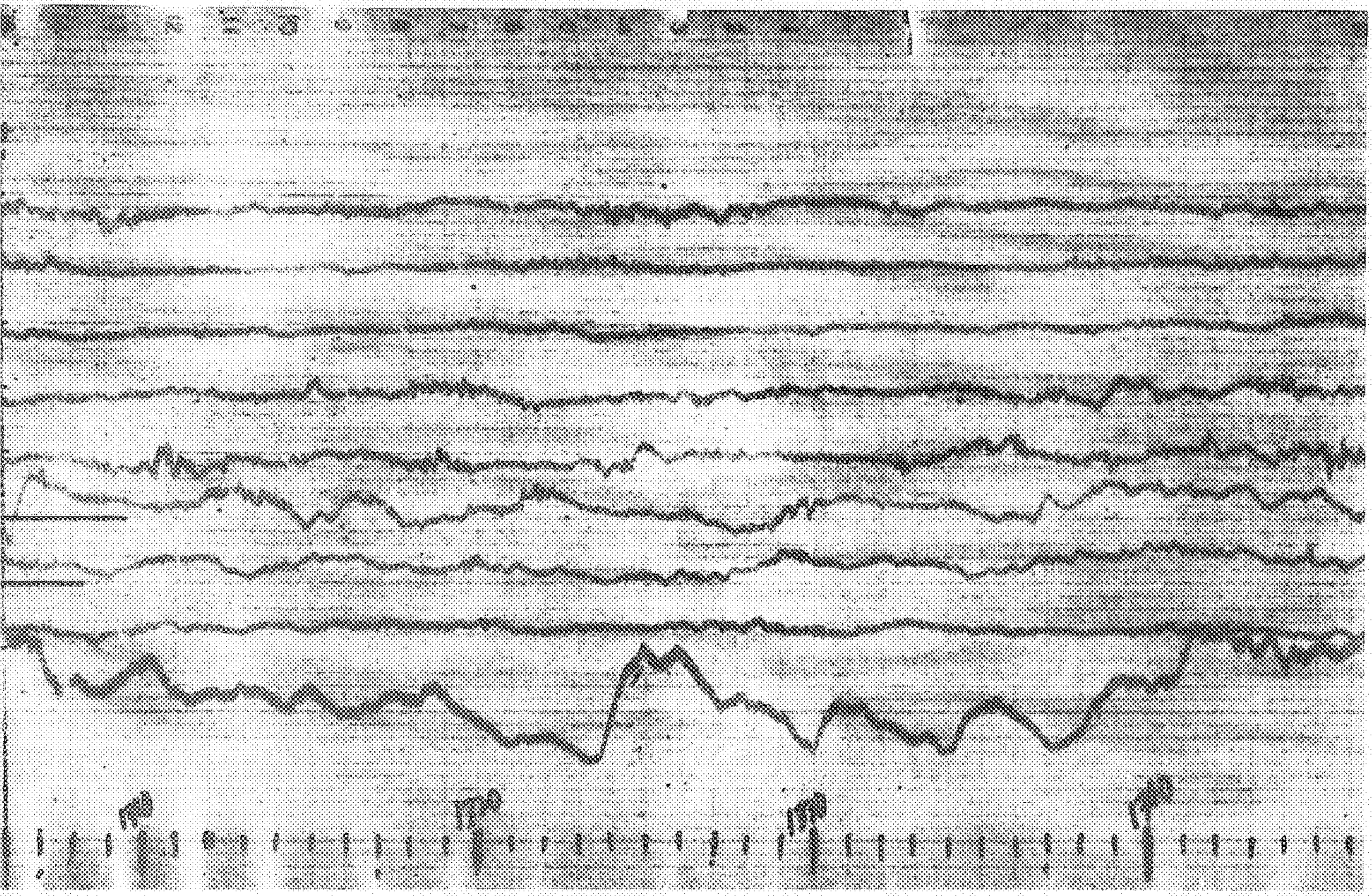

FIGURE 5

PORTION OF TYPICAL CHART RECORD SHOWING WIND SPEEDS AND WIND FLUCTUATIONS WITH TIME

BR 3879

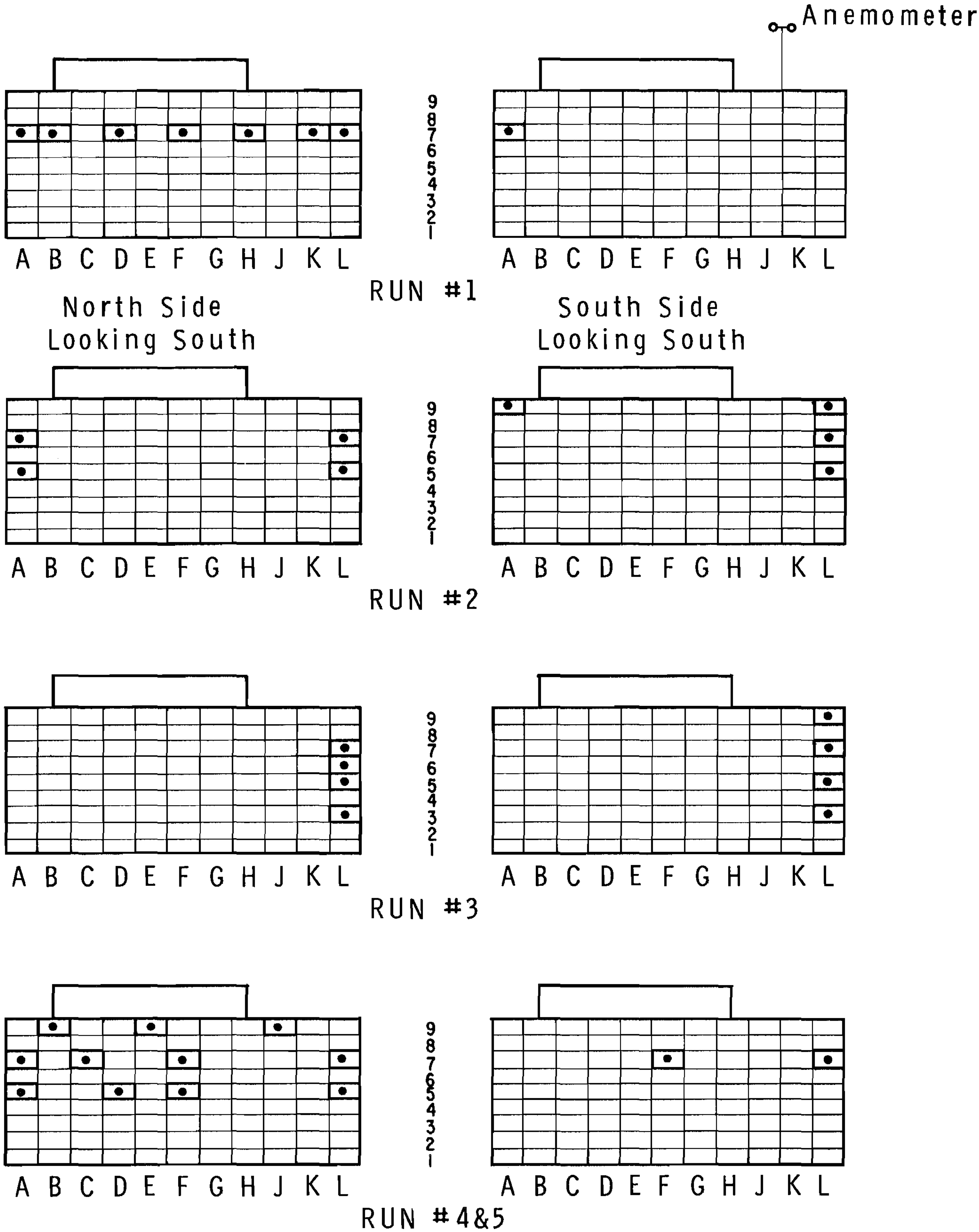

FIGURE 6

LOCATION OF TRANSDUCERS AT POST OFFICE BUILDING

BR 3825-1

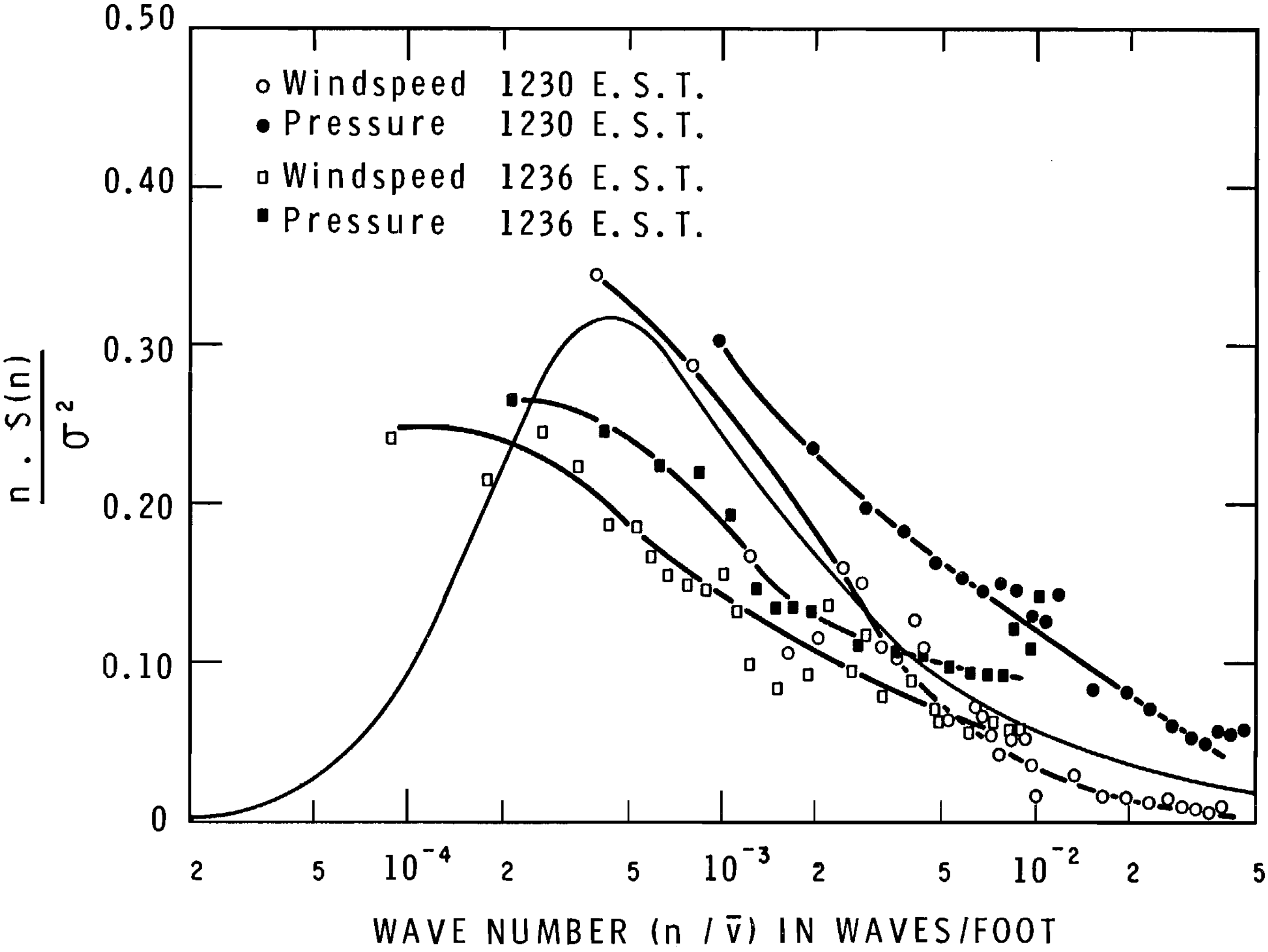

FIGURE 7

SPECTRA OF HORIZONTAL WINDSPEED AND POINT PRESSURES
Run #1 - Post Office Building Records 28 Sept 1962

BR 3825-2

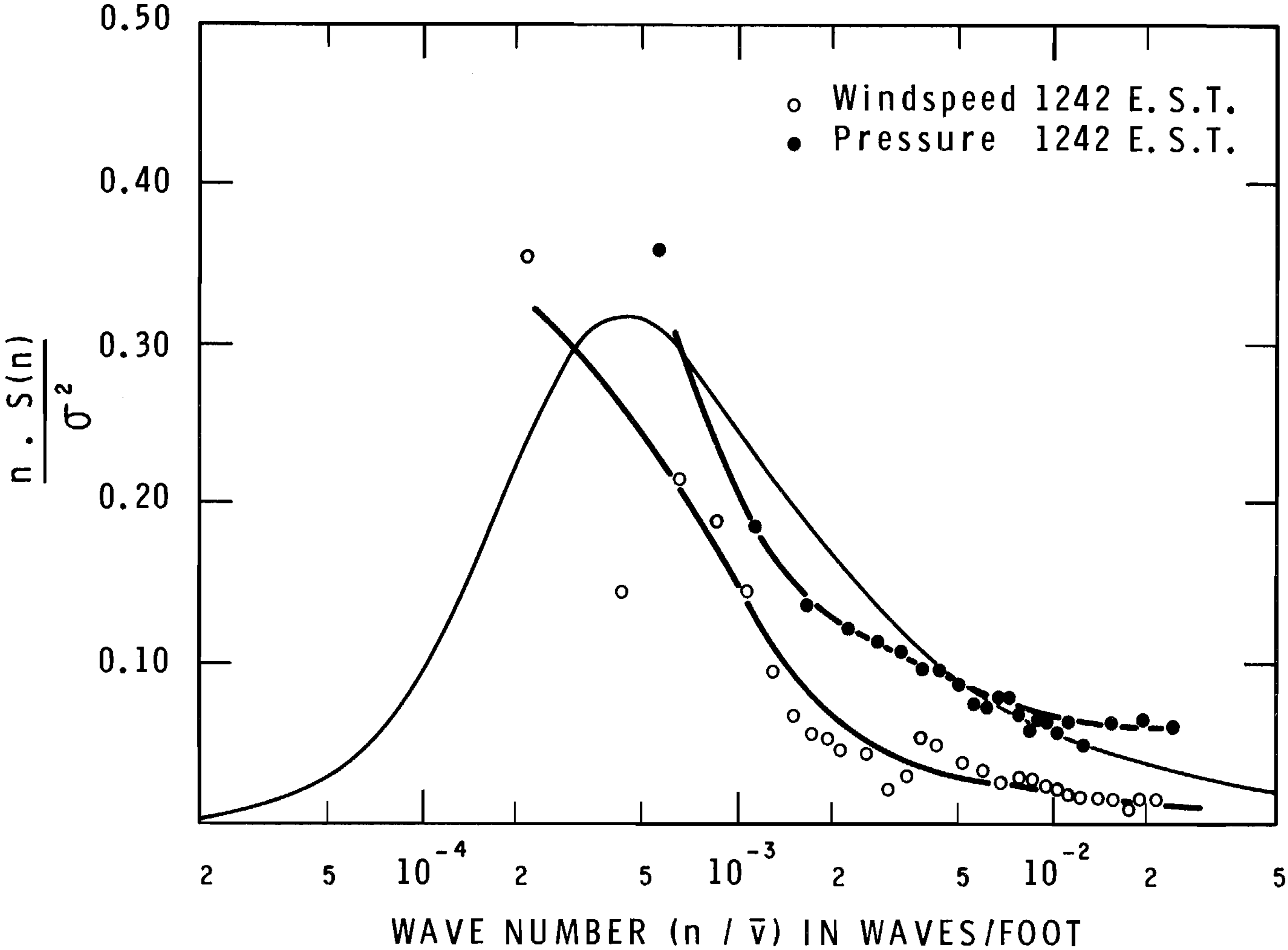

FIGURE 8

SPECTRA OF HORIZONTAL WINDSPEED AND POINT PRESSURES
Run #2 - Post Office Building Records 12 Oct 1962

BR 3825-3

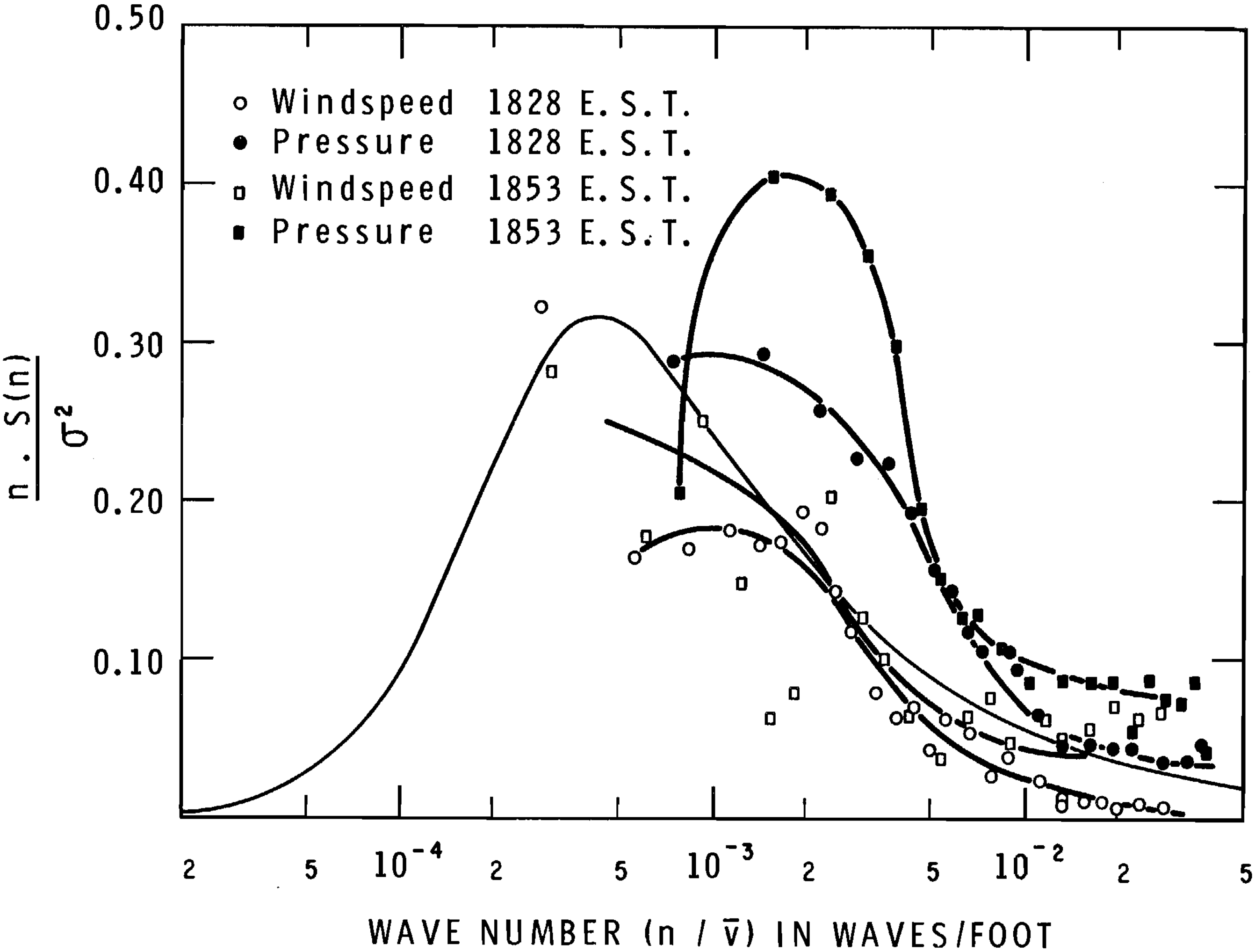

FIGURE 9

SPECTRA OF HORIZONTAL WINDSPEED AND POINT PRESSURES
Run #3 - Post Office Building Records 29 Dec 1962

BR 3825-4

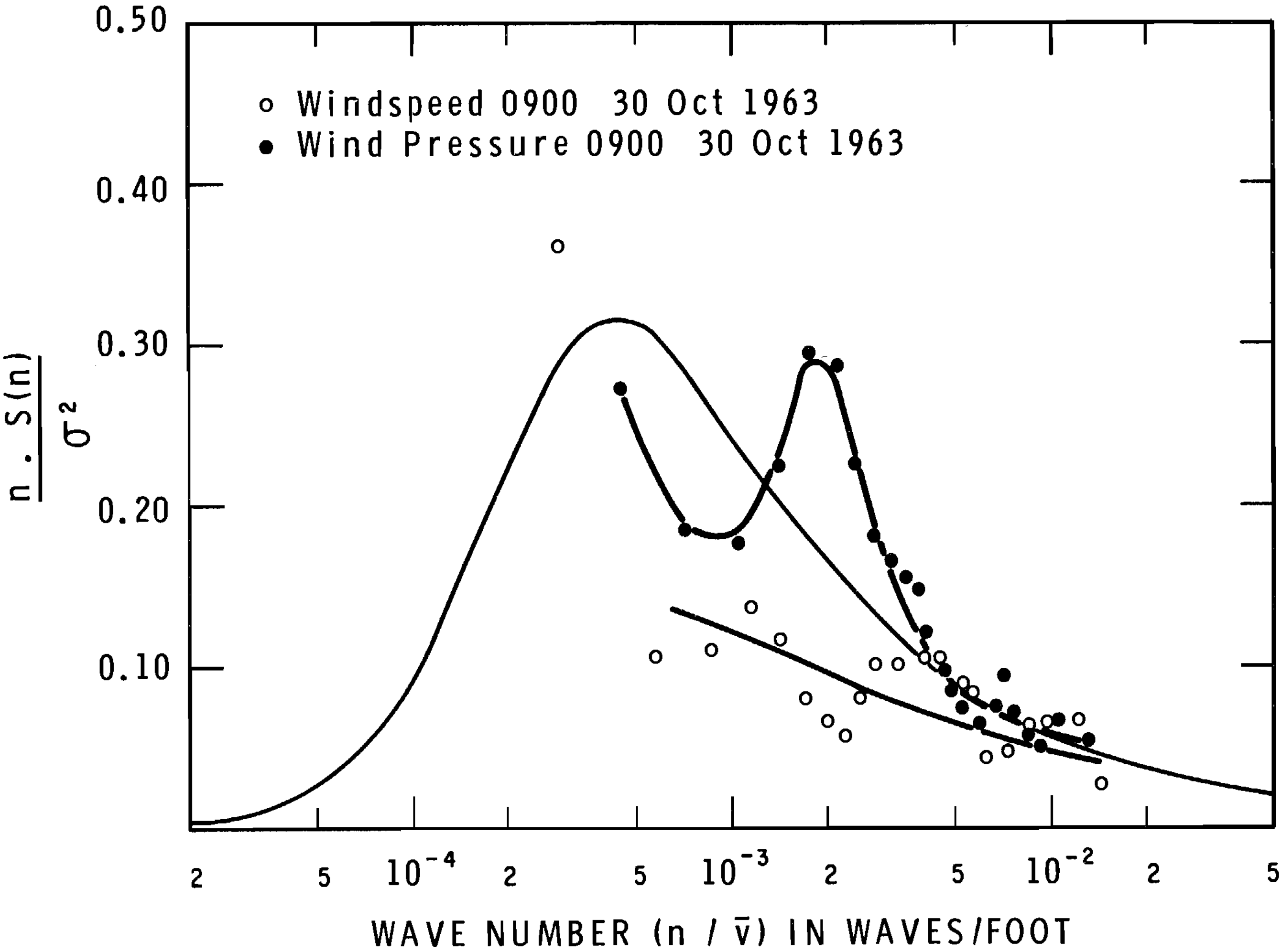

FIGURE 10

SPECTRA OF HORIZONTAL WINDSPEED AND POINT PRESSURES
Run #4 - Post Office Building Records 30 Oct 1963

BR 3825-5

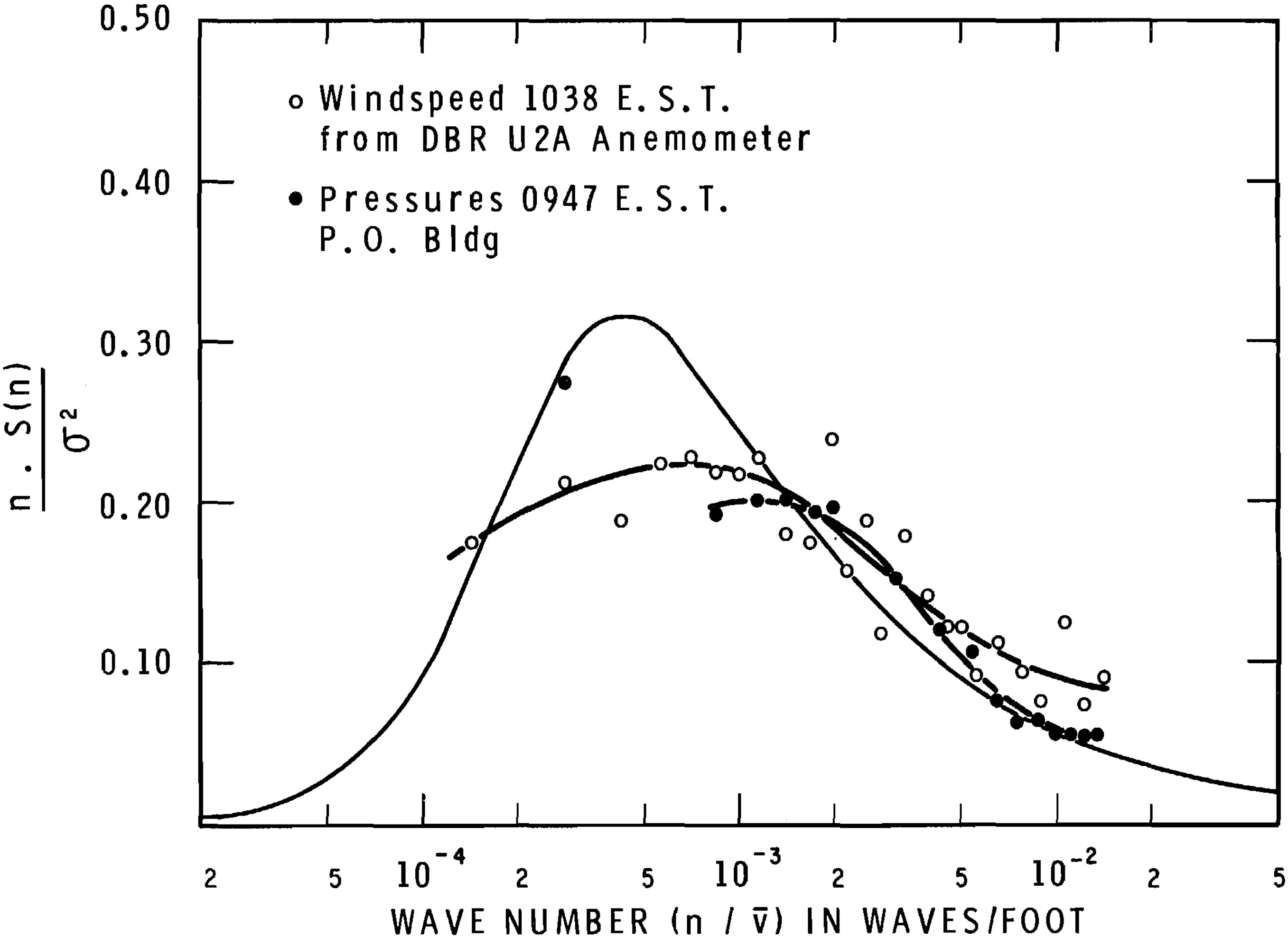

FIGURE 11

SPECTRA OF HORIZONTAL WINDSPEED AND POINT PRESSURES
Run #5 - Post Office Building & DBR Records, 23 Nov 1963

BR3825-6

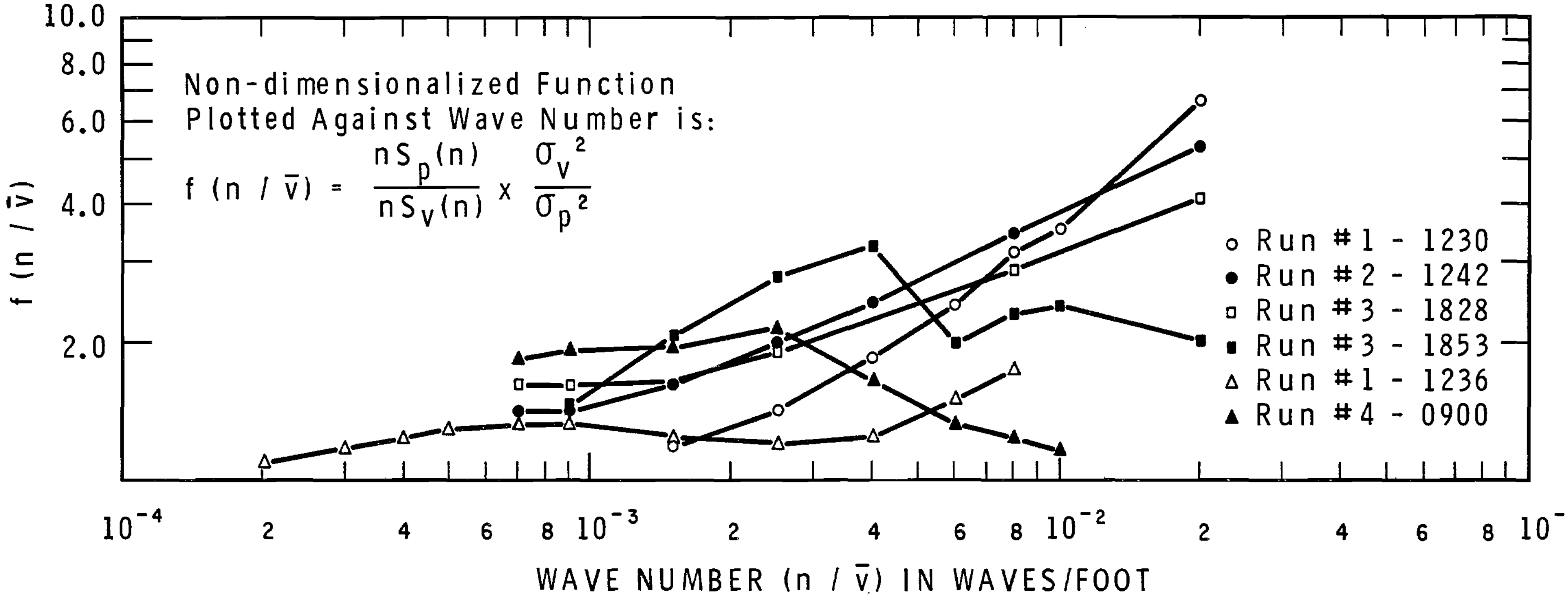

FIGURE 12

RATIOS OF WIND PRESSURE SPECTRA TO WIND SPEED SPECTRA
- Based on Post Office Building Records

BR3825-7

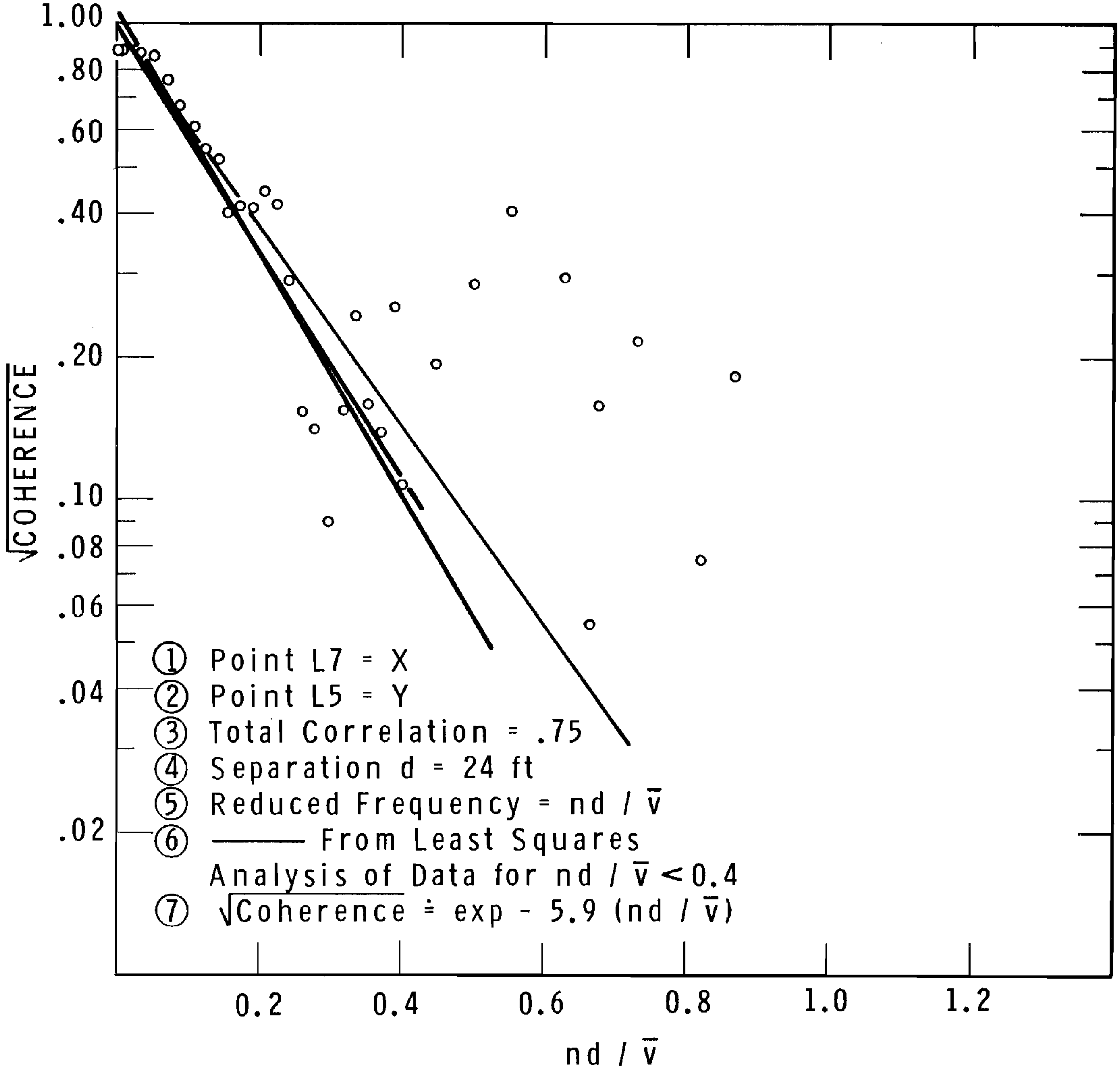

FIGURE 13

RELATION BETWEEN √COHERENCE AND REDUCED FREQUENCY
Run #3 - 1828, Post Office Building Records 29 Dec 1962.

BR 3825-8

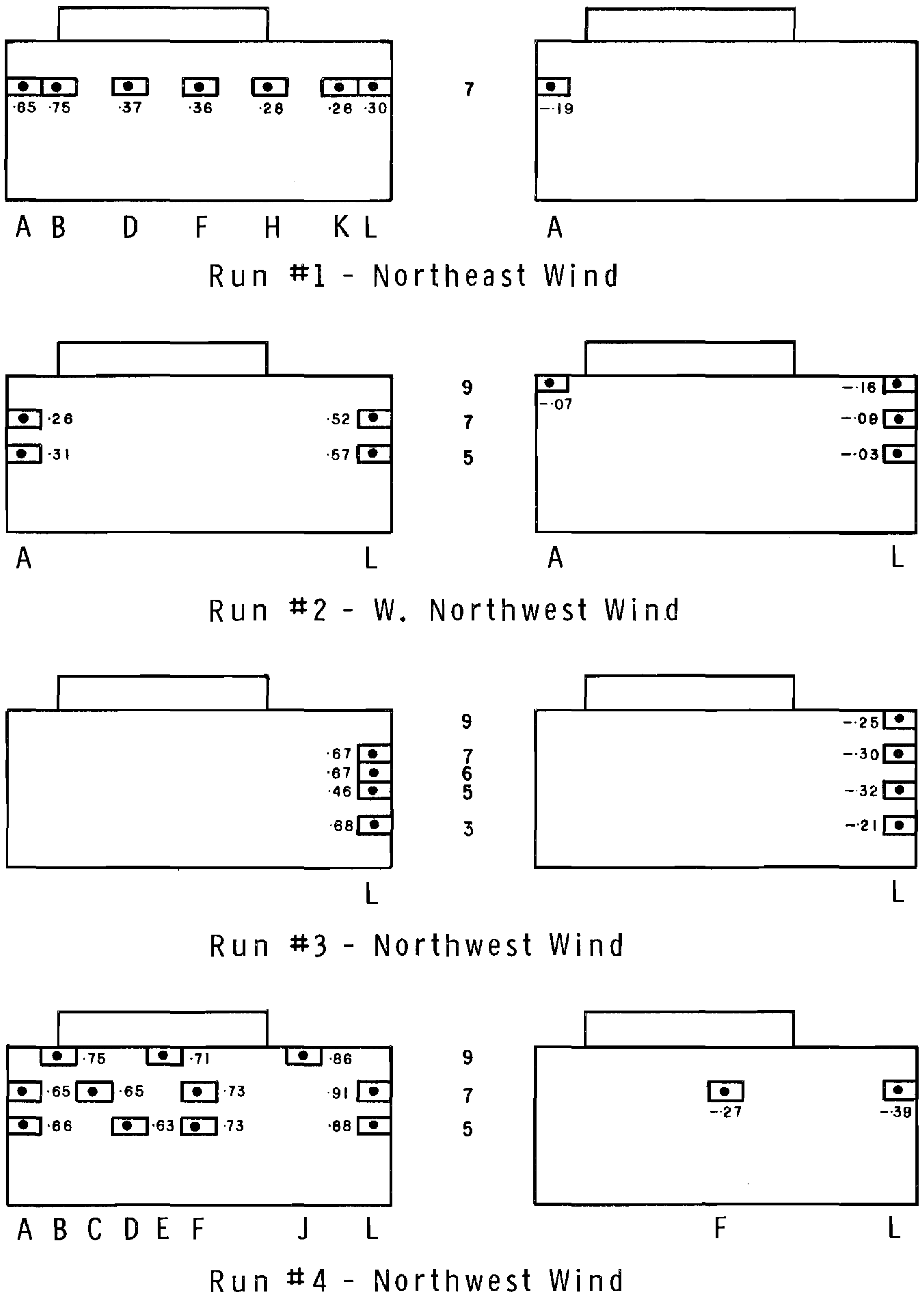

FIGURE 14

TIME - AVERAGED PRESSURE COEFFICIENTS

BR 3825 – 9

APPENDIX A

CHOICE OF RECORDER AND HANDLING OF RECORDS

Several methods of recording pressures and wind speed were considered before choosing a particular system. Among analogue methods there were multi-channel recorders writing on paper with ink-pen type galvanometers, electric stylus, ultraviolet-light beam galvanometers, and multi-track magnetic tape recorders. Digital methods make use of a sampling, or scanning valve, an electronic digital voltmeter, and some sort of printer or tape punch.

Because of its advantages of versatility and transportability the C. E. C. S-124 ultraviolet-light beam galvanometer oscillograph was finally chosen. It was in a package that included calibrating, balancing, and amplification equipment as well as a multi-channel recorder and interchangeable galvanometer. The cost per channel, around $500 not including pressure transducers, was the lowest of any equipment commercially available at the time.

Signals are traced simultaneously and continuously onto a single strip chart of 7-in. wide light-sensitive paper by as many as 14 individual light beam galvanometers supplied from a mercury vapour arc-lamp.

One difficulty encountered in the system chosen was that of processing the records, i. e., the development and permanizing of them. To facilitate this, two methods were suggested by the manufacturers but only one was recommended. The recommended procedure involved loading the paper, taking the record, and developing it all in complete absence of light so was unacceptable for our operation. No special precautions were necessary for the other procedure, and the record was developed by exposing it to any ultraviolet light source.

If the records had to be kept legible for any length of time, however, it was necessary either to protect them carefully from prolonged exposure to light or to treat them chemically to fix the record and prevent degradation.

The permanizing technique suggested by the manufacturers proved to be unsatisfactory. After a great deal of experimenting, a modified technique was developed which gave acceptable but far from good results. Added to this difficulty was the fact that new and improved versions of the paper are frequently made available and this will require further experimentation for satisfactory permanizing.

One complete record was washed out accidentally while attempting to permanize it. Eventually the conclusion was reached that permanizing was not worth the effort and at present the records are viewed sparingly and kept out of direct light.

The second difficulty resulted from overcrowding of the signal traces on the 7-in. width of the chart. Overlapping of the traces allowed adequately large deflections for each channel, but caused trouble in identification of the traces. Separation and reduced deflection scales to avoid crossing of traces was eventually concluded to be the better alternative.

The inherent weakness of paper chart recording from the data-handling point of view is that the chart has to be read manually and digital values taken off for later use with a digital computer. This involves a considerable amount of hand labour, even with the invaluable assistance of an oscillographic scanner and readout device which considerably speeds up this part of the work.

In summary, the disadvantages of the recording system used (strip chart multi-channel oscillograph) were found to be:

1. difficulty in preserving the records;

2. overcrowding of signal traces onto a 7-in. chart width; and

3. necessity for manual digitization of the records in preparation for automatic data processing.

On the positive side, the cost of the system at the time of purchase was less than half that of a magnetic tape system to do the same job. The oscillographic system also compared favourably with all others for portability and adaptability to other jobs. Finally, the direct display of records during the recording process and the complete visual record were essential for a pilot study of this nature.

Now that the pilot study has been made and procedures established for automatic processing of the records, it is no longer essential to look at all the records visually. It is now much more important to eliminate the manual digitization, not only because it is tedious, but also to improve the accuracy of measurements and to eliminate one source of error in the recording process.

Consideration is now being given to replacing the multichannel oscillograph by a data acquisition system having magnetic tape as the output medium. Several new systems are now on the market and the prices are now much more competitive with other systems than they were four or five years ago.

APPENDIX B

ROUGHNESS PARAMETERS

The degree of surface roughness of the site is the major factor in determining the character of mechanically produced wind turbulence. The basic parameters of surface roughness with reference to the production of turbulence are the roughness length, z_o (in cm, or m), the surface drag coefficient, k_z (appropriate to height z above ground) and the friction velocity V_*.

Roughness length and friction velocity are the important parameters needed to determine the vertical profile of wind speed according to the logarithmic law:

$$V_z = \frac{V_*}{K} \ell n \left(z / z_o \right) \tag{B 1}$$

where K is Von Karman's Constant $\approx 0.4 \rightarrow 0.38$.

The surface drag coefficient is related to V_* and $\bar{V}_z$ as follows:

$$V_*^2 = k_z \bar{V}_z^2 . \tag{B 2}$$

z_o and V_* are usually established by measuring wind speed at more than one height and substituting the experimental data in Eq. (B 1). Wind speed was measured at only one height (152 ft = 46.34 m.) at the Post Office Building, however, so the records gathered were insufficient to establish the values of z_o, V_* or k_z.

Some idea of the values to be expected could be gained by reference to Davenport's papers (4, 6) and by observation of the general appearance of the terrain. Regardless of how they are chosen, the values used should be consistent with one another.

The need for consistency arises, for example, in the choice of the proportionality factor for the equation of the empirical spectral density curve, to which the experimental points are compared in Figures 7 to 11:

$$\frac{n\,S_v(n)}{k_z\,\bar{V}_z^{\,2}} = \frac{n\,S_v(n)}{V_*^{\,2}} = \frac{f\,x^2}{(1 + x^2)^{4/3}}\,. \tag{B 3}$$

The total variance $\sigma_v^{\,2}$ can be computed, and is given by:

$$\sigma_v^{\,2} = \int_o^{\infty} S_v(n)\,dn. \tag{B 4}$$

Substituting from (3) into (4),

$$\sigma_v^{\,2} = V_*^{\,2} f \int_o^{\infty} \frac{x\,dx}{(1 + x^2)^{4/3}}$$

$$= \frac{V_*^{\,2} f}{2} \int_1^{\infty} u^{4/3}\,du = \frac{3\,V_*^{\,2} f}{2} \tag{B 5}$$

Once f has been selected, V_* can be calculated from Eq. (5) and the experimentally determined $\sigma_v^{\,2}$. If V_* is then used in the normalization of the spectral density estimates (Eq. (3)) the consistency of the ordinate scale of the plotted points with the empirical curve is assured.

The choice of f also permits the calculation of roughness length z_o from σ_v^2 and $\bar{V}_z$ using Eqs. (5) and (1):

$$\ell n\,(z/z_o) = \frac{K\bar{V}_z}{V_*} \qquad \text{(B 1a)}$$

$$V_* = \sqrt{\frac{2}{3f}}\;\sigma_v \qquad \text{(B 5a)}$$

$$z_o = z\,e^{-\left(\frac{K\bar{V}_z}{\sigma_v}\sqrt{\frac{3f}{2}}\right)} \qquad \text{(B 6)}$$

Power Law Exponent

The logarithmic profile is generally considered to be better for the height range from 0 to 200 ft or so above ground, but power law profile is also widely used, and works well from 20 or 30 ft up to gradient height of 1,000 to 2,000 ft above ground. The two profiles cannot actually be equated because their equations are of different forms, but an appropriate power law exponent can be found which gives the best agreement over a certain height range to the logarithmic profile.

The power law exponent used (0.30) was determined from the roughness length (82 cm) by computing the ratio of wind speed at height z to wind speed at 10 m for 11 heights ranging from 10 m to 60 m from a modification of Eq. (1):

$$V_z/V_{10} = \frac{\ell n\,(z/z_o)}{\ell n\,(10/z_o)} \qquad \text{(B 1b)}$$

A power law curve was then fitted by least squares, to the points after linearization of the records as follows:

$$\ell n\,(V_z/V_{10}) = x\,\ell n\,(z/10) + \beta \qquad \text{(B 7)}$$

Results

Two values of f were considered and the one giving results closest to the values expected by comparison with Davenport's publications was chosen. The f used by Davenport is 4, and the other value tried and eventually used in this report is 8/3 (also suggested by Davenport in discussing the Post Office Building records with the author).

ROUGHNESS LENGTH AND POWER LAW EXPONENT

	f = 4	f = 8/3
z_o	33 cm	82 cm
α	0.24	0.30

APPENDIX C

DERIVATION OF AN ALGEBRAIC IDENTITY

Part I

Definition:

$$M_n = \frac{1}{T} \int_0^T (x - \bar{x})^n \, dt \tag{C 1}$$

where

M_n is the n^{th} moment about the mean $\bar{x}$ of the data $x(t)$.

$$M_4 = \frac{1}{T} \int_0^T \left(x^4 - 4x^3 \bar{x} + 6x^2 \bar{x}^2 - 4x\bar{x}^3 + \bar{x}^4 \right) dt \tag{C 2}$$

$$= \overline{x^4} - \frac{4\bar{x}}{T} \int_0^T \left(x^3 - 3x^2 \bar{x} + 3x\bar{x}^2 - \bar{x}^3 + \frac{3}{2} x^2 \bar{x} - 2x\bar{x}^2 + \frac{3\bar{x}^3}{4} \right) dt \tag{C 3}$$

$$= \overline{x^4} - 4\bar{x} M_3 - \frac{6\bar{x}^2}{T} \int_0^T \left(x^2 - 2x\bar{x} + \bar{x}^2 + \frac{2}{3} x\bar{x} - \frac{1}{2} \bar{x}^2 \right) dt \tag{C 4}$$

$$= \overline{x^4} - 4\bar{x} M_3 - 6\bar{x}^2 m_2 - 4\bar{x}^4 + 3\bar{x}^4 . \tag{C 5}$$

Finally,

$$M_4 = \overline{x^4} - 4\bar{x} M_3 - 6\bar{x}^2 M_2 - \bar{x}^4 . \tag{C 6}$$

Note that

$$M_2 = \sigma_x^2 . \tag{C 7}$$

Part II

Definition:

$$\sigma_{x^2}^{\;2} = \frac{1}{T}\int_0^T \left(x^2 - \overline{x^2} \right)^2 dt \tag{C 8}$$

$$= \frac{1}{T}\int_0^T \left(x^4 - 2x^2\,\overline{x^2} + \overline{x^2}^{\,2} \right) dt \tag{C 9}$$

$$= \overline{x^4} - 2\,\overline{x^2}^{\,2} + \overline{x^2}^{\,2} \tag{C 10}$$

$$= \overline{x^4} - \overline{x^2}^{\,2} . \tag{C 11}$$

Similarly,

$$\sigma_x^{\;2} = \frac{1}{T}\int_0^T \left(x - \bar{x} \right)^2 dt \tag{C 12}$$

$$= \overline{x^2} - \bar{x}^2 \tag{C 13}$$

or,

$$\overline{x^2}^{\,2} = \left(\sigma_x^{\;2} + \bar{x}^2 \right)^2 = \sigma_x^{\;4} + 2\sigma_x^{\;2}\,\bar{x}^2 + \bar{x}^4 . \tag{C 14}$$

Combining (11) and (14) and rearranging,

$$\overline{x^4} - \bar{x}^4 = \sigma_{x^2}^{\;2} + 2\bar{x}^2\,\sigma_x^{\;2} + \sigma_x^{\;4} . \tag{C 15}$$

Combining (6) and (15), taking account of (7)

$$M_4 + 4\bar{x}\,M_3 = \sigma_{x^2}^{2} - 4\bar{x}^{2}\,\sigma_x^{2} + \sigma_x^{4} . \qquad \text{(C 16)}$$

Dividing by $4\bar{x}^4$

$$\left(\frac{M_4}{4\bar{x}^4} + \frac{M_3}{\bar{x}^3} \right) = \frac{\sigma_x^{4}}{4\bar{x}^4} + \frac{\sigma_x^{2}}{\bar{x}^2} \left(\frac{\sigma_{x^2}^{2}}{4x^2\sigma_x^{2}} - 1 \right) \qquad \text{(C 17)}$$

$$= \frac{C^4}{4} + C^2 \left(\frac{\sigma_{x^2}^{2}}{4x^2\sigma_x^{2}} - 1 \right) \qquad \text{(C 18)}$$

Where C is defined as $\dfrac{\sigma_x}{\bar{x}}$.