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THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Final Report

# DISPERSION AND PENETRATION OF POLLENS AND INDUSTRIAL CONTAMINANTS

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# ABSTRACT

The investigation commenced with a comprehensive survey of the literature on the dispersion of pollen in the atmosphere. A theoretical analysis was undertaken by Dr. V. C. Liu in which allowance was made for the relative motion of particles and fluid in turbulent flow. The analysis first discusses the influence of extraneous forces, fluid resistance, and fluid inertia, and then relates these quantities in a stochastic differential equation. The mathematical representation of the turbulent velocity field is next developed in terms of the spectrum density and autocorrelation functions. With certain simplifying assumptions the particle equation is solved by use of Wiener's generalized harmonic analysis. Particle dispersion and probability distributions are next analyzed and the treatment concluded with an illustrative example using a prescribed form for the spectrum density and an indication of practical applications of the theory.

The discussion of the main experimental program is preceded by brief descriptions of clinical studies of ragweed-pollen allergy, using project equipment, and of a survey of meteorological instrumentation of the type used in the field experimentation.

The field studies of penetration of particulates into structures were based on the working hypothesis that penetration is induced by a pumping action of atmospheric turbulence, whereby the particles enter the structure through cracks and openings around windows, doors, and elsewhere. The experimental procedure was as follows. Ragweed pollen which occur naturally in the area from the middle of August to the end of September were the particulates employed. First the pollen initially in the test room were filtered from the air. Then simultaneous measurements of pollen concentration were made at selected intervals for chosen periods both inside the test room and outside the structure. At the same time, measurements of wind speed and turbulence were made outside for the duration of the runs. The analytical problem was then that of relating the inside concentrations to those outside and to the wind speed and turbulence.

The tests during the 1954 ragweed season were held in and near a small room on the roof of the East Engineering Building. Pollen concentrations inside and outside were made by drawing measured volumes of air through millipore filters and counting under a microscope the number of pollen grains caught on each filter. The wind speed was measured by a Beckman-Whitley anemometer and the gustiness or turbulence by a bridled-cup gust accelerometer. The linear regression of the gust count against mean wind speed was computed and the correlation coefficient determined. The ratio of pollen count inside to that

outside was next calculated, and this ratio compared with mean wind speed and the gust count. The ratio tended to increase with wind speed and gustiness when the window was open, but not when it was closed. Tests were made to determine the representativeness of concentrations near the position of the volumetric sampler intake.

Experimental work was also performed between the 1954 and 1955 ragweed-pollen seasons. The procedure was to emit a cloud of pollen from an atomizer located upwind from the test room for a specified period of time, and to measure inside concentrations, along with meteorological variables. A three-dimensional array of petrolatum-coated microscope slides was set up to ascertain the degree of uniformity of the outside pollen plume.

The building itself caused such erratic wind behavior that it was decided to establish a test structure in an open meadow on the North Campus for the 1955 pollen season. Twenty-two experiments were conducted between August 20 and September 2, a period of relatively high natural pollen concentrations. The "total gustiness" was evaluated from the wind record, employing a special technique devised for the purpose. A differential equation was developed to express the penetration as a function of the ventilation rate and other parameters, and used to evaluate the ventilation rate, which was in turn analyzed in relation to the measured wind speed by quadratic regression equations. A second index, the "ventilation effectiveness," was devised and evaluated, and analyzed in relation to wind speed. These studies led to the conclusion that ventilation is more simply and directly expressed in terms of wind speed than in terms of turbulence. The analysis concludes with a study of ventilation dynamics, in which the basic differential equation was solved for a sinusoidal time variation of outside pollen concentrations. The ventilation rates obtained by this method agreed well with those found by the first method.

The report ends with a summary list of conclusions, and suggestions for further research.

# OBJECT

The object of the research is to study both theoretically and experimentally (1) the dispersion of airborne particulates and (2) the penetration of these particulates into structures as a function of atmospheric turbulence and wind speed.

## LIST OF PAPERS PUBLISHED UNDER THE CONTRACT

1. Hewson, E. W., 1954: "Atmospheric Pollution in Relation to Microclimatology and Micrometeorology: Some Problems," in *Proceedings of the Toronto Meteorological Conference 1953*. London, Royal Meteorological Society, 240-252.

2. Dingle, A. N., 1955: "A Meteorologic Approach to the Hay Fever Problem," *Journal of Allergy*, Vol. 26, No. 4, 297-304.

3. Hewson, E. W., 1956: "Meteorological Measurements in Air Pollution Studies," in *Encyclopedia of Instrumentation for Industrial Hygiene*. Ann Arbor, University of Michigan, Institute of Industrial Health, 521-540.

4. Liu, V.-C., 1956: "Turbulent Dispersion of Dynamic Particles," *Journal of Meteorology*, Vol. 13, No. 4, 399-405.

# CHAPTER 1

# THE SCOPE OF THE RESEARCH

Since the terms of reference of the investigation include research on both dispersion and penetration of atmospheric particulates, the discussion of the program will center around these two phases.

## 1.1 DISPERSION STUDIES

Two main areas of study of dispersion were undertaken in the course of the investigation. First, the problem of dispersion of pollen in the atmosphere was reviewed comprehensively. Then the dynamic behavior of particulates such as pollen in a turbulent atmosphere was investigated theoretically.

1.1.1 Dispersion of Pollen.—The dispersion of pollen in the atmosphere has not been studied systematically by meteorologists. A comprehensive review of the available literature, conducted at the beginning of the investigation, revealed that such dispersion is influenced by a number of meteorological factors. The amount of precise knowledge of such meteorological influences is strictly limited, however.

Analyses of the existing situation and of possible future areas of research are presented in the following reports and publications:

E. Wendell Hewson, "Some Aspects of the Dispersion of Pollens and Industrial Contaminants in Relation to Micrometeorology," Scientific Report No. 1, October, 1953.

E. Wendell Hewson, "Atmospheric Pollution in Relation to Microclimatology and Micrometeorology: Some Problems," in *Proceedings of the Toronto Meteorological Conference 1953*. London, Royal Meteorological Society, 1954, pp. 240-252.

A. Nelson Dingle, "A Meteorologic Approach to the Hay Fever Problem," *Journal of Allergy*, Vol. 26, No. 4, 1955, pp. 297-304.

1.1.2 Dispersion of Dynamic Particles.—The behavior of small particles in a turbulent atmosphere is an important aspect of the dispersion problem. The usual approach in theoretical studies in the past has been to neglect possible relative motion of particles and fluid in turbulent flow. The present study analyzes turbulent dispersion of particles whose size and inertia are such that it cannot be assumed that they will follow exactly the fluctuations of the fluid elements with which they are associated. The turbulent field is assumed to be stationary, homogeneous, and isotropic. Stationary, extraneous force fields for the particles may exist. The method of generalized harmonic analysis as developed by Wiener is used to determine the statistical particle dispersion parameters in terms of the spectrum density of the turbulent field and the physical characteristics of the particles. The discussion is restricted to one-dimensional problems; it includes consideration of the relation between turbulent dispersion and Brownian motion of the particles due to molecular impacts. An illustrative example of a dispersion calculation using a given turbulence spectrum is presented, and the treatment concludes with a brief discussion of practical applications of the theory.

Full details of the theoretical development have been presented in the following:

Vi-Cheng Liu, "Turbulent Dispersion of Dynamic Particles," Scientific Report No. 2, October, 1955.

Vi-Cheng Liu, "Turbulent Dispersion of Dynamic Particles," Journal of Meteorology, Vol. 13, No. 4, 1956, pp. 399-405.

These two treatments are practically identical.

1.1.3 Related Investigations.—The volumetric pollen sampling techniques developed for this research and described in detail later in this report were used by personnel of The University of Michigan Medical School in clinical studies of ragweed-pollen allergy. These studies led to the publication of the following papers:

S. Cryst, C. W. Gurney, and W. Hansen, "A Method for Determining Aero-Allergen Concentrations with the Molecular Membrane," Journal of Laboratory and Clinical Medicine, Vol. 46, No. 3, 1955, pp. 471-475.

C. W. Gurney and S. Cryst, "Aeroallergen Studies with the Molecular Filter Membrane," Journal of Allergy, Vol. 26, No. 6, 1955, pp. 533-541.

Early in the program a survey of meteorological instruments appropriate for micrometeorological studies was undertaken. This survey was published as the following paper:

E. W. Hewson, "Meteorological Measurements in Air Pollution Studies," in Encyclopedia of Instrumentation for Industrial Hygiene. Ann Arbor, University of Michigan, Institute of Industrial Health, 1956, pp. 521-540.

## 1.2 PENETRATION OF ATMOSPHERIC PARTICULATES

The experimental phases of the research were concerned with determining the rate of penetration of particulates into structures as a function of meteorological variables, notably wind speed and atmospheric turbulence. As a working hypothesis, it was assumed that penetration is induced by a pumping action of atmospheric turbulence, whereby the particles enter the structure through cracks and openings around windows, doors, and elsewhere.

In general terms, the experimental procedure was as follows. The particulates used were ragweed pollen, which are found in abundance in the area from the middle of August until late September. First, the pollen in a room in the structure were removed by suitable filtering devices. Then simultaneous measurements of pollen concentration were made at selected intervals for chosen periods both in the room and outside the structure. At the same time, measurements of wind speed and turbulence were made outside for the duration of the runs.

The analytical problem was then one of relating the inside concentrations to those outside and to the wind speed and turbulence. The experimental and analytical procedures developed and used in the course of the research are described in detail in the remainder of the report.

# CHAPTER 2

# TESTS DURING SUMMER, 1954

## 2.1 THE TEST ROOM

For the ragweed-pollen season of 1954, instrumentation was completed and personnel employed to begin observations on the penetration of pollen grains into a test room situated on the roof of the East Engineering Building. The design of this room is shown in Figs. 1a and 1b. The outside walls are of concrete-block construction, and the windows are the steel louvre-opening industrial type. There is some crackage around these windows and around the door, but very little in the walls themselves. Thus the room construction is quite different, as regards natural ventilation, from an ordinary dwelling, barracks, or other frame structure.

## 2.2 INSTRUMENTATION

The instrumentation used for the 1954 tests is shown in Figs. 2 and 3. Figure 2 shows, from left to right: the solenoid valves controlling the sampling heads used for pollen concentration measurements (in this case the heads are mounted for a vertical distribution study); the bag filter used for cleaning the test room; the portable sampling unit (on pedestal outside the window); the Beckman-Whitley anemometer (West, 1952); and the bridled-cup gust accelerometer (Hewson and Gill, 1944). Figure 3 shows the meters and recorders in the instrument room (see plan, Fig. 1a).

## 2.3 PROCEDURE

As is frequently the case in the early stages of a program of relatively exacting measurements, the initial attempts were less than satisfactory. Tests that could be accepted as valid were made from August 30 through September 10, by which date the natural production of ragweed pollen had fallen too low for further regular sampling to be profitable.

In these tests, the procedure was to sample the air outside and inside the test room simultaneously, using millipore filters, the flow through which was metered. During some runs the air in the test room was kept stirred by an oscillating electric fan. The standard sampling period used was 15 minutes and the sample volume was 150 liters. The pollen grains were identified and counted under the microscope using 100X magnification. Before each pair

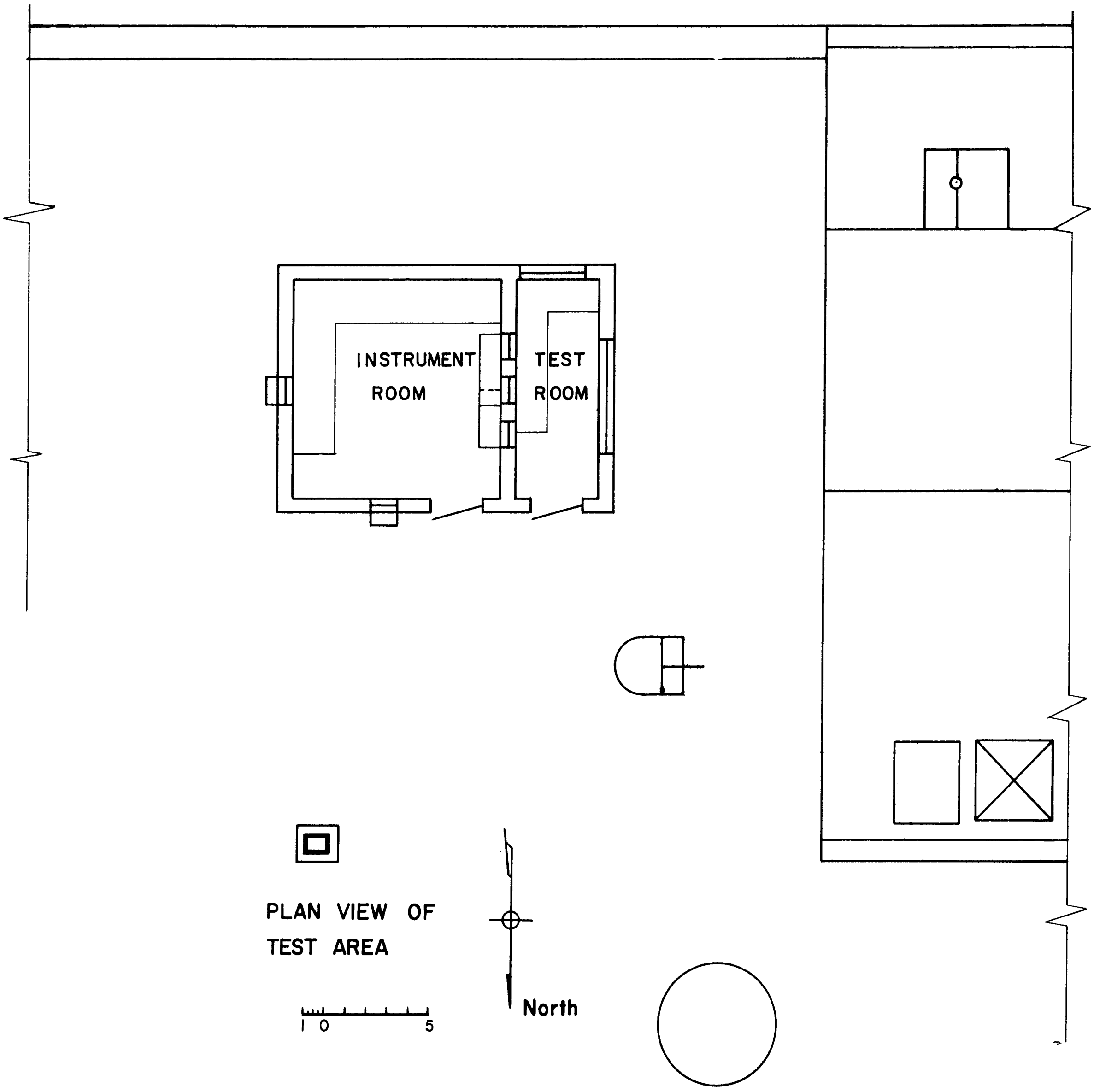

INSTRUMENT ROOM
TEST ROOM
PLAN VIEW OF TEST AREA
1 0 5
North

Fig. 1a.

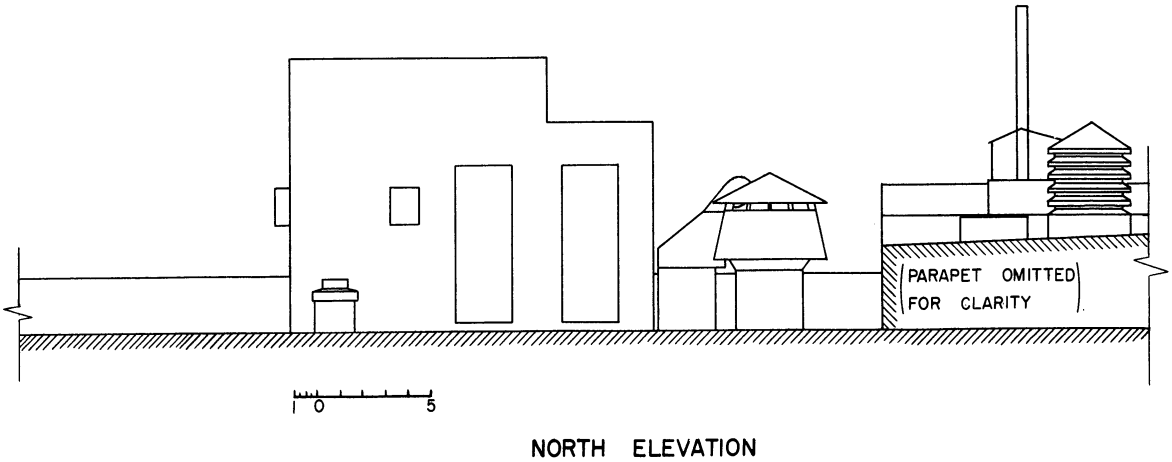

PARAPET OMITTED FOR CLARITY
1 0 5
NORTH ELEVATION OF TEST AREA

Fig. 1b.

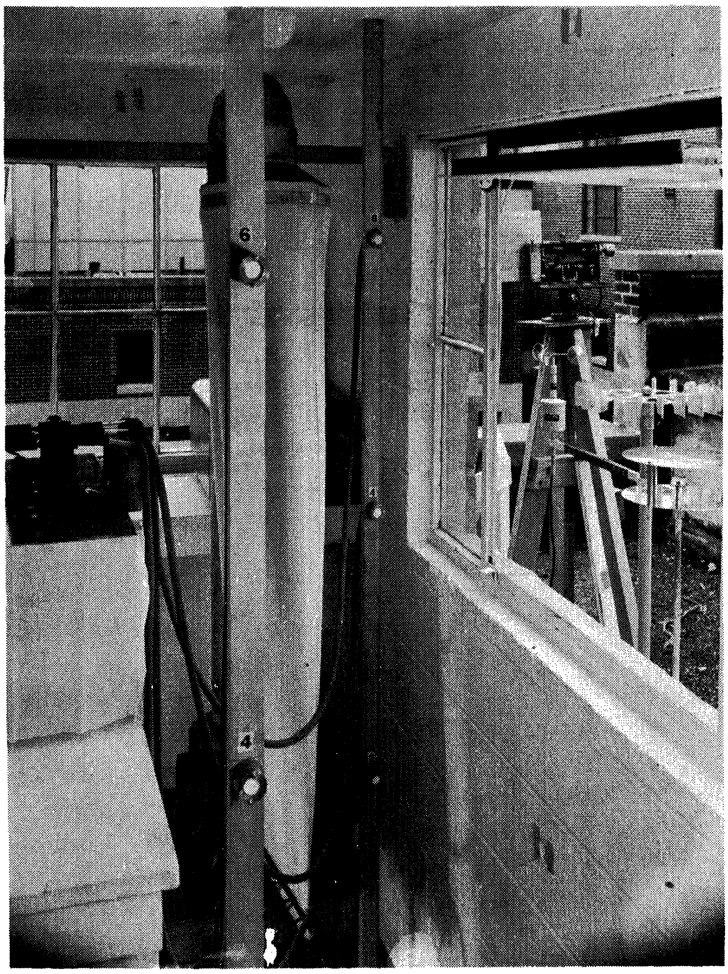


Fig. 2. Interior View of Test Room.

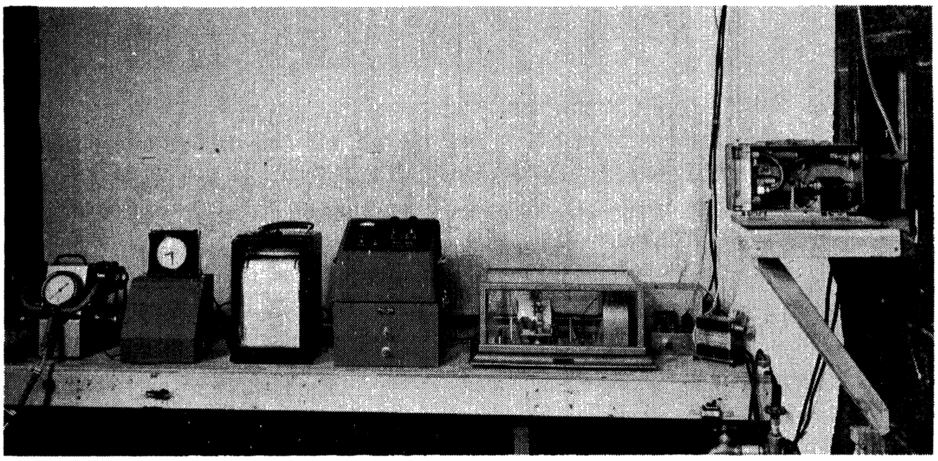


Fig. 3. Interior View of Instrument Room.

of samples was taken, the test room was cleaned thoroughly by means of a large bag filter shown in Fig. 2, for a period of one hour. Gust counts and wind speeds were recorded, using the bridled-cup gust accelerometer (Hewson and Gill, 1944) and the Beckman-Whitley anemometer (West, 1952), respectively. The gust count represents the number of changes of wind speed of 2 mi/hr during the period. It is directly proportional to the mean gust acceleration. Table I summarizes the results of these tests. Figures 4, 5, and 6 present some interrelations among the basic variables.

## 2.4 ANALYSIS: WIND

The wind-speed and gust-count records were quite difficult to read with precision, partly because the chart speeds used were too low; nonetheless, the gust count, $G'$, and the average wind speed, $\bar{v}$, taken over 15-min periods, show relatively good correlation (Fig. 4). The linear regression of $G'$ on $\bar{v}$ for the 49 cases treated is

$$G' = 85.1\,\bar{v} - 215.6$$

with a correlation coefficient

$$r = 0.80\ .$$

The linear relationship between $G'$ and $\bar{v}$ is intuitively to be expected, but the correlation of 0.80 is extraordinary in meteorology even for an anticipated relationship. This will be discussed further in Chapter 4.

## 2.5 ANALYSIS: POLLEN COUNTS

The production and release of ragweed-pollen grains by the plants under natural conditions result from complex interactions of biological and meteorological factors, both antecedent and current, which affect details of plant growth and maturation. As a result, the weather dependency of atmospheric pollen concentration remains obscure. This is not to say that such dependency may not be established, but rather that its establishment is a problem of some complexity requiring prolonged direct study. This was not feasible within the limits of the present program.

In order to eliminate biological and meteorological problems of maturation, release, and transport of the pollen grains, so that the problems of ventilation and penetration could be attacked directly, the pollen counts were reduced to the ratio

$$\frac{\text{pollen count inside the test room}}{\text{pollen count outside the test room}} = \frac{x}{m}\ .$$

## TABLE I. SUMMARY OF 1954 RAGWEED-POLLEN PENETRATION TESTS

All Samples Taken at 10 liter/min for 15 min

| Test No. | Sample No. | Date 1954 | Pollen Counts | | x/m % | Window | Bag Filter | Fan | Gust Count G' | Wind Speed $\overline{v}$(mi/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Outside m | Inside x | | | | | | |
| 1 | 1 | 8/30 | 19 | 3 | 15.8 | closed | off | off | 64 | 5.4 |
| | 2 | | 6 | 3 | 50.0 | closed | off | off | 150 | 4.0 |
| | 3 | | 34 | 3 | 8.8 | closed | off | off | 170 | 4.5 |
| 2 | 1 | 8/31 | 189 | 15 | 7.9 | closed | off | off | 280 | 5.6 |
| | 2 | | 218 | 21 | 9.6 | closed | off | off | 72 | 7.8 |
| | 3 | | 181 | 3 | 1.7 | closed | off | off | 200 | 6.6 |
| 3 | 1 | 9/1 | 98 | 16 | 16.3 | closed | off | off | 62 | 3.2 |
| | 2 | | 64 | 14 | 21.9 | closed | off | on | 63 | 3.4 |
| | 3 | | 53 | 8 | 15.1 | closed | on | on | 76 | 3.4 |
| | 4 | | 44 | 3 | 6.8 | closed | off | on | 38 | 3.0 |
| | 5 | | 72 | 13 | 18.1 | closed | off | on | 31 | 3.0 |
| 4 | 1 | 9/2 | 205 | 39 | 19.0 | closed | off | off | 24 | 2.5 |
| | 2 | | 182 | 24 | 13.2 | closed | off | on | 64 | 3.0 |
| | 3 | | 167 | 7 | 4.2 | closed | on | on | 16 | 2.5 |
| | 4 | | 139 | 16 | 11.5 | closed | off | on | 57 | 3.4 |
| | 5 | | 147 | 23 | 15.6 | closed | off | on | 47 | 3.5 |
| | 6 | | 117 | 15 | 12.8 | closed | off | on | 83 | 3.6 |
| | 7 | | 99 | 32 | 32.3 | closed | off | on | 51 | 3.2 |
| 5 | 1 | 9/3 | 173 | 15 | 8.7 | closed | off | off | 181 | 5.2 |
| | 2 | | 152 | 22 | 9.7 | closed | off | on | 140 | 4.1 |
| | 3 | | 105 | 8 | 7.6 | closed | on | on | 338 | 5.3 |
| | 4 | | 248 | 25 | 10.1 | open | off | on | 301 | 5.4 |
| | 5 | | 109 | 47 | 43.1 | open | off | on | 380 | 6.1 |

TABLE I (Concluded)

| Test No. | Sample No. | Date 1954 | Pollen Counts |  | x/m % | Window | Bag Filter | Fan | Gust Count G' | Wind Speed $\bar{v}$(mi/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Outside m | Inside x |  |  |  |  |  |  |
| 6 | 1 | 9/4 | 184 | 34 | 18.5 | open | off | on | 13 | 2.7 |
|  | 2 |  | 140 | 11 | 7.8 | closed | off | on | 12 | 2.6 |
|  | 3 |  | 196 | 4 | 2.1 | closed | off | on | 55 | 3.2 |
|  | 4 |  | 147 | 38 | 25.9 | open | off | on | 58 | 3.6 |
|  | 5 |  | 178 | 22 | 12.4 | open | off | on | 61 | 3.7 |
|  | 6 |  | 168 | 34 | 20.2 | open | off | on | 110 | 4.2 |
|  | 7 |  | 185 | 33 | 17.8 | open | off | on | 50 | 4.3 |
|  | 8 |  | 187 | 30 | 16.1 | open | off | on | 104 | 3.9 |
| 7 | 1 | 9/7 | 194 | 18 | 9.3 | closed | off | on | 120 | 3.0 |
|  | 2 |  | 40 | 0 | .0 | closed | on | on | 116 | 3.7 |
|  | 3 |  | 44 | 26 | 59.1 | open | off | on | 234 | 4.5 |
| 8 | 1 | 9/9 | 41 | 5 | 12.2 | closed | off | on | 17 | 2.8 |
|  | 2 |  | 17 | 6 | 35.3 | closed | on | on | 20 | 2.8 |
|  | 3 |  | 14 | 2 | 14.3 | closed | off | on | 15 | 3.3 |
|  | 4 |  | 18 | 18 | 100.0 | closed | off | on | 37 | 3.5 |
|  | 5 |  | 65 | 2 | 3.1 | closed | off | on | 46 | 3.9 |
|  | 6 |  | 49 | 8 | 16.3 | open | off | on | 106 | 4.4 |
|  | 7 |  | 42 | 3 | 7.1 | open | off | on | 21 | 3.5 |
| 9 | 1 | 9/10 | 38 | 9 | 23.7 | open | off | on | 486 | 5.6 |
|  | 2 |  | 23 | 3 | 13.1 | open | off | on | 281 | 5.9 |
|  | 3 |  | 38 | 8 | 21.1 | open | off | on | 365 | 5.6 |
|  | 4 |  | 20 | 16 | 80.0 | open | off | on | 348 | 5.4 |
|  | 5 |  | 35 | 15 | 42.9 | open | off | on | 176 | 4.6 |
|  | 6 |  | 38 | 11 | 28.9 | open | off | on | 339 | 5.4 |
|  | 7 |  | 77 | 25 | 32.5 | open | off | on | 539 | 7.5 |
|  | 8 |  | 44 | 15 | 34.1 | open | off | on | 573 | 7.6 |

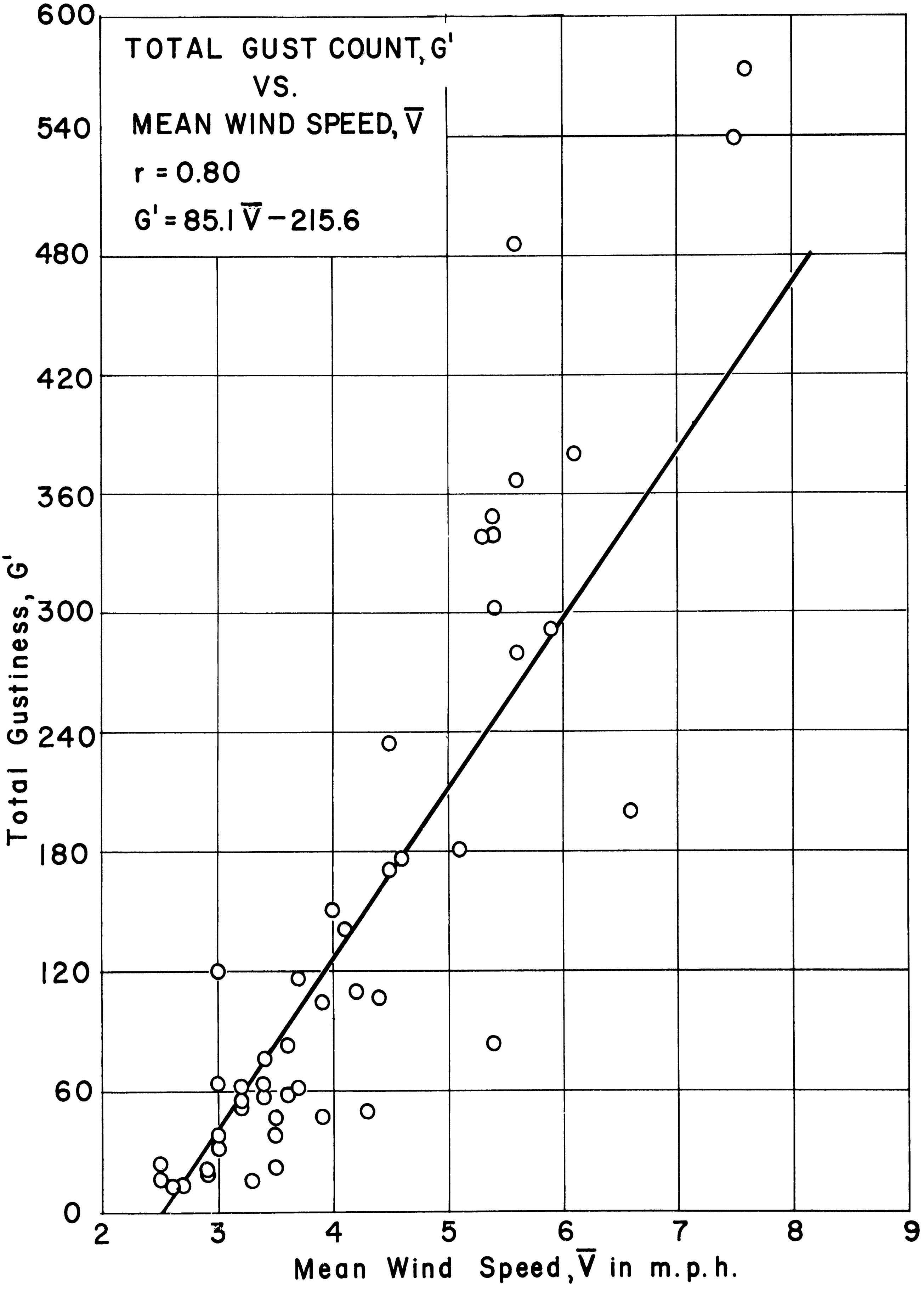

TOTAL GUST COUNT, G'
VS.
MEAN WIND SPEED, $\overline{V}$
r = 0.80
G' = 85.1 $\overline{V}$ − 215.6
Total Gustiness, G'
Mean Wind Speed, $\overline{V}$ in m.p.h.
600
540
480
420
360
300
240
180
120
60
0
2
3
4
5
6
7
8
9

Fig. 4.

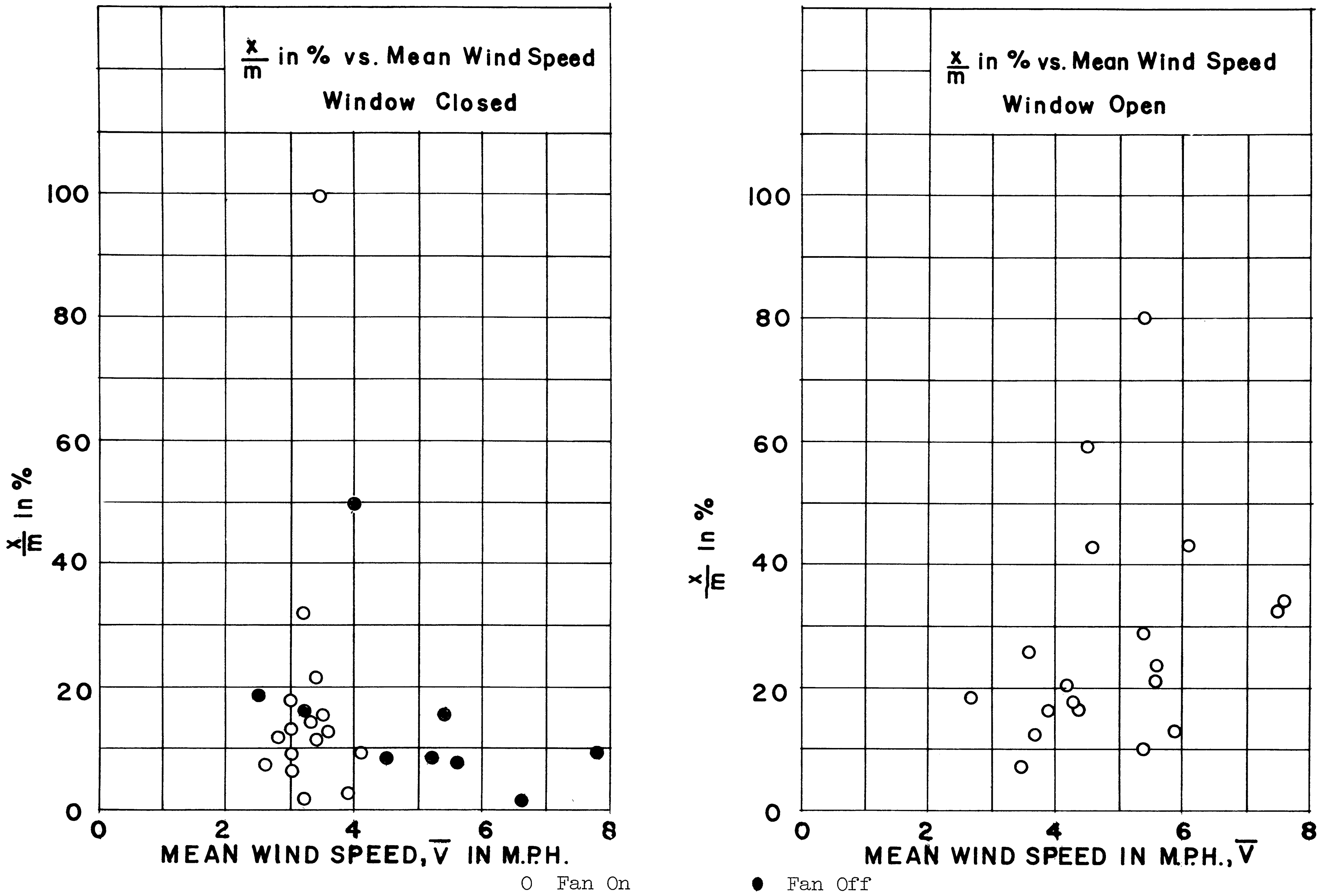

$\frac{x}{m}$ in % vs. Mean Wind Speed
Window Closed
$\frac{x}{m}$ in %
100
80
60
40
20
0
0
2
4
6
8
MEAN WIND SPEED, $\overline{V}$ IN M.P.H.
$\frac{x}{m}$ in % vs. Mean Wind Speed
Window Open
$\frac{x}{m}$ in %
100
80
60
40
20
0
0
2
4
6
8
MEAN WIND SPEED IN M.P.H., $\overline{V}$
O Fan On
● Fan Off

Fig. 5.

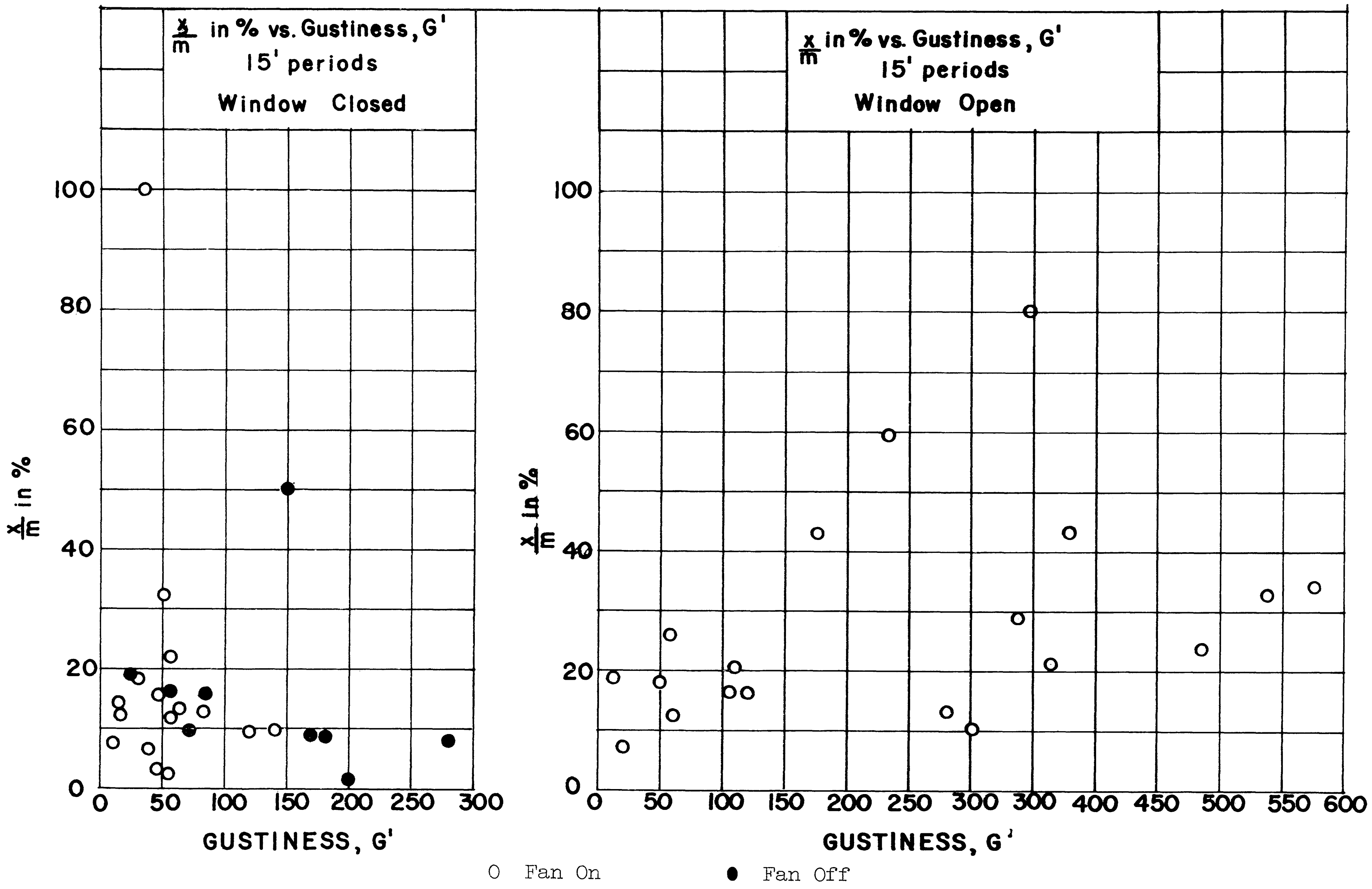

$\frac{x}{m}$ in % vs. Gustiness, G'
15' periods
Window Closed
$\frac{x}{m}$ in %
0
20
40
60
80
100
0
50
100
150
200
250
300
GUSTINESS, G'
$\frac{x}{m}$ in % vs. Gustiness, G'
15' periods
Window Open
$\frac{x}{m}$ in %
0
20
40
60
80
100
0
50
100
150
200
250
300
300
400
450
500
550
600
GUSTINESS, G'
○ Fan On
● Fan Off

Fig. 6.

Figures 5 and 6 show x/m plotted against $\bar{v}$ and G', respectively, for cases when the west window of the test room was closed and for those when it was open. As should be anticipated on the basis of the high correlation between G' and $\bar{v}$, the two pairs of graphs are quite similar. No strong relationship is apparent, but some general observations may be made: (a) the closed room was apparently too tight to be ventilated effectively by winds up to 8 mi/hr and gust counts up to 300 in 15 min; (b) some of the scattered points in the closed-window tests appear to be the product of experimental accident; (c) the open-window tests show some agreement with the general hypothesis that increased wind speed and/or gust count provides increased ventilation.

The question of experimental accident demands some elaboration. Two important possibilities were present in the experimental setup.

2.5.1 Accidents in Handling.—The experimental procedure was still in process of development. The necessity of handling the millipore filters before they could be examined (removing filter from sampling head, placing on microscope slide, staining with Calberla solution, and covering) and the difficulty of some of the steps introduced substantial chance for pollen grains to be lost from or added to the sample accidentally, particularly in the hands of inexperienced personnel.

2.5.2 Nonrepresentative Sampling.—Although a fan (12-in. diameter, oscillating) was used for the purpose of stirring the air in the test room during most of the tests, the furnishing of the room provided rather extensive baffles making a complete stirring of the test-room air very difficult. Some indication of this condition is evident in Fig. 2. In a few cases, however, tests were made with the fan off when the window was closed. These cases are indicated by the black circles in the left-hand portions of Figs. 5 and 6. Whereas one might infer from Fig. 5 that the inside samples (x) taken at wind speeds above 4 mi/hr would have been larger if the fan had been running, the three tests at 4 mi/hr and lower wind speeds with the fan off are not consistently lower than those with the fan on. The left-hand portion of Fig. 6 tends to indicate that a similar observation is appropriate in regard to the gustiness index, G'. On the basis of the comparison between the "fan on" and "fan off" results shown in Figs. 5 and 6, considering only those points at nearly equal values of wind speed and gustiness, it appears that having the fan on did not consistently or appreciably increase the counts obtained at the inside sampling position. This may be interpreted to mean that the stirring produced by the fan was insufficient to guarantee representative sampling at this position. Some further study of this problem is described below.

## 2.6 SPOT SAMPLING TESTS

A series of tests was made near the end of the ragweed-pollen season (September 7-20, 1954) in order to see how well the pollen count taken at the position of the inside sampler represented the concentration in the room. Because it was not possible to sample volumetrically at many positions in the room at once, the tests were made gravimetrically by the use of upward-facing microscope slides distributed as shown in Appendix A. A summary of the results of these tests is presented in Table II. More complete data are presented in Appendix A.

TABLE II. RESULTS OF SPOT SAMPLING TESTS, 1954

| Test | Date | Duration (hr) | Window | Fan | No. of Samples | x/Avg. % |
|---|---|---|---|---|---|---|
| 1 | 9/4-7 | 65 | open | off | 4 | 50 |
| 2 | 9/7-8 | 16 | open | on | 4 | 89 |
| 3 | 9/10-11 | 18 | open | on | 4 | 83 |
| 4 | 9/11 | 2 | closed | off | 4 | 44 |
| 5 | 9/13-14 | 24 | open | on | 9 | 91 |
| 6 | 9/16 | 1 | open | on | 6 | 190 |
| 7 | 9/17-18 | 15 | open | on | 10 | 82 |
| 8 | 9/19-20 | 24 | open | off | 8 | 71 |

These tests are all much longer than the sampling periods used during the penetration tests. The reason for this is that the ragweed-pollen pollution had fallen off considerably, and longer periods were required to collect an adequate sample. Furthermore, by the expedient of placing slides at the close of the working day and collecting them at the beginning of the next working day, these samples could be obtained without disturbing other phases of the experimentation. Apparently, according to the above results, the fan did produce a marked effect at the sampling position. The 1-hr test, No. 6, shows x to be nonrepresentative mainly because the individual samples were small (see Appendix A). Otherwise the tests with the window open and the fan on show x to be in the range 82 to 91 percent of the average, which should be judged fairly representative. Those with the fan off give distinctly unrepresentative samples at position x. Extension of the time of sampling appears not to improve representativeness when the fan is not used, but appears to be quite important when the fan is used, especially when pollen concentrations in the air are low. It is therefore concluded that the 15-min sampling periods used in the penetration tests were probably too short to provide representative samples inside the test room except at the height of the pollen season, and at least some of the scatter of the points in Figs. 5 and 6 is accountable to this factor. It should be clear, however, that the time required to procure a representative sample might be reduced by improving upon the thoroughness of stirring of the test-room air.

# CHAPTER 3

# EXTRA-SEASONAL EXPERIMENTATION AND PREPARATIONS, 1954-1955

One of the important special characteristics of the ragweed-pollen grain as an interesting and useful particle for the study of dispersion and penetration of atmospheric contaminants is its relatively uniform size, near 20-μ diameter. Comparatively little study of the behavior of particles of this size in the natural wind field has been made. Because ragweed pollen is both procurable and identifiable, the relatively rare opportunity to study natural dispersion in this special size category appeared obvious. In addition, for penetration studies, extra-seasonal experimentation with ragweed pollen provides an identifiable particulate that may be dispensed artificially to provide a pollen "shower" on the test structure. Experimentation with artificial dispensation of pollen from the bulk supply was undertaken with this objective and that of studying pollen cloud dispersal in view.

## 3.1 ARTIFICIAL DISPENSATION OF RAGWEED POLLEN

A bulk supply of pollen of Ambrosia trifida was procured from the Greer Drug Company, Lenoir, N. C. Investigation and experimentation led to the design of a small dust atomizer (Fig. 7) which served very well to produce puffs of well-separated pollen grains from the bulk supply. Operation of the atomizer is as follows:

> A source of compressed air (about 15 lb/in.$^2$) is connected to tube A. When the air valve is opened, the resulting jet from the drawn tip lowers the pressure at the venturi. When valve B is opened, air enters the pollen reservoir C through tube D in a jet which impinges on the bulk pollen and whirls it against the wall of the reservoir. The pollen-laden air current proceeds upward peripherally and passes to the venturi via tube E. In these steps pollen clumps are reduced in size by violent turbulence and erosion, and in number by centrifugal and gravitational action. Finally, in passing through the high-velocity section of the venturi and into the low-velocity region above the outlet tube, the pollen passes through one more highly turbulent and erosive region.

The atomizer was made small so that the amount of pollen dispensed could be measured by weighing in a microbalance. Total mass of the unit is about 35 gm divided between the reservoir section (21 gm) and the nozzle section (14 gm). A charge of about 0.5 gm of pollen (roughly 1.9 x $10^8$ pollen

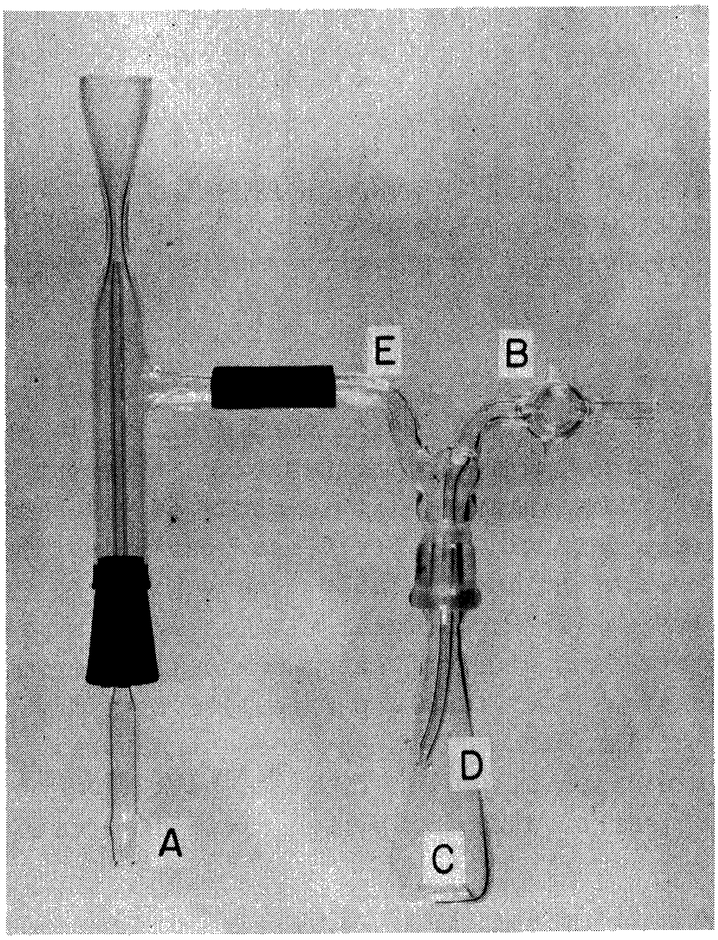


Fig. 7. The Pollen Atomizer.

grains) was used. The buildup of electrostatic charge on the atomizer was a source of difficulty because it caused the pollen to coat the entire nozzle during operation and thus made post-dispensation weighing more or less futile. This difficulty can be reduced by coating the glass with a very thin conductive film (e.g., by dipping in silver nitrate solution and drying before use) and grounding the nozzle. This was not done during this set of experiments because as the work proceeded knowledge of the amount of pollen dispensed appeared to be a secondary matter.

### 3.2 POLLEN PLUME DISPERSAL

For the purpose of sampling the artificial pollen plumes to examine the behavior of the pollen in the wind field, frames were designed to support samplers in a spatial array. The arrangement is shown in Fig. 8. Each sampling station supported two petrolatum-coated microscope slides, one vertical facing upwind and one horizontal facing upward.

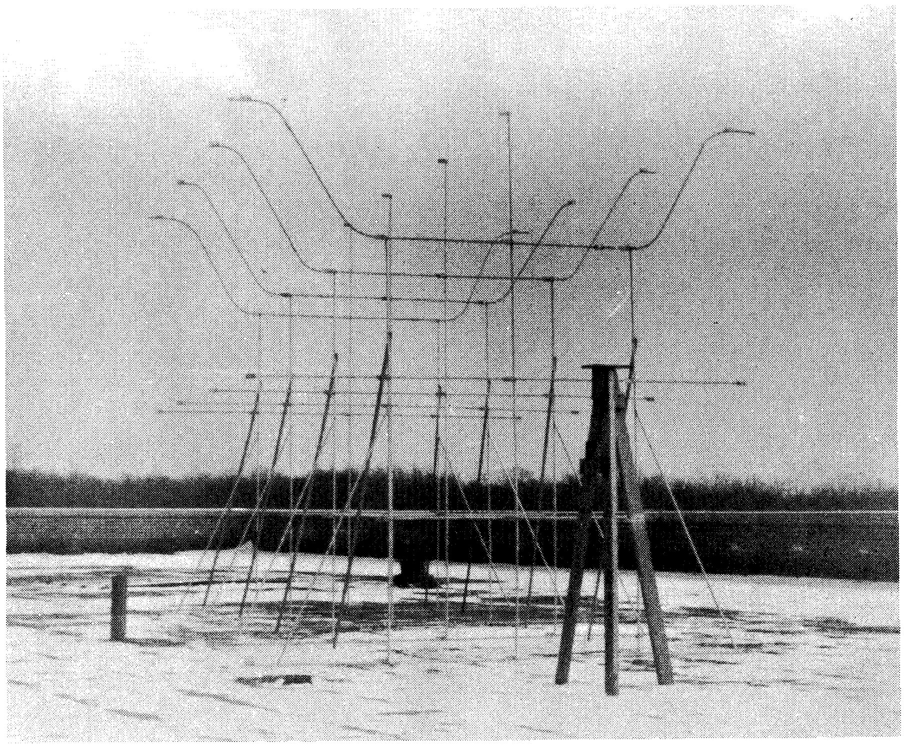


Fig. 8. The Spatial Sampling Array.

The results of one preliminary experiment with this method are shown in Figs. 9 through 11. This particular experiment was run at 1530 hr on January 28, 1955. About 0.2 gm of pollen was dispensed in about 30 sec. The wind was from WNW, 6-10 mi/hr, gusty; the weather was cool (20°F) and partly cloudy with cirrus predominating. In the graphic presentation of the results, the isopleths are drawn for 5, 10, 50, and 100 pollen grains per slide. Several comments may be made. First of all, it is interesting that the upward-facing horizontal slides (Fig. 9) caught no significant numbers of pollen grains, with only two exceptions: (a) the slide at station B-2H (6 ft above and 12 ft downwind from the source) caught 31 pollen grains and (b) the slide at station C-6H (3 ft above, 3 ft to the right, and 18 ft downwind from the source) caught 35. This suggests that concentrated fallout or downward impaction of pollen tended to occur in relatively narrow streamers. Secondly, the vertical slides yielded an interesting distribution of counts. In vertical cross section (Fig. 10) we find that the pollen plume remained quite symmetric with respect to its axis for the first 6 ft (frame A), but that in the next 6 ft the plume split into two distinct maxima, each displaced from the initial axis (frame B). On frame C, 18 ft downwind, the plume seems to have missed the samplers, for on frame D the sample of 20 is more than double the maximum sample caught on the vertical samplers of frame C. In horizontal section (Fig. 11) the vertical samplers 3 ft above and at the level of the source appear to provide the most interesting patterns of data.

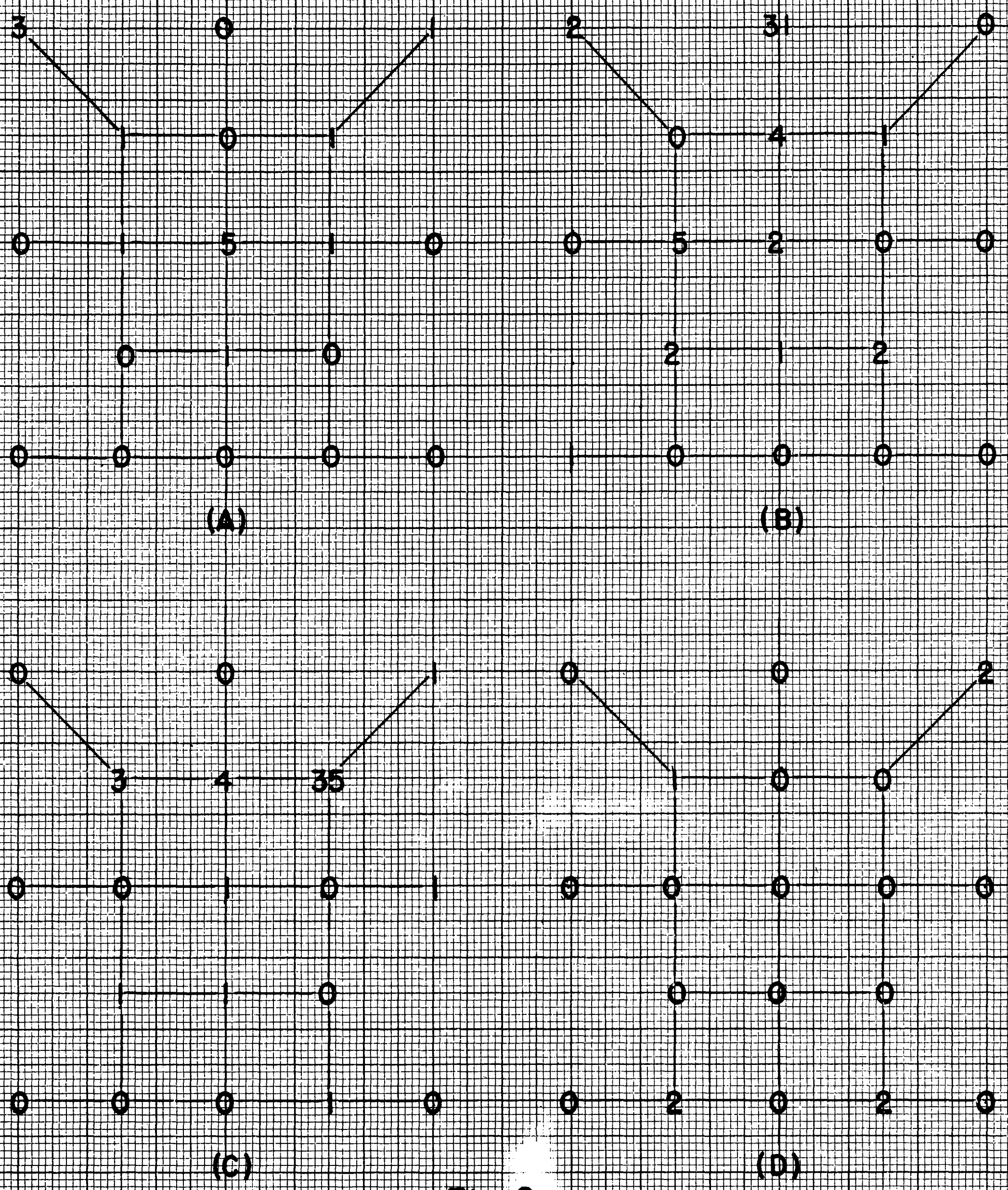


Fig. 9
Vertical cross sections thru plume showing catch on horizontal slides, Jan. 28, 1955

A – 6 ft. from source

Scale: 1cm = 2 ft.

B – 12 ft. from source

C – 18 ft. from source

D – 24 ft. from source

Fig. 9.

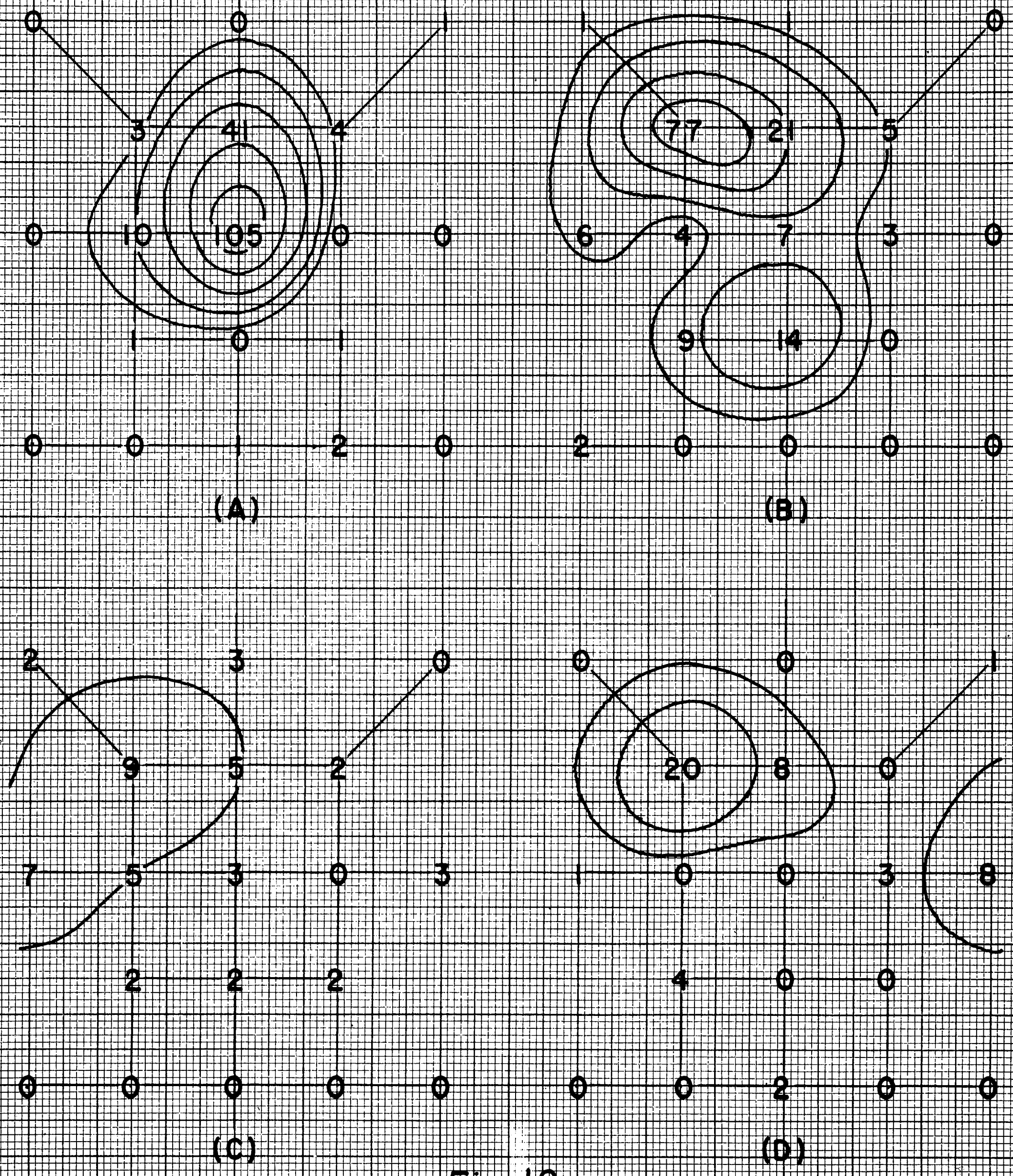


Fig. 10
Vertical cross-sections thru plume showing catch on vertical slides, Jan. 28, 1955

A – 6 ft. from source

B – 12 ft. from source

C – 18 ft. from source

D – 24 ft. from source

Scale: 1 cm = 2 ft.

Fig. 10.

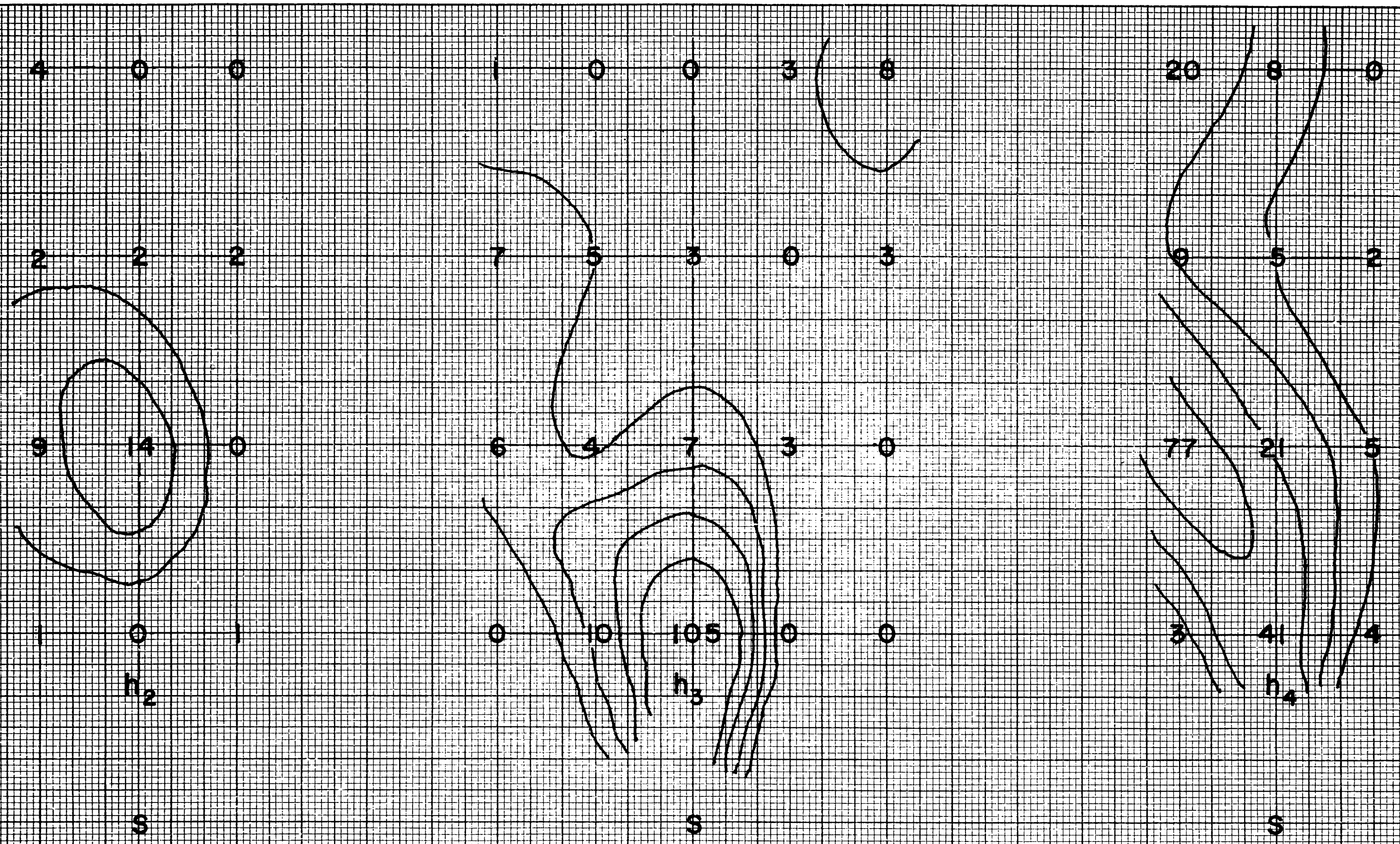


Fig. 11 — Horizontal sections thru plume showing catch on vertical slides, Jan. 28, 1955

$h_2$ — 3' below source

Scale: 1 cm = 2 ft.

$h_3$ — at level of source

$h_4$ — 3' above source

S — Source

Fig. 11.

The vertical slide counts do not in any way aid in explaining the two significant horizontal slide counts. Quite evidently one gets two different impressions of the behavior of the pollen plume, depending on which set of counts he studies. This suggests that a closer array of samplers should be used for tracing plumes of such short duration as this one (about 30 sec).

A second relatively successful experiment was run on April 29, 1955, at 1550 hr. The wind was again gusty as shown by the wind-speed record. (Table III. This table was obtained by the method outlined in Appendix B.) The wind direction was changeable at the experimental site (roof of East Engineering Building), shifting from NE to NW within a minute or so, and, accordingly, the frames were oriented to face north. In this experiment the pollen was emitted in a series of 50 puffs over a time period of about 1.5 min, and the puffs were observed to drift toward SE at first, then toward S, and later toward SW. The results of this experiment are shown in Figs. 12 through 14.

TABLE III. WIND-SPEED RECORD ANALYSIS, APRIL 29, 1955

| Time | $\bar{V}$ (mi/hr) | Gusts (mi/hr) | | | | | |
|---|---|---|---|---|---|---|---|
| | | ± 1 | ± 2 | ± 3 | ± 4 | ± 5 | Total |
| 1550-1551.5 | 5.1 | 11 | 8 | 7 | 2 | 0 | 28 |

The distribution patterns shown by the horizontal and vertical slides in this experiment (Figs. 12 and 13) are more nearly alike than those shown in the first experiment. The catch of the horizontal slides was again markedly less than that of the vertical slides on the nearer frames, but they are remarkably similar on frame D, 24 ft from the source. The horizontal spreading observed during the experiment shows up in Fig. 13 on the nearest frame, but the plume appears to have changed shape and orientation rapidly as it progressed downwind. The four horizontal sections of Fig. 14 present another view of the distribution, emphasizing its changeable character.

Isolated large counts did not occur in the second experiment the way they did in the first one. Obviously, this may be attributed either to the difference of the time "duration" of the plume or to basic differences in the character of turbulence encountered, or to both. Both experiments were influenced strongly by turbulent elements produced by the building itself and by obstructions on the roof. It therefore appears likely that the effect of increasing the duration of the plume by using puffwise emission in the second experiment helped to eliminate spotty results. Because one objective of the experiments was to develop a technique for use in bathing the test room with an artificial shower of pollen, the elimination of the inexplicable spotty counts was important.

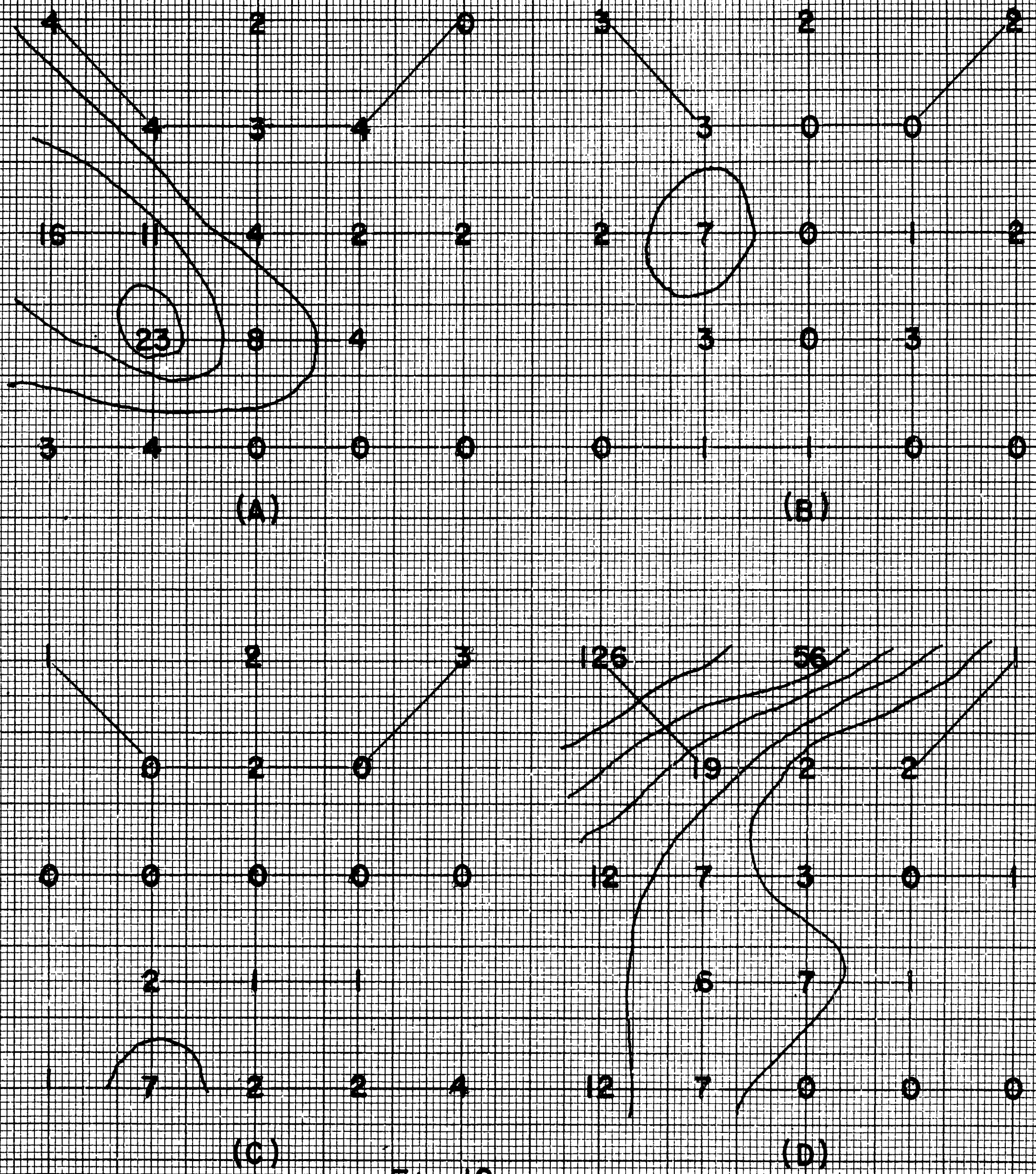


Fig. 12

Vertical sections thru plume showing catch on horizontal slides

April 29, 1955

A – 6' from source

B – 12' " "

C – 18' " "

D – 24' " "

Fig. 12.

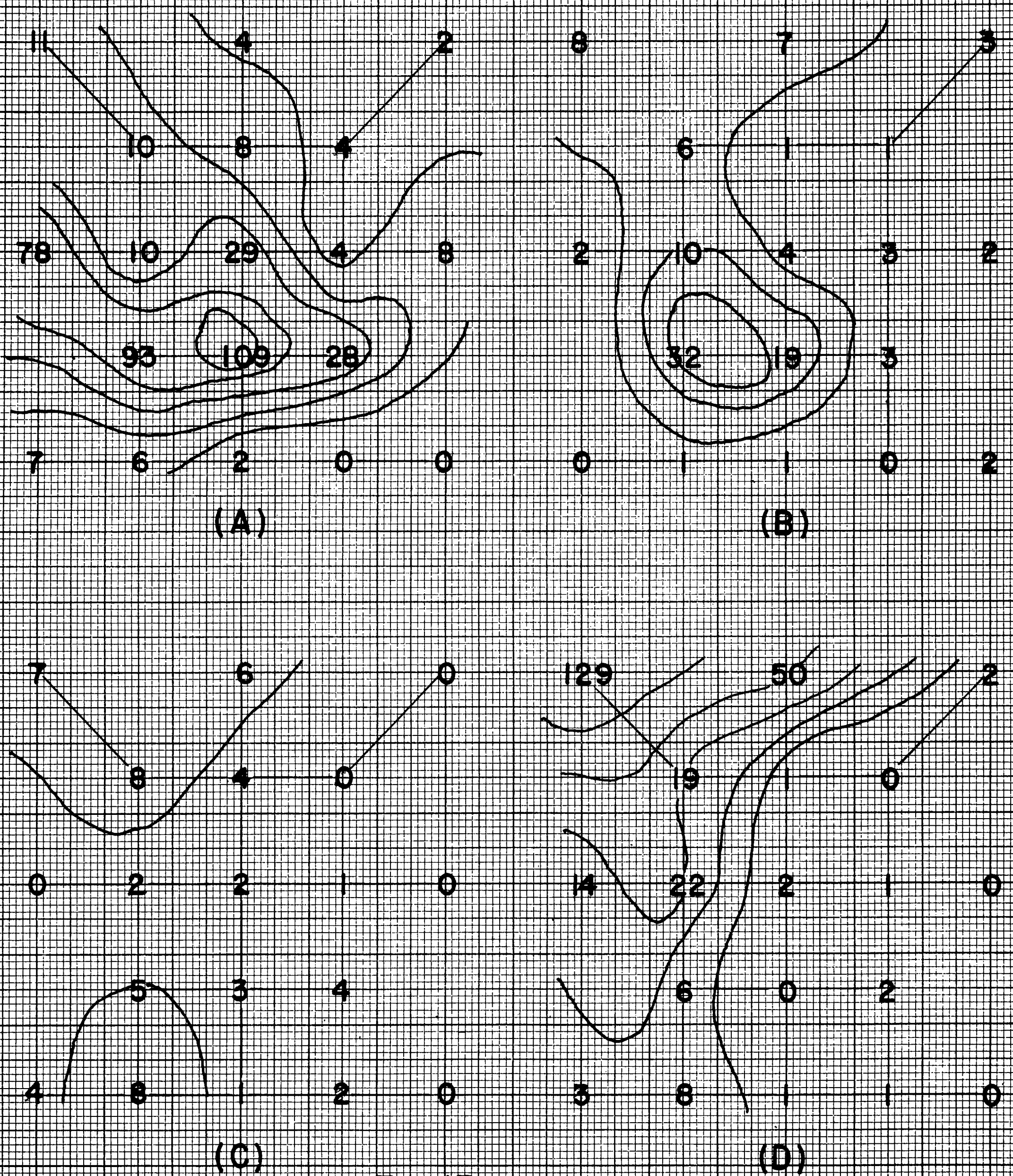


Fig. 13
Vertical sections thru plume showing catch on vertical slides

April 29, 1955

A – 6' from source

B – 12' " "

C – 18' " "

D – 24' " "

Fig. 13.

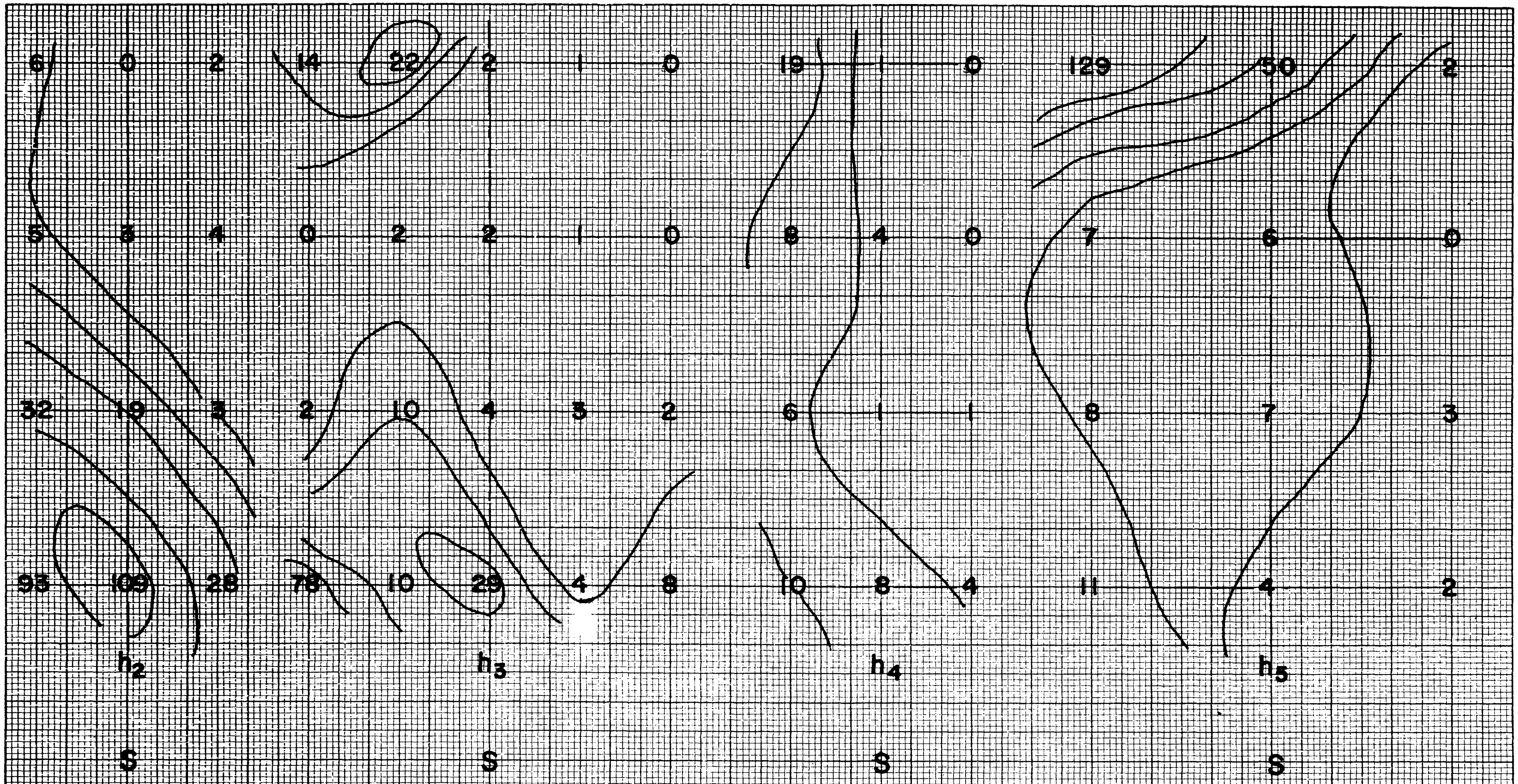


Fig. 14 – Horizontal sections thru plume showing catch on vertical slides, April 29, 1955

$h_2$ – 3' below source    S - Source    Scale: 1 cm = 2 ft.

$h_3$ – at level of source

$h_4$ – 3' above source

$h_5$ – 6' above source

Fig. 14.

## 3.3 PENETRATION

The roof area adjacent to the test room is badly obstructed by ventilators and other superstructures (see Fig. 1b). The possible arrangements of the spatial array of samplers were therefore so limited that it was not possible to arrange the array in the most desirable geometric relation to the wind direction for the penetration experiment. Thus, although the wind on May 16, 1955, was blowing mainly from NE, the array was arranged as shown in Fig. 15. The wind speed averaged 4.4 mi/hr during the period of emission of the pollen. Evaluation of the wind trace is given in Table IV. The puffwise dispensing technique was used over a period of about 1 min 50 sec, for which the first line in the table is given. Difficulty was encountered in finding the best source position for the experiment because of the variability of the wind direction, but the results indicate that the mission was successfully accomplished (Figs. 16 through 19).

TABLE IV. WIND-SPEED RECORD ANALYSIS, MAY 16, 1955

| Time (min) | $\bar{v}$ (mi/hr) | Gusts (mi/hr) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ± 1 | ± 2 | ± 3 | ± 4 | ± 5 | ± 6 | ± 7 | Total |
| 0-1.8 | 4.4 | 15 | 11 | 4 | 1 | 1 | 1 | 0 | 33 |
| 0-3 | 3.8 | 17 | 14 | 2 | 1 | 1 | 1 | 1 | 37 |
| 3-6 | 3.4 | 22 | 12 | 3 | 2 | 2 | 1 | 1 | 43 |
| 6-9 | 3.6 | 25 | 11 | 5 | 2 | 0 | 0 | 0 | 43 |
| 9-12 | 4.0 | 30 | 19 | 7 | 4 | 2 | 1 | 1 | 64 |
| 12-15 | 4.7 | 30 | 20 | 10 | 5 | 3 | 2 | 0 | 70 |
| 15-18 | 4.8 | 18 | 21 | 14 | 4 | 2 | 3 | 2 | 64 |

It is clear from Fig. 15 and from the results that the pollen plume cut across the array from left to right (from NE toward SW). The relative evenness of the distribution of pollen caught by the vertical slides of frame D (Fig. 17) is gratifying since this frame was nearest the test room. The breadth and evenness of the plume 6 ft above the roof surface on frame D is also favorable for the estimation of the degree of pollen fumigation of the test room via the open west window.

In addition to the monitoring of the pollen plume by means of the spatial array of samplers, six successive 3-min volumetric samples were taken inside the test room, starting at the time that pollen emission began. The results of these measurements are given in Table V.

The results of the analytical considerations of Section 4.4 may be applied to the data of Table V in order to compute the effective ventilation

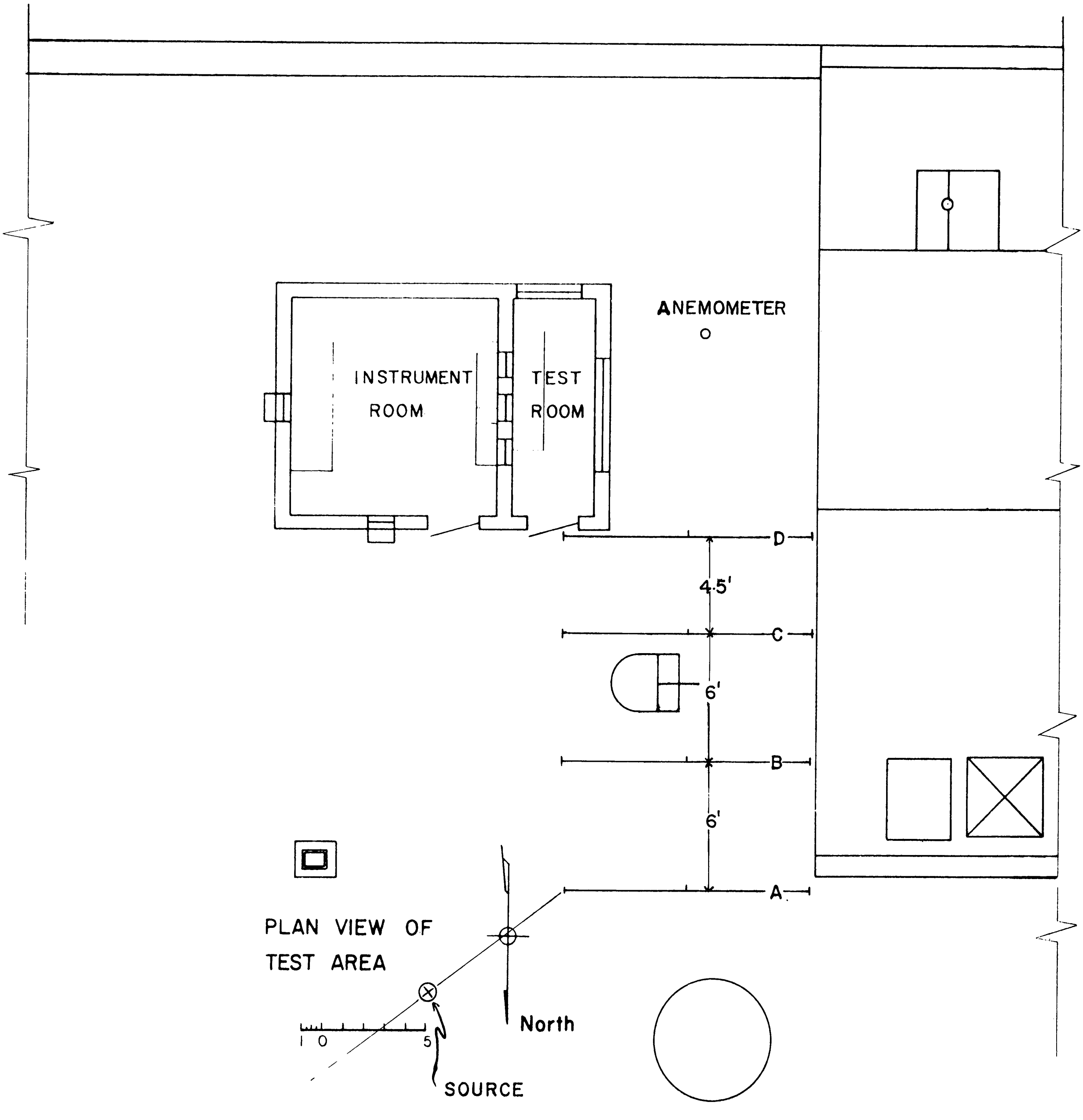

ANEMOMETER
INSTRUMENT ROOM
TEST ROOM
D
4.5'
C
6'
B
6'
A
PLAN VIEW OF TEST AREA
North
SOURCE
1 0 5

Fig. 15.

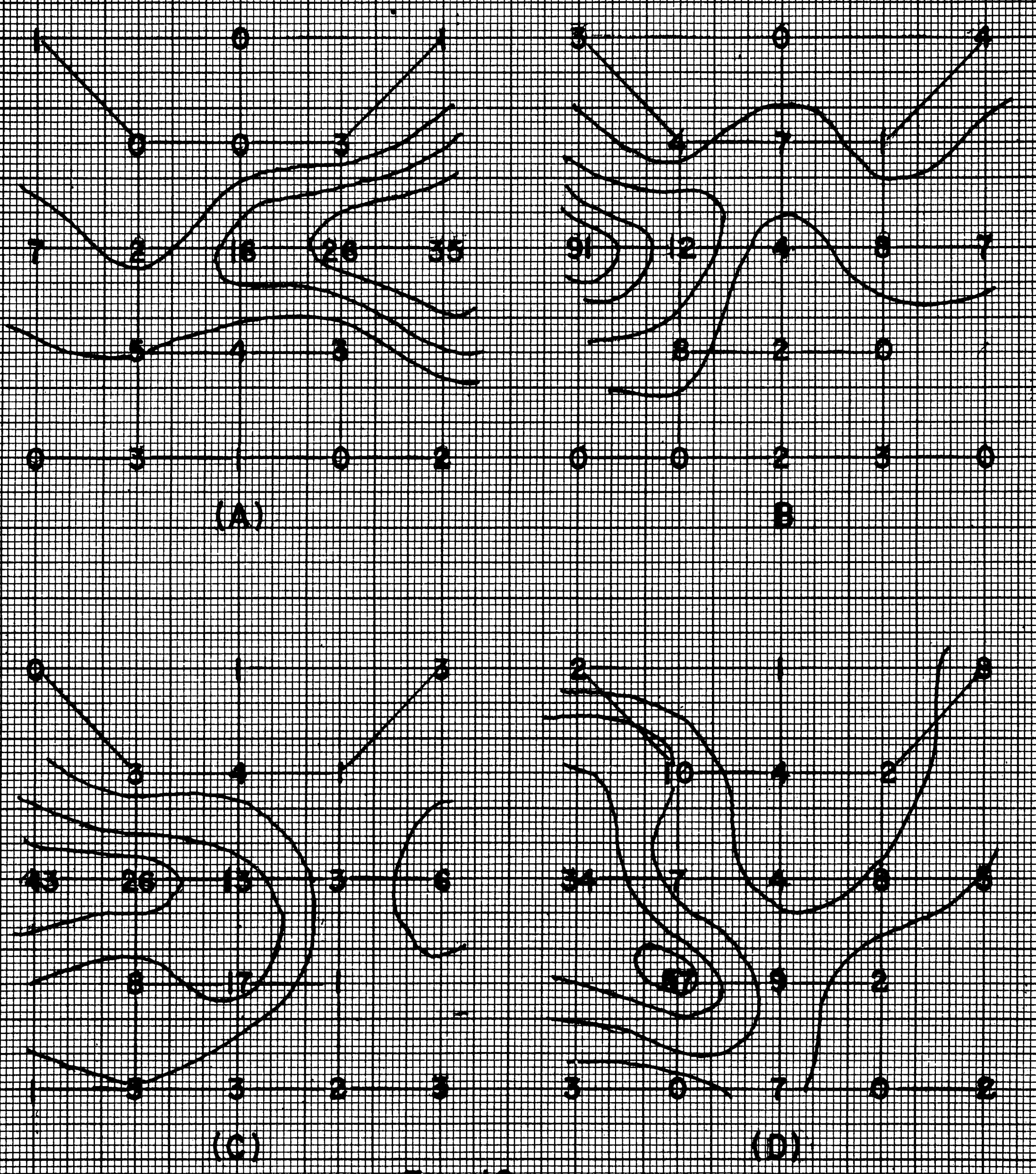


Fig. 16
Vertical sections thru plume showing catch on horizontal slides

May 16, 1955

Fig. 16.

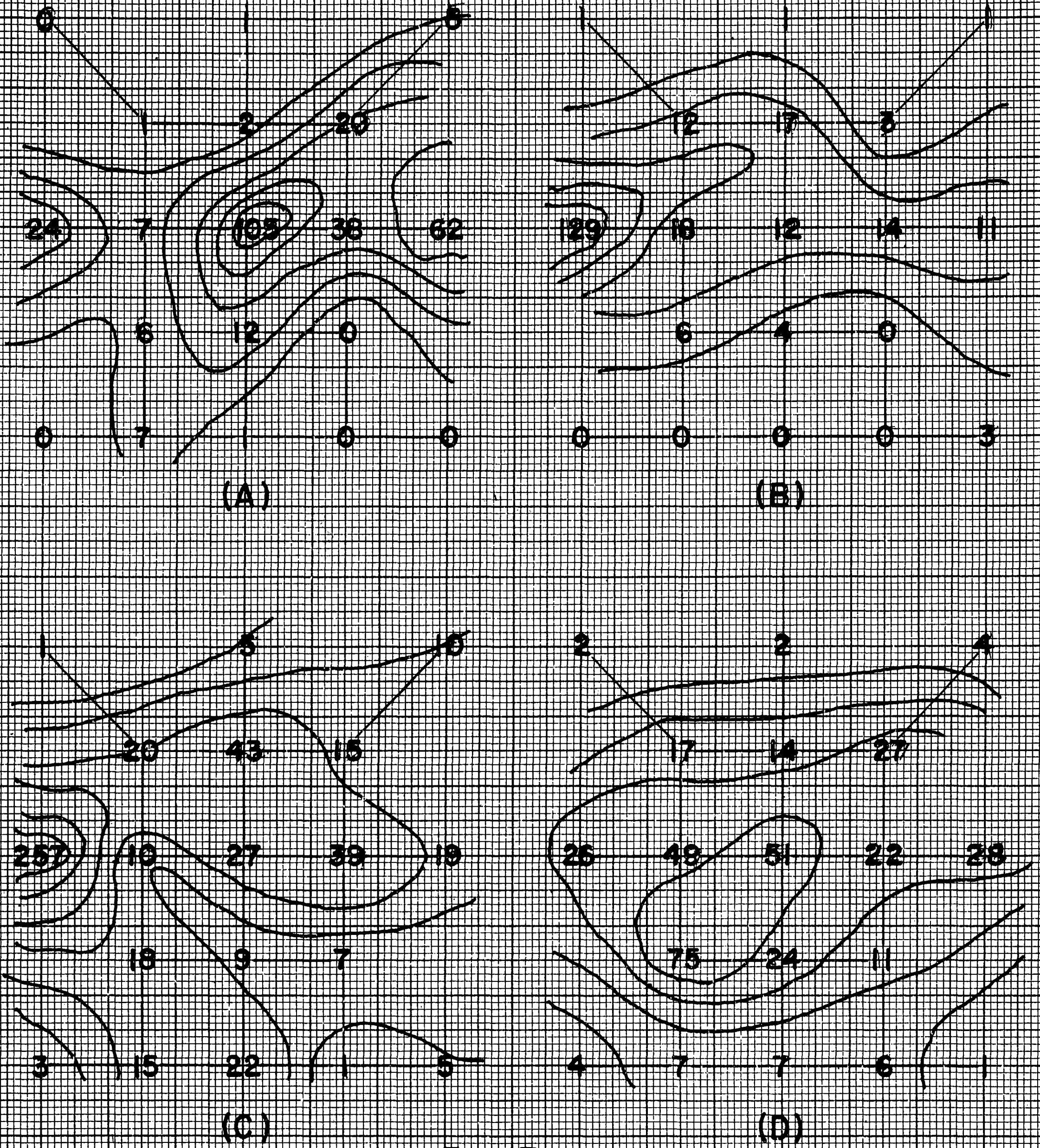


Fig. 17
Vertical sections thru plume showing catch on vertical slides

May 16, 1955

Fig. 17.

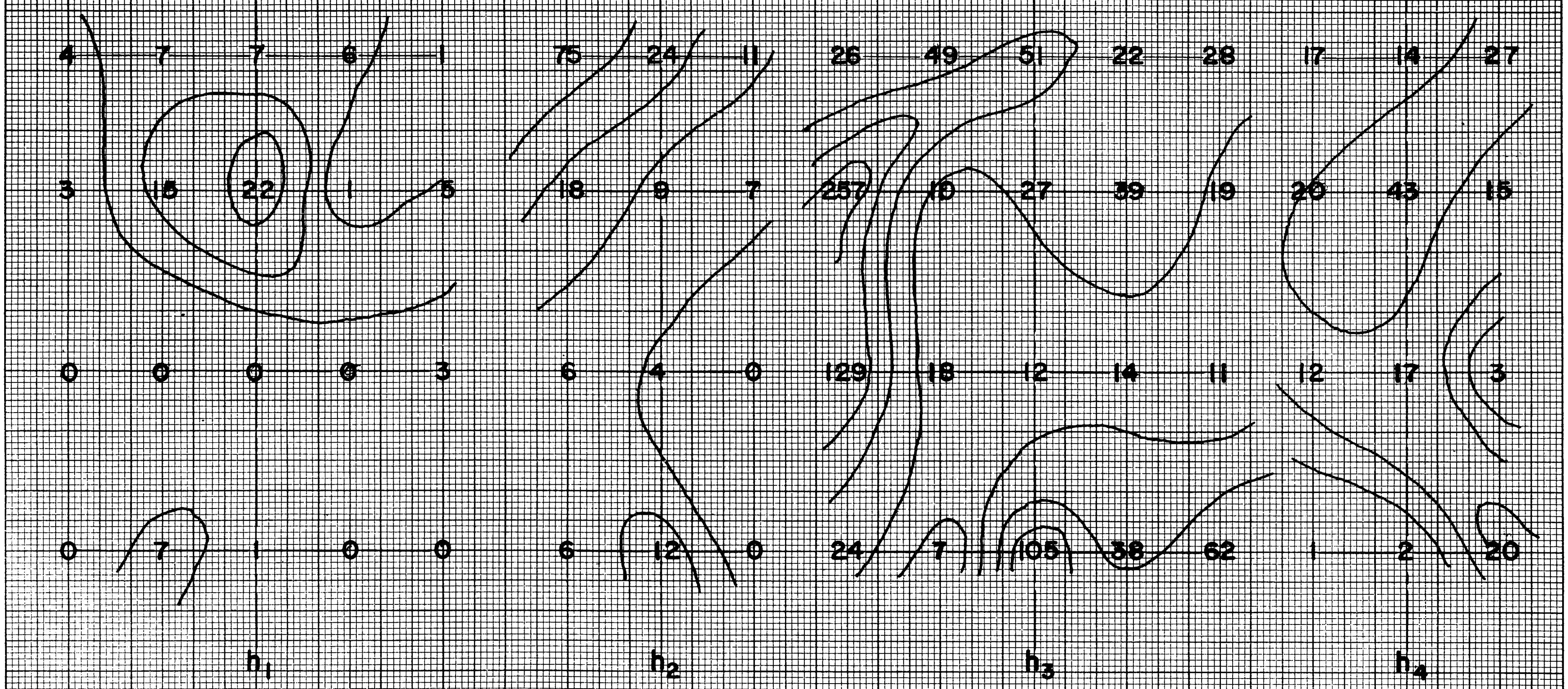


Fig. 18 — Horizontal sections thru plume showing catch on vertical slides, May 16, 1955

$h_1$ — 6' below source

$h_2$ — 3' below source

$h_3$ — at level of source

$h_4$ — 3' above source

Scale: 1cm = 2'

Fig. 18.

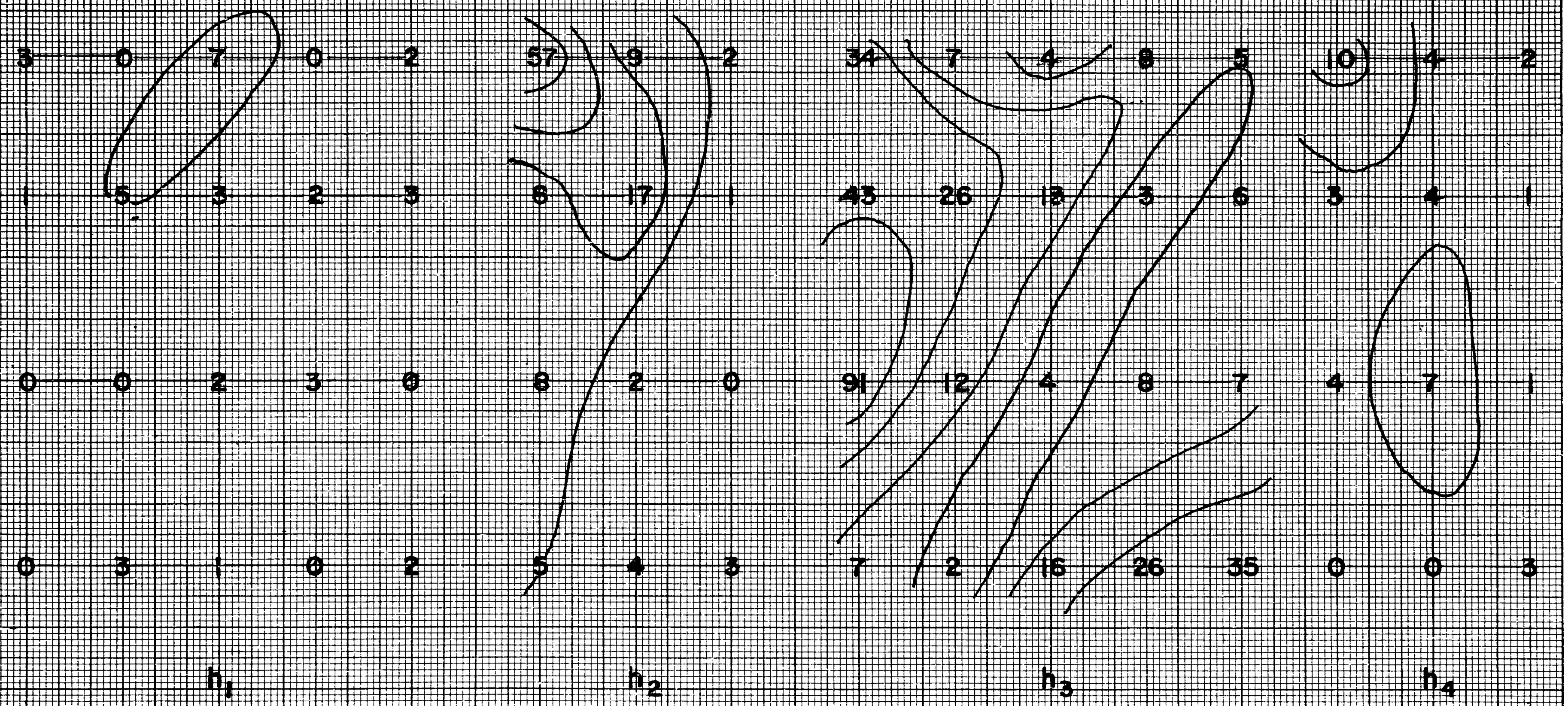


Fig. 19 —Horizontal sections thru plume showing catch on horizontal slides, May 16, 1955

Scale: 1 cm = 2 ft.

$h_1$— 6' below source

$h_2$— 3' below source

$h_3$— at level of source

$h_4$— 3' above source

Fig. 19.

TABLE V. VOLUMETRIC POLLEN COUNTS IN TEST ROOM, MAY 16, 1955

| Sample No. | Time (min) | Pollen Count | Average Wind Speed (mi/hr) | Total Gusts | Average Ventilation Rate $k_3$ |
|---|---|---|---|---|---|
| 1 | 0-3 | 94 | 3.8 | 37 | 0.866 |
| 2 | 3-6 | 25 | 3.4 | 43 | 0.654 |
| 3 | 6-9 | 12 | 3.6 | 43 | 0.642 |
| 4 | 9-12 | 6 | 4.0 | 64 | 0.897 |
| 5 | 12-15 | 1 | 4.7 | 70 | 0.420 |
| 6 | 15-18 | 1 | 4.8 | 64 | |

rate of the test room in this experiment. Assuming (a) that each sample represents the concentration of pollen in the test room, x, at the middle instant of each sampling period, and (b) that the polluted outside air blew away so that the outside pollen concentration, m, was zero after the first sampling period, the ventilation rate may be computed for each time interval from midperiod to midperiod according to the equation for $k_3$, i.e., m = constant. The results of these computations are entered in the right-hand column of Table V. The last two values are obviously questionable because the samples were too small to give reliable results. The first three values, however, are relatively firm values. In particular, the second and third figures (0.654 and 0.642), by virtue of the validity of the assumption that m = 0, and in view of their similarity, appear to be quite good. Further consideration of k will be undertaken below in Chapter 4.

## 3.4 PREPARATIONS

Experience acquired in the experiments on the roof of the East Engineering Building suggested that the wind field over the rooftop test sites was so disturbed by local obstructions and general turbulence around the building that a new site should be located and equipped for the 1955 ragweed-pollen season. Upon inquiry it was discovered that the project could obtain the use of a construction field office from the Detroit contracting firm of Darin and Armstrong. A field site was chosen in an open meadow on newly procured University property adjacent to the North Campus. This meadow was planted with a hay crop which was harvested just prior to the ragweed-pollen season, so the relative absence of ragweed-pollen sources in the meadow itself was assured.

3.4.1 The North Campus Field Site.—A topographic map of the area is shown in Fig. 20. Contours on this map are drawn at 1-ft intervals. The symbols plotted on this map are the result of the botanical survey and indicate the concentration of ragweed plants (*Ambrosia elatior*) according to the following scheme:

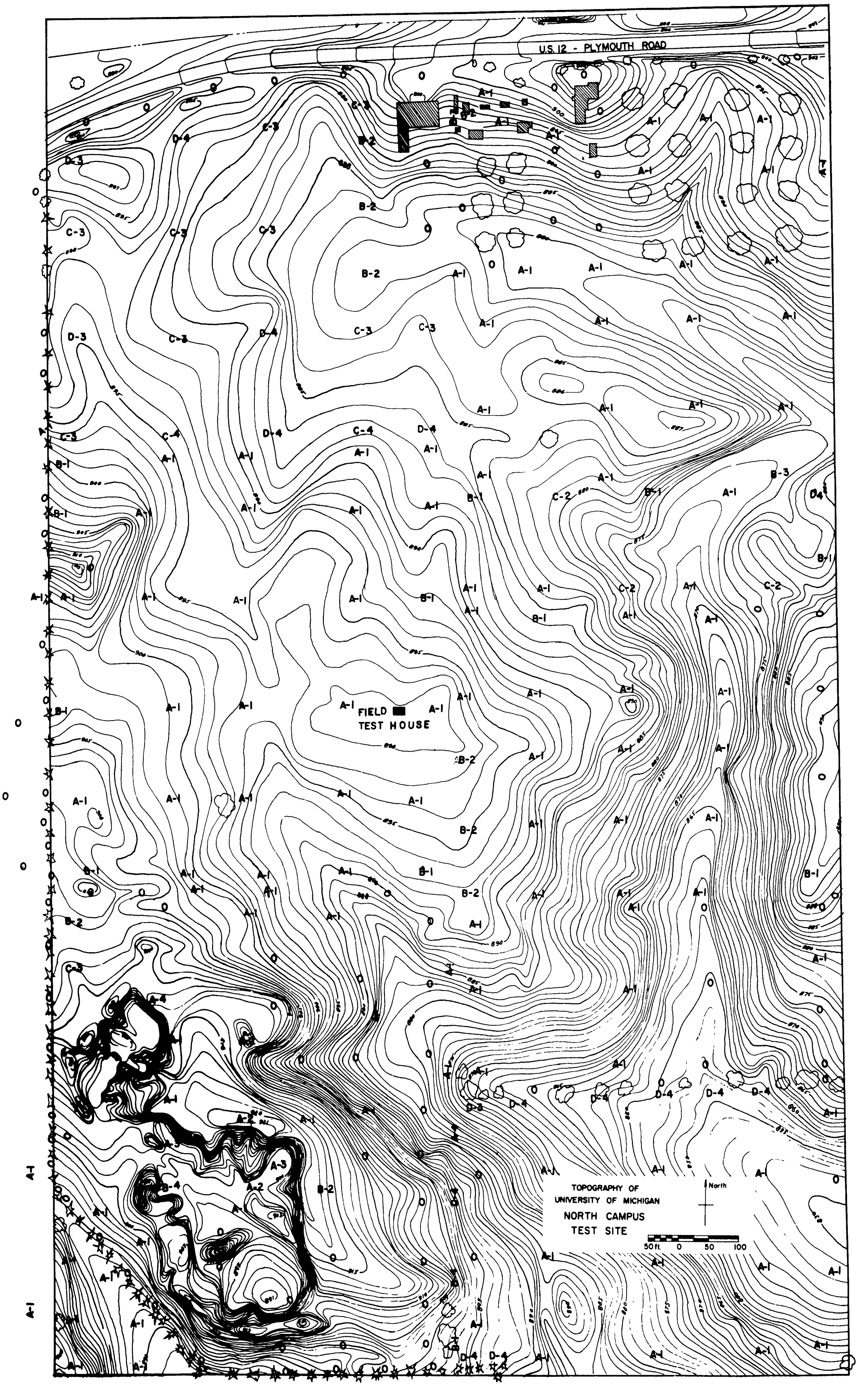


Fig. 20. Topographic Map of Field Site Showing Ragweed Survey Results.

Abundance is an expression of the number of individual plants per $m^2$ in four classes:

| | |
|---|---|
| A | 1-10 plants/$m^2$ |
| B | 11-20 plants/$m^2$ |
| C | 21-30 plants/$m^2$ |
| D | 31-40 plants/$m^2$ |

Density is a measure of the proportion of space occupied by the ragweed plants, arrived at by visual estimate and coded in four classes:

| | |
|---|---|
| 1 | 1-25 percent cover |
| 2 | 26-50 percent cover |
| 3 | 51-75 percent cover |
| 4 | 76-100 percent cover |

The relative paucity of ragweed plants in the vicinity of the test site is evident from this map.

3.4.2 *The Experimental Structure*.—The test house is shown in Fig. 21. It is of frame construction, relatively well-built for a field-office type of building, and differing from conventional frame structures mostly in that it is built upon heavy skids and strengthened for portability. Structural characteristics are shown in Fig. 22. Overall dimensions are 12 ft x 20 ft. The windows and doors are placed symmetrically in the west-, south-, and east-facing walls, the north wall having no openings. To provide suitable separation of the test-room portion (Fig. 23) and the instrument room (Fig. 24), a plywood partition was installed 8 ft from the east end. The test room was therefore 12 ft square in plan and 7 ft high, with one window (double hung, 26 in. x 54 in.) in the west wall and one in the south wall, besides a door (34 in. x 80 in.) in the south wall.

3.4.3 *The Instrumentation*.—The test room was equipped with four 12-in.-diameter oscillating fans, one in each corner of the room, each directed toward the center of the room, for the purpose of stirring the air thoroughly during all sampling runs. Although no tests similar to those described above for representativeness of the samples were made, the simplicity of the room shape, absence of furniture, and intensity of stirring provided by the four fans combined to assure a better sampling situation than that available in the rooftop test room.

Two electrostatic precipitators (Fig. 23) were used during the cleaning operation between tests. In addition, hand cleaning was done, and a vacuum sweeper was used. The samplers were hung in the center of the test room at a height of 6 ft above the floor. The outdoor air samplers were hung from a scaffold (Fig. 21) at a height of 7 ft above the ground and about 8 ft from the south wall of the test house. The Beckman-Whitley anemometer was erected nearby at a level of 8 ft above the ground.

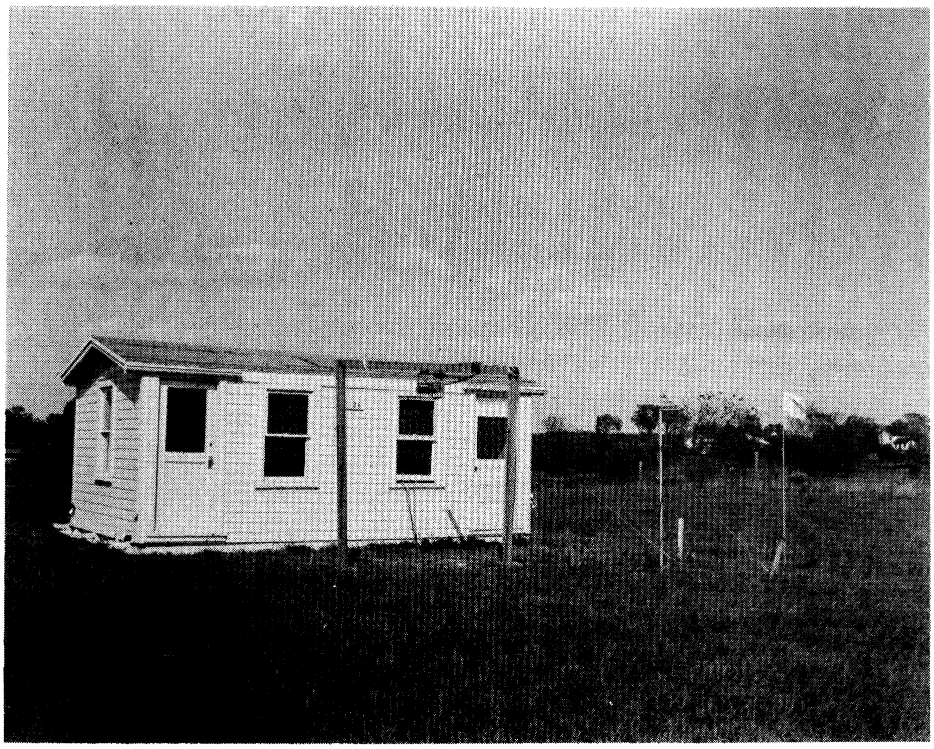


Fig. 21. The Field Test House

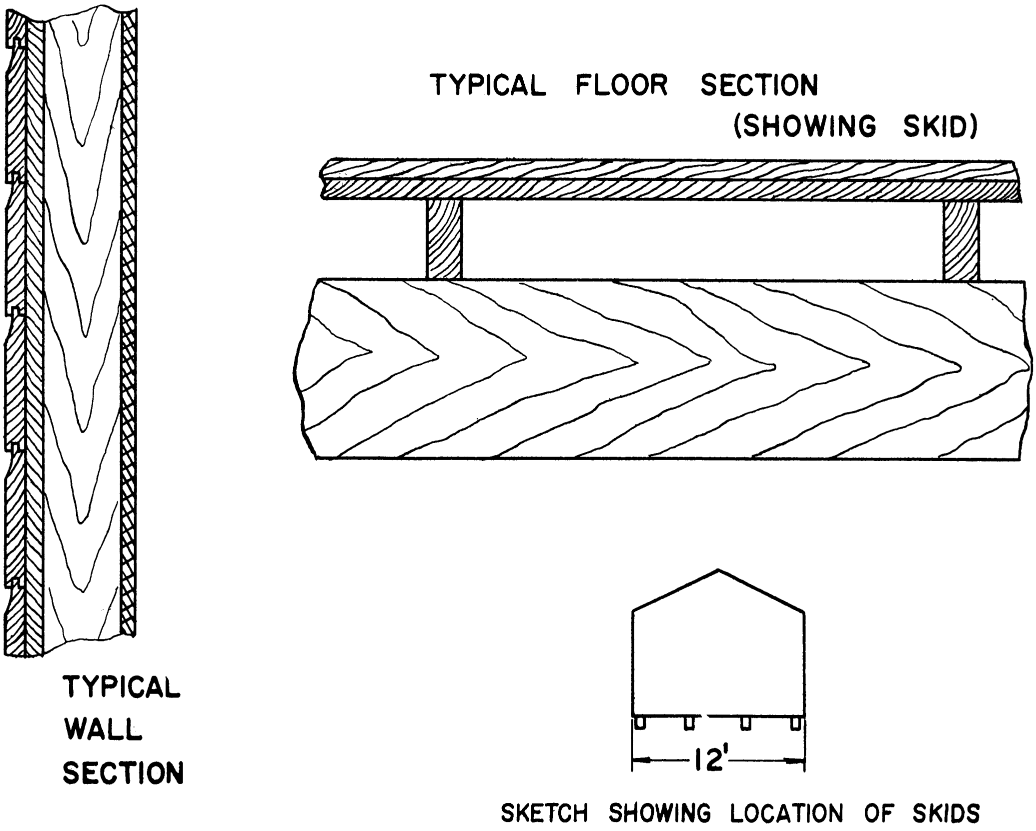


Fig. 22. Structural Detail of Test House.

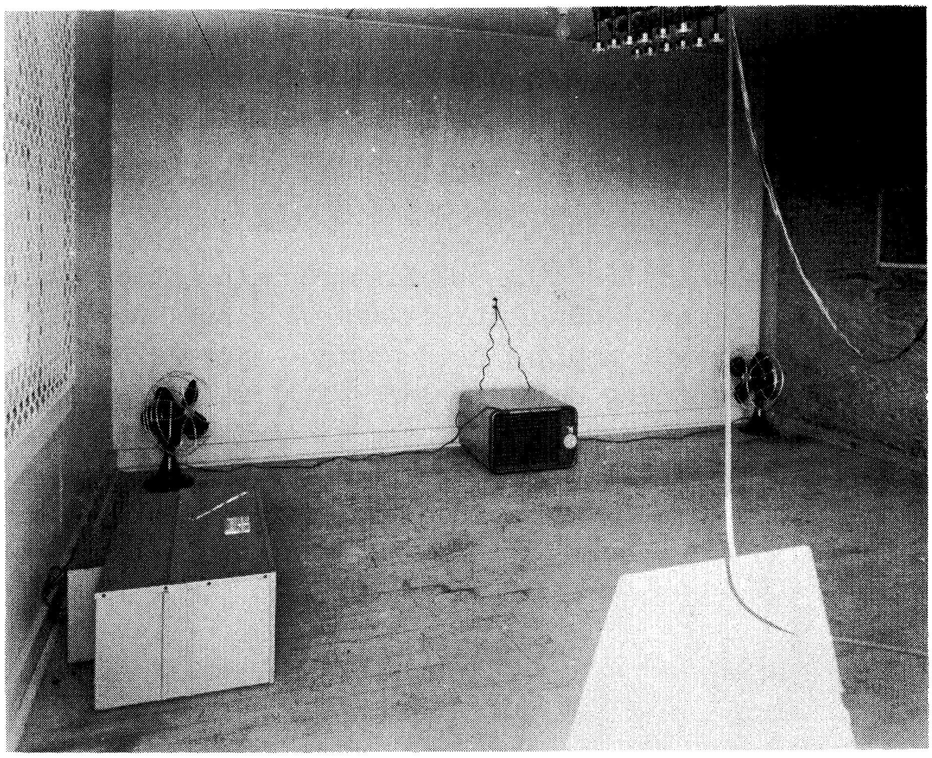


Fig. 23. Interior View of Test Room.

Fig. 24. Interior View of Instrument Room.

The electrical timers (Automatic Electric Mfg. Co.) controlling the sampling valves and the pumps, the Beckman-Whitley wind-speed recorder, and the Eberbach pumps were housed in the instrument room (Fig. 24). In addition, this room contained facilities for mounting the millipore filters on microscope slides and a microscope with accessories for counting the samples obtained.

The problems of handling the filters before they could be examined (see above, Chapter 2) were not entirely removed, but they were reduced substantially by an improved sampling head design. Figure 25 is a close view of the outside 12-head sampling unit in place with the improved heads. By disconnecting the air tube and unplugging the electrical cable, this unit could be lifted down and carried into the instrument room. The operator could then invert the unit on the table and remove the filters with a minimum of disturbance by unscrewing the knurled retainer ring of each filter head. A cross section of the sampling head is shown in Fig. 26.

The 12-head unit (Fig. 25) is an assembly of samplers plumbed to the air tube through individual solenoid valves. The cost of the valves was a minimum because they were available as war surplus. By means of the electrical control, the solenoid valves were opened one at a time for the desired sampling period. Simultaneity of sampling inside and outside the test room was obtained by connecting the respective inside and outside sampling valves in parallel to a 12-v d-c supply through the timer.

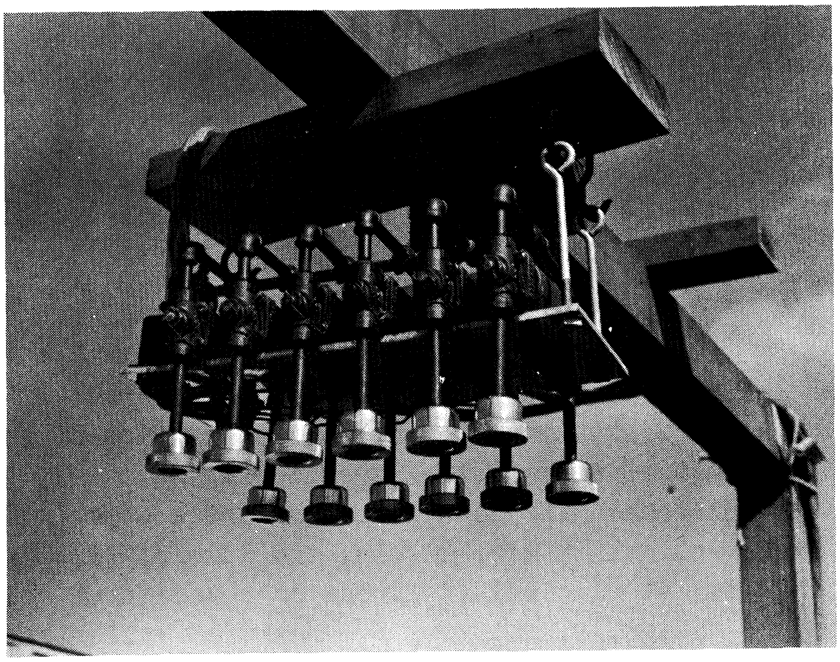
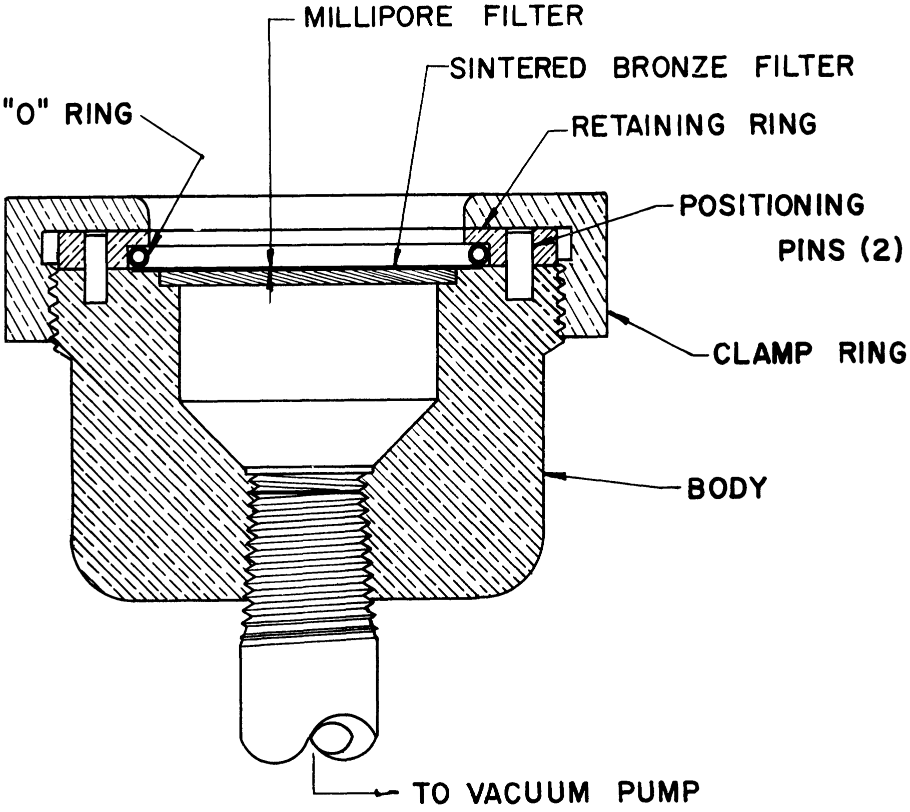


Fig. 25. Twelve-Head Sampling Unit on Scaffold.



CROSS-SECTION OF FILTER HEAD

Fig. 26.

# CHAPTER 4

## TESTS DURING SUMMER, 1955

At the height of the 1955 ragweed season, a series of 22 tests was made for the purpose of evaluating the rate of penetration of the airborne pollen grains into the test room of the experimental building. Table VI gives a summary of the tests made. The controlled variables were (1) duration of individual sampling periods: 5 min, 10 min, and 15 min; (2) window opening: none, 1 in., 3 in., and 12 in.; and (3) speed of rotation of stirring fans in test room: high, 1; medium, 2; and low, 3. Measured variables were wind speed, which was recorded continuously during each test, using the Beckman-Whitley anemometer; wind direction, which was observed visually; the neighboring distribution of ragweed plants; and the pollen concentrations inside and outside the test room.

### 4.1 PROCEDURE

Before the beginning of each test, the test room was closed and cleaned thoroughly, using a vacuum cleaner. During the cleaning both the fans and the electrostatic precipitators were operated, and these were left in operation for at least 45 min. The test was then begun by shutting off the precipitators and starting the timing system and the wind-speed recorder. The timers were adjusted in advance to give the desired sampling periods and to shut off all electricity automatically after the completion of the test. Corresponding samplers outside and inside the test room were operated simultaneously in all the tests.

Upon completion of a test, the filters were removed from the sampling heads and mounted on standard 1 in. x 3 in. microscope slides. The samples were protected with cover glasses and stored for later counting.

In the counting operation, a 100-fold magnification was used and the entire area of each filter was examined. The tediousness of this stage of the work is an important consideration requiring reduction of the filter area to a minimum.

Appendix C contains tabulations of the counts obtained. In this table, the tests are identified by the numbers used in Table VI: m designates the outside counts and x the inside counts. In addition, the mean wind speeds for the respective sampling periods $\bar{v}$ are tabulated herein. A fundamental problem is raised by the observation during the counting procedure that the

TABLE VI. RAGWEED-POLLEN PENETRATION TESTS, SUMMER, 1955

| Test No. | Date 1955 | Time Beg. | Time End | *Kind (see key) | Window Opening (in.) | Fan Speed | Avg. Pollen Count (no. per sample) Outside | Avg. Pollen Count (no. per sample) Inside | Avg. Wind Speed (mi/hr) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 8/20 | 9:30a.- | 8:45p. | A | 0 | 2 | 15.6 | 7.5 | 8.3 |
| 2 | 8/20-21 | 10:30p.- | 9:45a. | A | 0 | 2 | 36.6 | 6.4 | 5.2 |
| 3 | 8/21 | 12:00n.- | 11:15p. | A | 0 | 2 | 31.4 | 4.7 | 5.7 |
| 4 | 8/24 | 2:00p.- | 3:05p. | B | 12 | 2 | 89.9 | 40.2 | 3.6 |
| 5 | 8/24 | 4:30p.- | 6:30p. | C | 12 | 2 | 94.4 | 40.4 | 4.6 |
| 6 | 8/26 | 10:00a.- | 11:00a. | B | 3 | 2 | 53.5 | 14.5 | 3.3 |
| 7 | 8/26 | 2:00p.- | 3:00p. | B | 3 | 2 | 54.5 | 25.4 | 4.9 |
| 8 | 8/26 | 4:00p.- | 5:00p. | B | 3 | 2 | 50.3 | 13.3 | 3.2 |
| 9 | 8/30 | 2:50p.- | 3:50p. | B | 0 | 2 | 19.7 | 19.1 | 15.1 |
| 10 | 8/30 | 4:40p.- | 5:40p. | B | 0 | 2 | 10.5 | 7.2 | 13.5 |
| 11 | 8/30 | 6:30p.- | 7:30p. | B | 0 | 2 | 7.7 | 4.3 | 8.9 |
| 12 | 8/31 | 11:05a.- | 12:05p. | B | 1 | 2 | 31.4 | 24.0 | 9.9 |
| 13 | 8/31 | 1:00p.- | 2:00p. | B | 1 | 2 | 20.3 | 14.4 | 9.4 |
| 14 | 8/31 | 3:00p.- | 4:00p. | B | 1 | 2 | 23.9 | 12.4 | 9.7 |
| 15 | 8/31 | 4:45p.- | 5:45p. | B | 1 | 1 | 7.8 | 5.6 | 9.0 |
| 16 | 8/31 | 6:30p.- | 7:30p. | B | 1 | 3 | 5.7 | 4.2 | 6.6 |
| 17 | 9/1 | 12:06p.- | 3:01p. | D | 0 | 2 | 47.1 | 10.5 | 6.2 |
| 18 | 9/1 | 4:20p.- | 7:15p. | D | 0 | 2 | 38.0 | 5.8 | 4.1 |
| 19 | 9/1 | 8:00p.- | 10:55p. | D | 0 | 2 | 33.8 | 5.8 | 2.0 |
| 20 | 9/2 | 6:23a.- | 9:18a. | D | 1 | 2 | 29.3 | 3.8 | 1.9 |
| 21 | 9/2 | 9:50a.- | 12:45p. | D | 1 | 2 | 25.5 | 19.1 | 4.6 |
| 22 | 9/2 | 1:24p.- | 4:19p. | D | 1 | 2 | 27.2 | 9.3 | 4.9 |

*Kind of test, key:

A. 12 - 15-min samples with 45-min lapse between.
B. 12 - 5-min samples with no time lapse between.
C. 12 - 10-min samples with no time lapse between.
D. 12 - 10-min samples with 5-min lapse between.

pollen grains apparently land in clusters sometimes. From the viewpoint of the ragweed-sensitive person, the cluster of pollen grains would seem to be more effective in inducing symptoms than a single grain would be; however, from the viewpoint of particulate pollution of the air, the cluster of pollen grains is only one particle. Hence, when clusters occur, two different pollen counts are required to express the situation adequately. In Table VI the counts m and x are pollen particle counts (a cluster of several pollen grains is counted as one particle), whereas in Appendix C the counts are pollen grain counts. Only in Test No. 9 were clusters observed (Samples 8 and 9 inside) during this series of tests.

The wind speed was recorded, using a chart speed of 3/4 in./min so that "painted trace" problems could be avoided. There remained, however, considerable work in order to complete the reduction of the wind-speed records. This was finally done in a stepwise manner, the first step being to estimate visually the mean speed for each minute by balancing the chart areas above and below the mean. These means were then combined as necessary to get the mean wind speeds for the respective sampling periods.

## 4.2 ANALYSIS: WIND

In addition, as a measure of wind variability, the number of occurrences of wind speeds in excess of ± 2, ± 3, ± 4, ± 5, mi/hr, respectively, from the sampling period mean, were tabulated for each sampling period. A sample tabulation of this type is given in Appendix B. On the basis of these data the "total gustiness," G, is defined as follows:

$$G = n_2 + n_3 + n_4 + n_5 \quad ,$$

in which the subscripts designate the respective intensity categories (± 2, ± 3, ± 4, and ± 5 mi/hr) for which the gusts were counted, and n is the number of gusts. Figure 27a is a plot of G against $\overline{v}$ for the 5-min sampling periods of the summer's work (142 points). As was found for G', Chapter 2, it is seen that G bears a linear relation to $\overline{v}$ within small error. The simple correlation and the linear regression of G on $\overline{v}$ were computed:

$$r = 0.91$$

$$G = 9.94\ \overline{v} - 24.02 \quad .$$

This correlation represents an appreciable improvement upon that found between G' and $\overline{v}$. The fact that the latter derived from a wind field seriously disturbed by local obstructions on the roof of the East Engineering Building, by the building itself, and by adjacent structures and trees, whereas the present correlation derives from a relatively obstruction-free field site, is worthy of some note.

The index G was devised for analysis of the continuous wind-speed

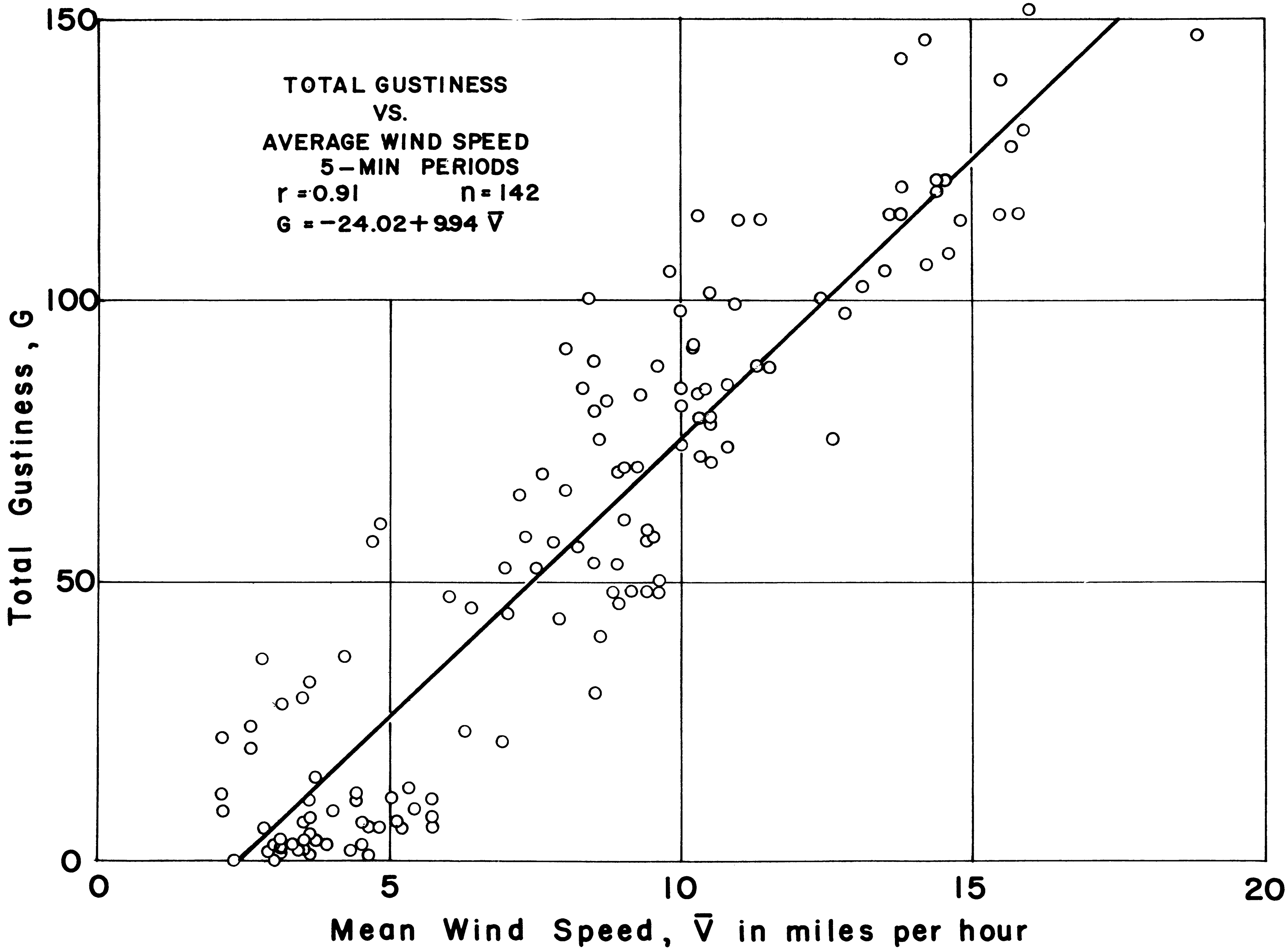

TOTAL GUSTINESS
VS.
AVERAGE WIND SPEED
5-MIN PERIODS
r = 0.91 n = 142
G = −24.02 + 9.94 V̄
Total Gustiness, G
150
100
50
0
0
5
10
15
20
Mean Wind Speed, V̄ in miles per hour

Fig. 27a.

record to yield approximately the same measure of turbulence as that given by the gust accelerometer (G'). This was necessary because the latter was out of service much of the 1955 season. The two regression equations have different coefficients as a result, but the ratio G'/G given by division of the regression equations is almost exactly 8.56:

$$\frac{G'}{G} = \frac{85.1\,\bar{v} - 215.6}{9.94\,\bar{v} - 24.02} = 8.56 - \frac{10.1}{9.94\,\bar{v} - 24.02} \quad .$$

For $\bar{v}$ in the range 4 to 8 mi/hr, the remainder is -0.36 to -0.18, respectively. Thus, despite the great difference between the two sites, these two regression lines show important similarities.

This finding was sufficiently interesting that some additional wind observations, made in connection with a separate investigation, were studied in a similar way. These observations were also recorded by the Beckman-Whitley anemometer and were analyzed by 5-min intervals. They were, however, taken over a relatively open area of the East Engineering Building roof adjacent to the Meteorological Laboratory. As in the other cases, the anemometer was set about 8 ft above the roof surface. The results for these data are shown in Fig. 27b. The correlation of G on $\bar{v}$ in this case is +0.97 and the linear regression equation is

$$G = 16.41\,\bar{v} - 37.70 \quad .$$

This regression is almost exactly 1.651 times the previous regression for G on $\bar{v}$. The slope of the regression is thus variable from one situation to another and appears to increase as the degree of nearby obstruction to the wind field increases.

Giblett (1932) found a similar linear relationship between the "mean variation of wind" and mean wind speed for the range 10-40 mi/hr. In his experiments, all measurements were made on towers 50 ft above the ground in a broad expanse of open level country. He defined the "mean variation of wind" as the average magnitude of the vector differences between consecutive 5-sec mean-wind vectors, averaged by 10-min periods. Giblett is careful to state that all his records were "... during daylight hours so that this relationship does not necessarily hold under conditions associated with inversions." As shown by Table VI, this restriction does not apply to the 1955 field data of the present project. Hewson and Gill (1944, Fig. 85) studied the relationship between turbulence and wind speed in the Columbia River valley near Trail, British Columbia. The turbulence was specified as the average amplitude of the wind-speed fluctuations. The anemometer employed was a Dines pressure-tube instrument with the sensing head mounted 40 ft above the ground. The variation of turbulence with speed was linear above 12 mi/hr but not below. The lack of linearity at low wind speeds may be due to the response characteristics of the Dines instrument, which probably did not record the full amplitude of the wind-speed fluctuations with lower winds.

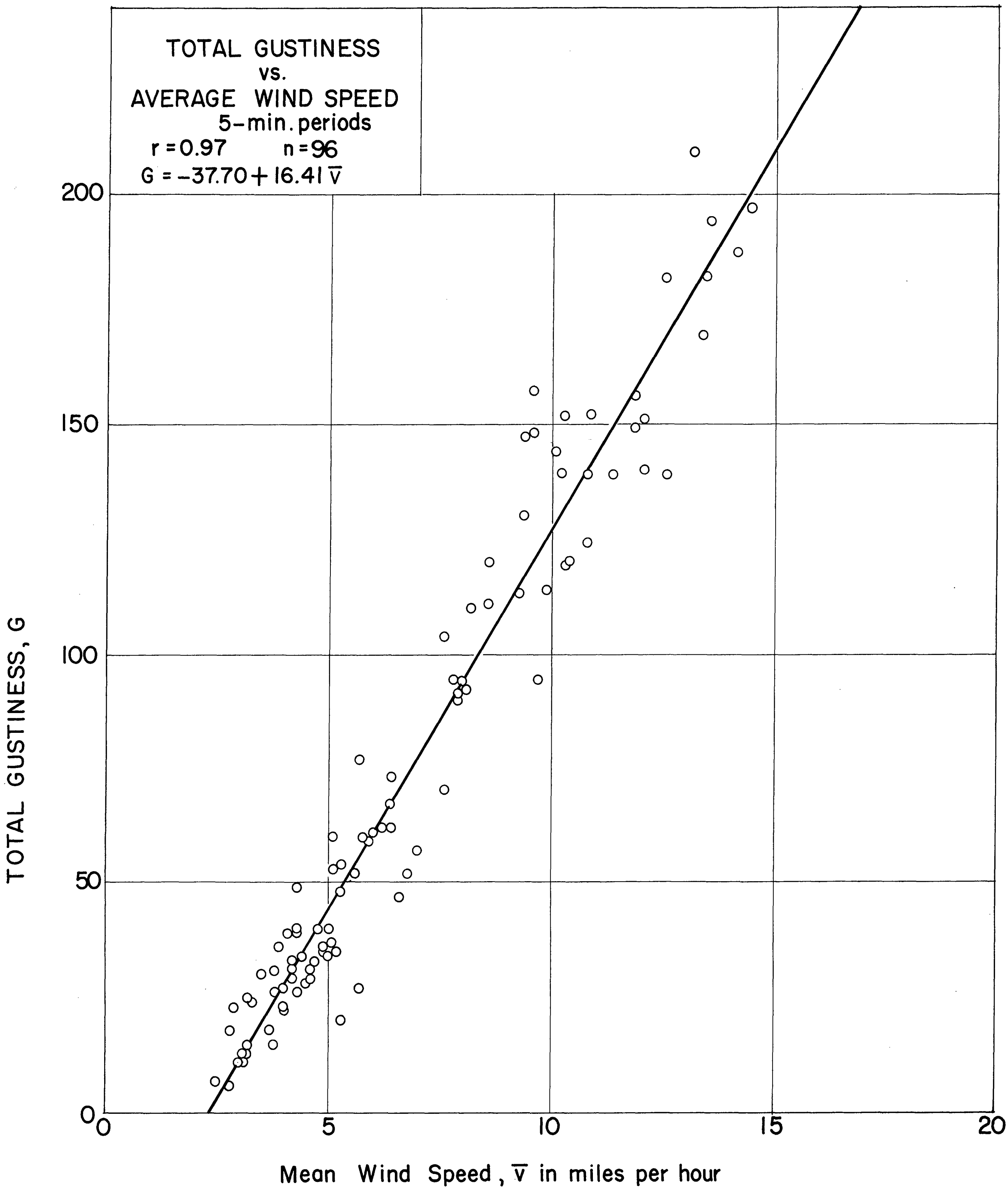

TOTAL GUSTINESS
vs.
AVERAGE WIND SPEED
5-min. periods
r = 0.97 n = 96
G = -37.70 + 16.41 $\overline{v}$
200
150
100
50
0
TOTAL GUSTINESS, G
0
5
10
15
20
Mean Wind Speed, $\overline{v}$ in miles per hour

Fig. 27b.

In the situations discussed above, the field experiment site was the least obstructed and the initial rooftop site (Chapter 2) was the most obstructed. It appears conceivable that the slope of the regression of G on $\overline{v}$ might well be used as an index of the degree of obstruction to the wind field (a type of roughness parameter). Further work is required in order to evaluate this possibility.

An additional observation of interest regarding the three regressions is that their $\overline{v}$ intercepts show that no gustiness is found below 2.53, 2.42, and 2.30 mi/hr mean wind speeds, respectively. These different estimates of this threshold evidently have no consistent dependence on the degree of wind obstruction, so their variability may be assumed accountable to errors inherent in the measurements. The magnitude of this threshold is undoubtedly associated with the choice of minimum gust intensity (± 2 mi/hr) used in each case.

To be sure, these findings are strictly empirical. As far as is known to the writers, no theoretical justification for the general applicability of these results exists, and many intuitive reservations regarding their general applicability assert themselves. However, that the linear relationship of wind variability to wind speed is found without selection of data in four such widely differing situations as the 1954 rooftop site (Chapter 2) using 15-min periods widely separated, the 1955 field site using 5-min and 10-min periods, the Columbia River valley site, and the 50-ft-high towers and 10-min periods used by Giblett, and that the linear regressions obtained from the present data are nearly proportional, despite the site differences and the instrumental differences, indicates strongly that this linear relationship is quite usual in the layer of air that is disturbed by friction with the earth's surface. The present findings show the correlation of wind-speed variability with wind speed to be very good, and the regression to be linear for wind measurements made about 8 ft from building and ground surfaces, the slope of the regression tending to increase with increasing degree of nearby obstruction to the wind flow. It is not demonstrable, with the data available, that the regression remains the same at the 50-ft level, but it does appear that relatively little is gained by the use of velocity vectors as compared to simple scalar speeds in studying details of the variability of the wind.

## 4.3 ANALYSIS: POLLEN COUNTS

In studying the pollen counts obtained, the ratio x/m appears useful for the reasons set forth in Section 2.5. Initial studies were designed to explore directly for relationships between this ratio and the wind speed and gustiness. Taking the averages of x and m for each of the tests, and computing a single point ($\overline{x}/\overline{m}$, $\overline{v}$) for each test, the graphs of Fig. 28 were plotted for window openings of 1 in. and 0. Since each point represents 12 samples, there are relatively few points, but some reasonable relationships are

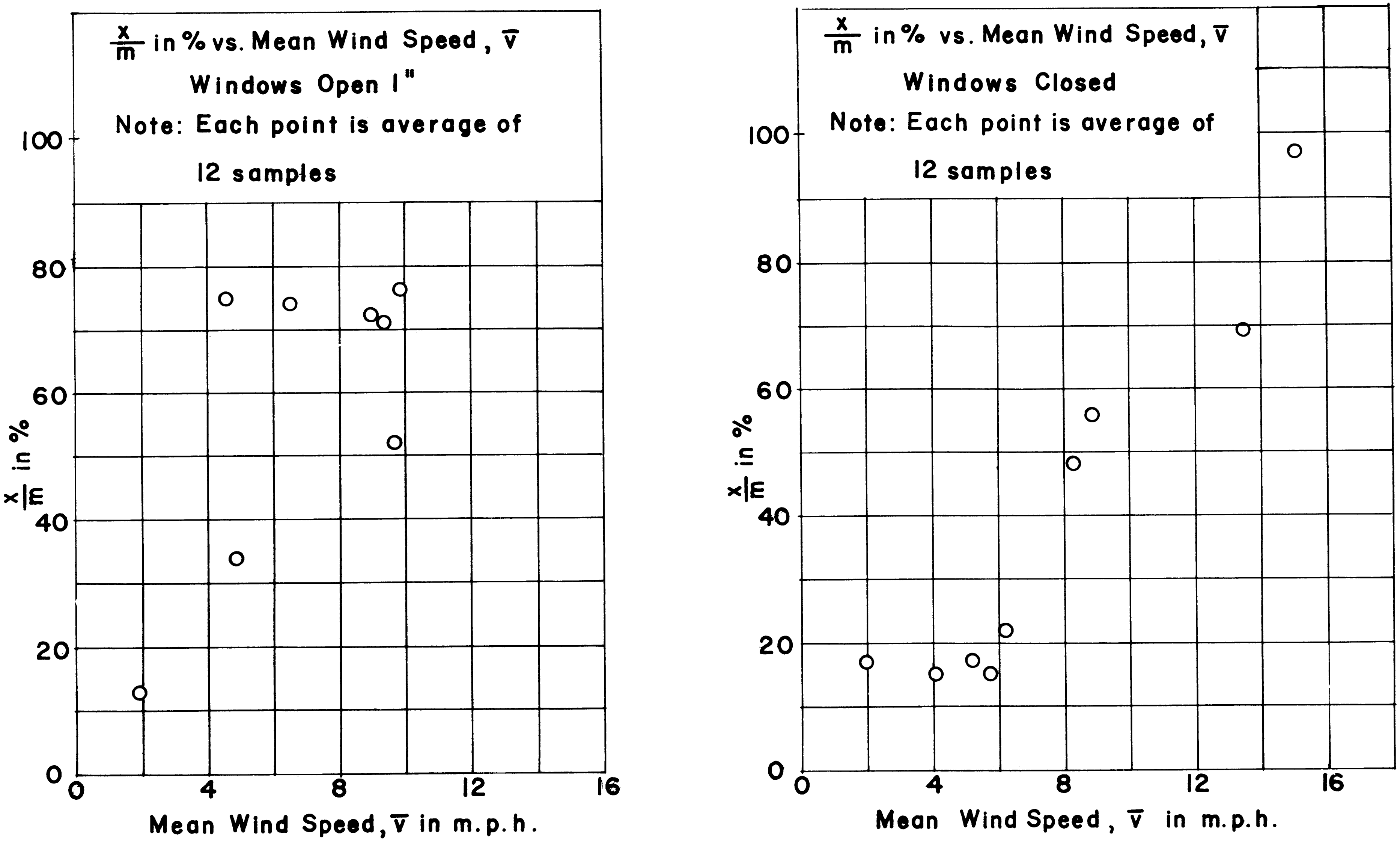

$\frac{x}{m}$ in % vs. Mean Wind Speed, $\bar{v}$
Windows Open 1"
Note: Each point is average of 12 samples
$\frac{x}{m}$ in %
0
20
40
60
80
100
0
4
8
12
16
Mean Wind Speed, $\bar{v}$ in m.p.h.
$\frac{x}{m}$ in % vs. Mean Wind Speed, $\bar{v}$
Windows Closed
Note: Each point is average of 12 samples
$\frac{x}{m}$ in %
0
20
40
60
80
100
0
4
8
12
16
Mean Wind Speed, $\bar{v}$ in m.p.h.

Fig. 28.

suggested. The low wind speeds are evidently more effective in increasing x when the windows are open than when they are not; and above 6-mi/hr average wind speed, x approaches m rapidly even with the windows shut. It may be inferred from this evidence that the ventilation rate is strongly affected by the wind speed, $\bar{v}$, and its associated turbulence. Similar graphs of $\bar{x}/\bar{m}$ against G are given in Fig. 29.

Further study of the relation of x/m to G and $\bar{v}$, using individual sample figures rather than the test (12 samples) averages, is suggested by these observations. Figures 30 and 31 are graphs of the individual sample values. Visual comparison of these graphs shows no clarification of functional relationships by the use of G as independent variable. In view of the high correlation of G on $\bar{v}$, present purposes will be served adequately by detailed consideration of Fig. 30 alone.

The correlations of x/m on $\bar{v}$ for the three different experimental conditions are as follows:

(a) windows closed, $r = +0.53$, $n = 117$
(b) windows open 1 in., $r = +0.23$, $n = 88$
(c) windows open 3 in., $r = +0.64$, $n = 34$

and the respective linear regressions for x/m in percent on $\bar{v}$ in mi/hr are:

(a) $x/m = 6.89\,\bar{v} - 1.07$
(b) $x/m = 6.52\,\bar{v} + 24.82$
(c) $x/m = 13.14\,\bar{v} - 10.59$

Whereas the slopes of the regression lines are expected to increase as window opening increases (i.e., in the order a-b-c), the data for the 1-in. opening show a smaller slope than those for the zero opening. The scatter of points is also much worse for the 1-in.-opening data than for the other two situations, as shown by the correlation coefficients. It is probable that unit errors of counting, particularly in the case of small samples, may contribute significantly to the observed scatter of points. The relation between cases (a) and (c) appears consistent with physical expectation as regards the slopes of the regression lines. In each of these cases, according to the regressions, x/m goes to zero at a small value of $\bar{v}$, 0.16 and 0.80 mi/hr, respectively. Insofar as these intercepts may be considered significantly different, the data are inconsistent, because the lower intercept should be found for the greater window opening. The data are probably insufficient to yield information of this degree of refinement.

## 4.4 ANALYSIS: PENETRATION

Of the several mechanisms that operate to alter the volume concentration of the contaminant (ragweed-pollen grains) in the test room, ventilation

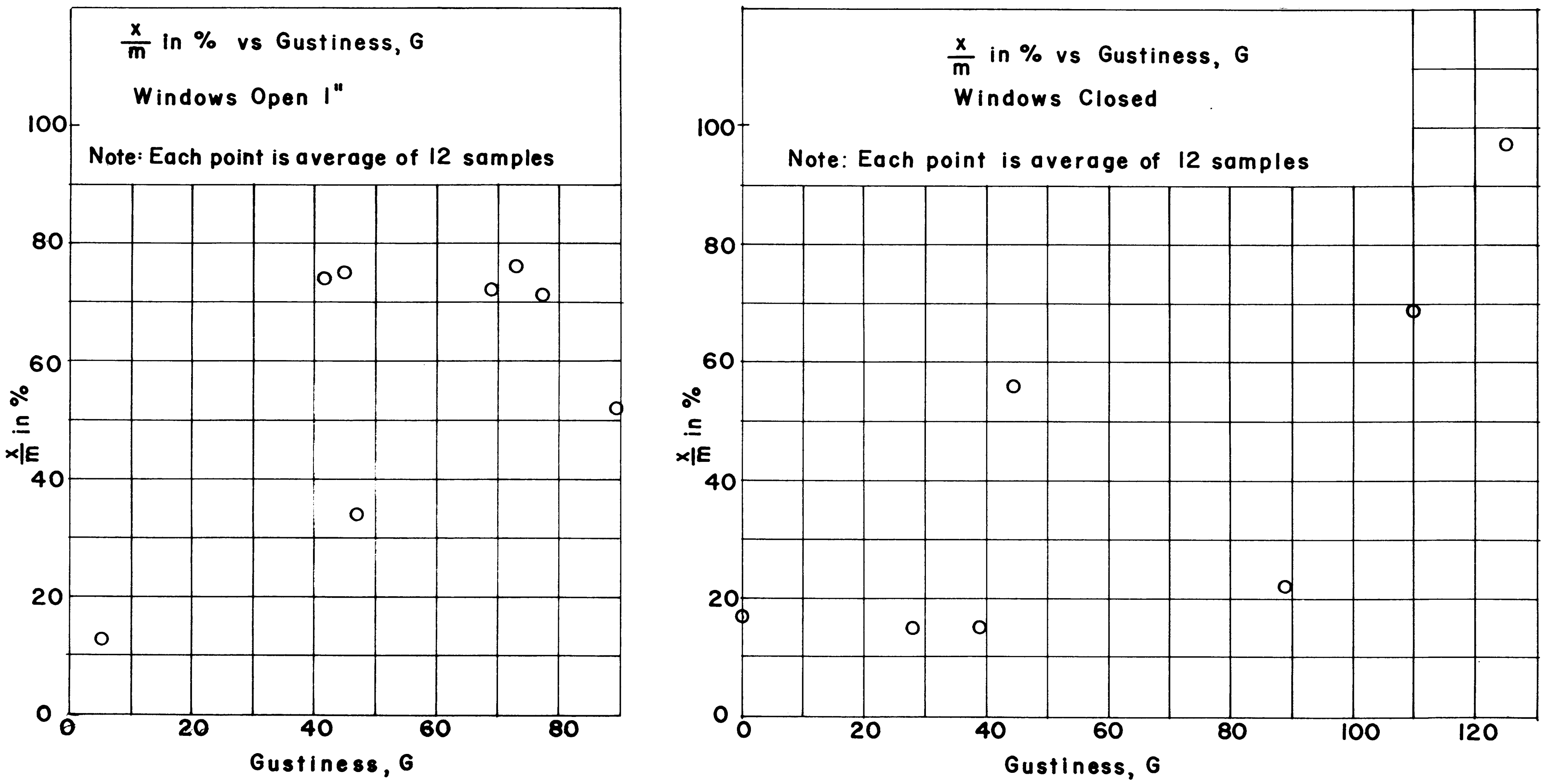

$\frac{x}{m}$ in % vs Gustiness, G
Windows Open 1"
Note: Each point is average of 12 samples
$\frac{x}{m}$ in %
0
20
40
60
80
100
Gustiness, G
$\frac{x}{m}$ in % vs Gustiness, G
Windows Closed
Note: Each point is average of 12 samples
120

Fig. 29.

suggested. The low wind speeds are evidently more effective in increasing x when the windows are open than when they are not; and above 6-mi/hr average wind speed, x approaches m rapidly even with the windows shut. It may be inferred from this evidence that the ventilation rate is strongly affected by the wind speed, $\bar{v}$, and its associated turbulence. Similar graphs of $\bar{x}/\bar{m}$ against G are given in Fig. 29.

Further study of the relation of x/m to G and $\bar{v}$, using individual sample figures rather than the test (12 samples) averages, is suggested by these observations. Figures 30 and 31 are graphs of the individual sample values. Visual comparison of these graphs shows no clarification of functional relationships by the use of G as independent variable. In view of the high correlation of G on $\bar{v}$, present purposes will be served adequately by detailed consideration of Fig. 30 alone.

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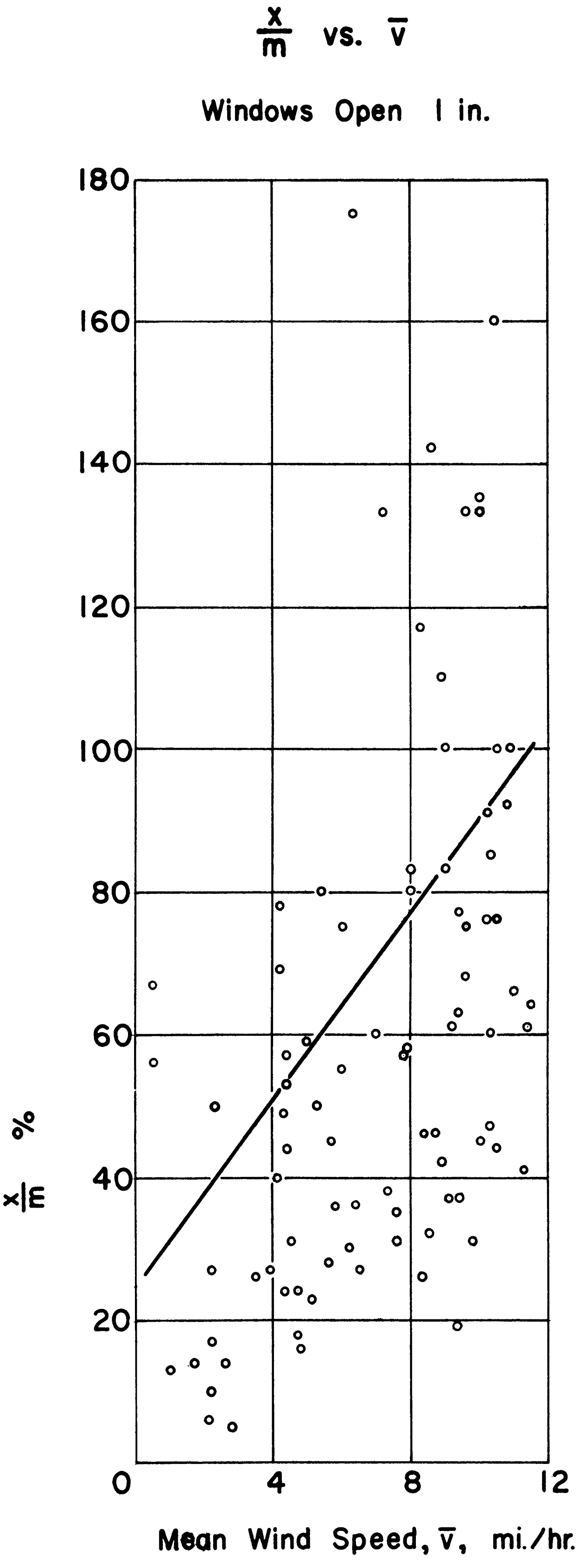


Fig. 30b. Ratio x/m vs $\bar{v}$ for Individual Samples Taken with Windows Open 1 in.

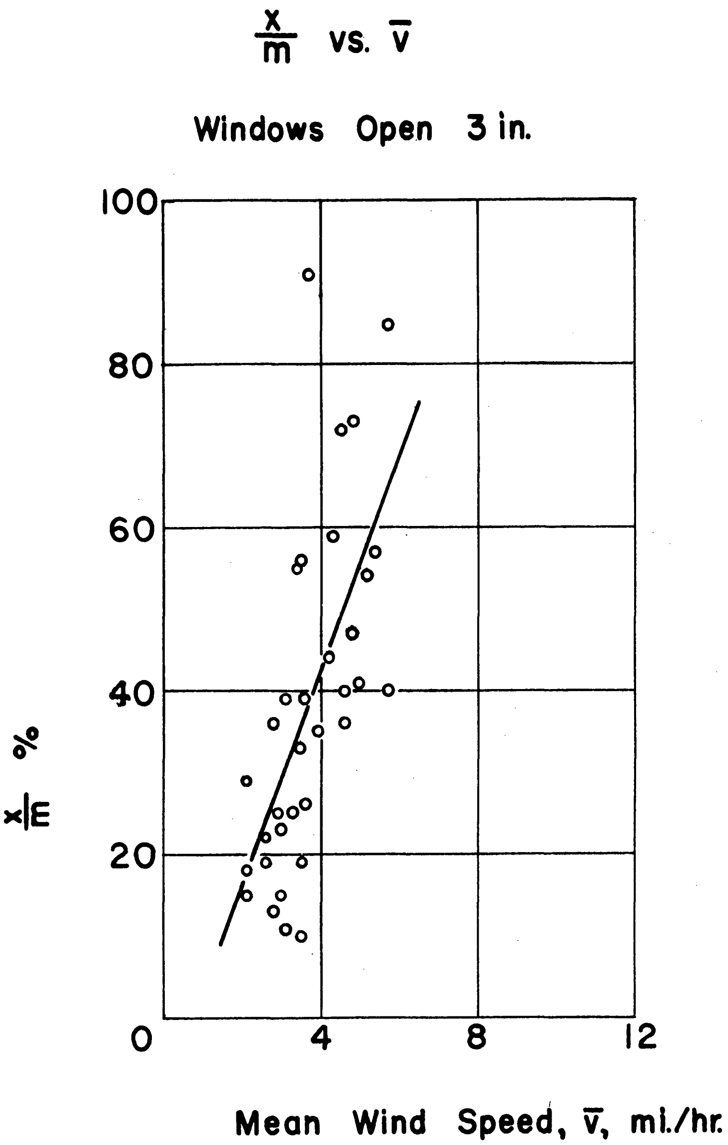


Fig. 30c. Ratio x/m vs $\bar{v}$ for Individual Samples Taken with Windows Open 3 in.

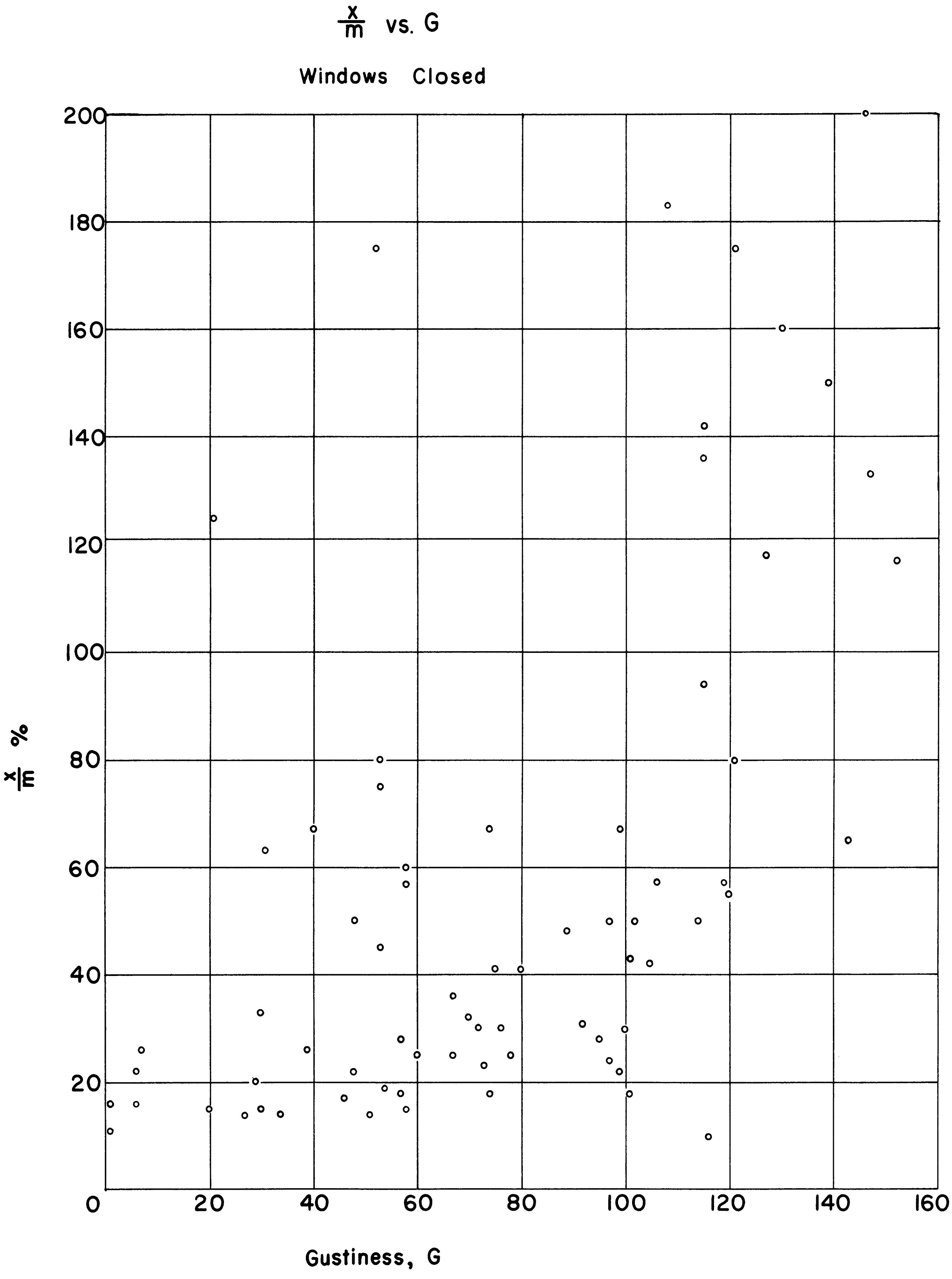


Fig. 31a. Ratio x/m vs G for Individual Samples Taken with Windows Closed.

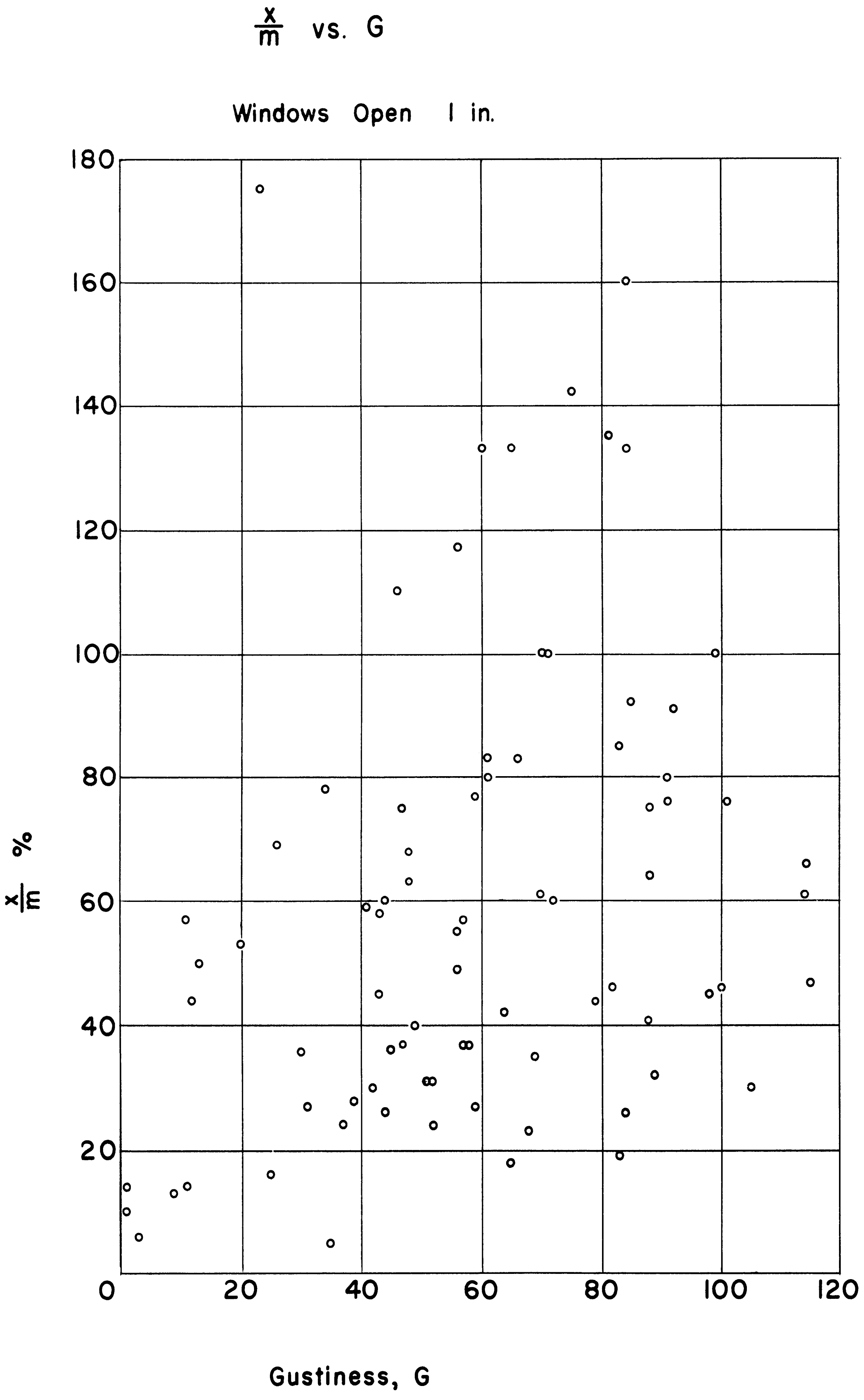


Fig. 31b. Ratio x/m vs G for Individual Samples Taken with Windows Open 1 in.

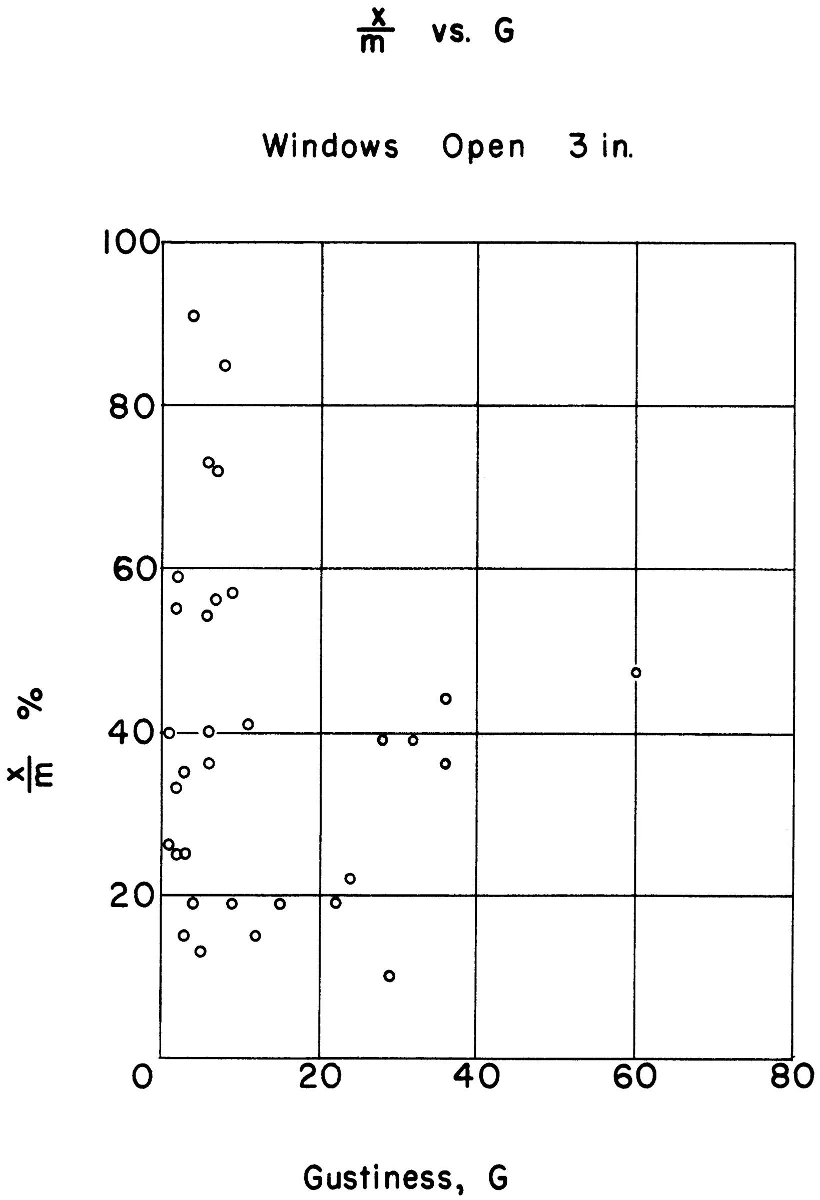


Fig. 31c. Ratio x/m vs G for Individual Samples Taken with Windows Open 3 in.

and sedimentation are probably predominant. Impaction is known to occur, particularly on the fan blades, but the countereffect of reflotation of some of the deposited pollen grains should also operate in some measure. In any case, relatively little is known about these two processes, and they must for the present be excluded from consideration in the analysis.

The effect of ventilation upon the concentration x of particles of the specified type in the test-room air depends on the difference between the concentrations in the air outside (m) and inside (x) the test room and the rate of ventilation. If a is the volume rate of ventilation and V is the volume of the room, then

$$k = \frac{a}{V} \tag{1}$$

is the air change rate of ventilation, i.e., the frequency with which the air in the room is replaced by air from outside.

The change of x in time $\Delta t$ due to ventilation is therefore

$$(\Delta x)_V = k\,(m - x)\,\Delta t \quad , \tag{2}$$

if k is constant over the time period $\Delta t$.

At the same time, all pollen grains in the room at any time have a gravitational settling component of motion. If w is the average settling speed of the pollen grains in still air, the number of particles removed from the air by sedimentation onto the floor in time $\Delta t$ is

$$\Delta N = - xwA\,\Delta t \tag{3}$$

in a room of area A in plan. This statement depends on the condition that turbulent elements of air motion contribute equally to upward and downward air movements.

The change of x in time $\Delta t$ due to the sedimentation process is therefore

$$(\Delta x)_S = \frac{\Delta N}{V} = \frac{\Delta N}{Ah} = -\frac{xw}{h}\,\Delta t \quad , \tag{4}$$

where h is the vertical dimension of the room.

Assuming other effects to be negligible, the change of x in time $\Delta t$ by both ventilation and sedimentation is

$$\Delta x = (\Delta x)_V + (\Delta x)_S = \left[k\,(m - x) - \frac{wx}{h}\right] \Delta t \quad ,$$

and as $\Delta t \rightarrow 0$,

$$dx = \left[k\ (m - x) - \frac{wx}{h}\right] dt \quad . \tag{5}$$

Equation 5 is the basic differential equation for the process envisioned. Depending on the observations, the functional relations of the ventilation rate k and the outside pollen concentration m to the time t vary from one test to another and from one time to another within tests. Various solutions of Equation 5 will therefore be discussed.

4.4.1 The Ventilation Rate, k.—The primary experimental factors affecting the value of k are: (a) the amount of crackage of the test room, (b) the amount of opening at the windows, and (c) the wind speed. A number of secondary factors may also be considered: (d) the degree of gustiness of the wind, (e) the wind direction and its variability, and (f) the speed of rotation of the fans in the test room. Of these factors, (a) is unknown, but usually assumed constant, and hence subject to deductive determination if other factors remain reasonably constant in a few cases; (b) is known and constant for each test, but varied from one test to another (see Table VI); (c) is observed and reduced from the detailed wind-speed record; (d) is estimated statistically from the detailed wind-speed record; (e) is observed only occasionally and hence cannot enter the computations, but the omission of this factor from the initial calculations is partially justified by the findings of Warner (1940) and Wellner (1932) that wind direction is distinctly subordinate to wind speed in its effect upon ventilation rate; and (f) is known and constant for each test (see Table VI).

The experimental data provide information that makes possible the computation of k for those cases which are simple enough to allow a solution of Equation 5. Examination of the differential equation suggests the kinds of situations for which solutions are readily available.

1. $x$ = constant, $dx/dt = 0$

In this case, Equation 5 reduces to

$$k_1 = \frac{w}{h}\left(\frac{x}{\overline{m}-x}\right) \tag{6}$$

2. $(m-x)$ = constant

$$k_2 = \left(\frac{\Delta x}{\Delta t} + \frac{w}{h}\,\overline{x}\right)\frac{1}{m-x} \tag{7}$$

3. $m$ = constant

$$k_3 = \left(\frac{\Delta x}{\Delta t} + \frac{w}{h}\,\overline{x}\right)\frac{1}{m-\overline{x}} \tag{8}$$

Suitable situations for the evaluation of k were selected by applying these respective criteria to the observational data. The resulting values of k are tabulated in Table VII together with average wind speeds for the respective time periods and the ratios $k/\bar{v}^2$, k/G, and k/V.E., which will be discussed below.

4.4.2 The Relation of Wind Characteristics to the Ventilation Rate.— The relation of k to the wind speed was explored by constructing graphs (Figs. 32, 33, 34, and 35) of k vs $\bar{v}$ for each of several window openings. These graphs include only values of $k_1$, but as reference to Table VII shows, reasonable estimates of k using Equations 7 and 8 were mostly redundant, so for the sake of uniformity the few additional points available from values of $k_2$ and $k_3$ have been omitted. There are relatively few points in these graphs, and the wind-speed range included in each test (composed of 12 pairs of simultaneous inside and outside samples) is relatively narrow. As a result, in Fig. 32, the data for tests 17, 18, and 19 (below 7 mi/hr) are separated from those for tests 9, 10, and 11 (above 9 mi/hr). The fact that the latter are much more broadly scattered than the former suggests that some factor other than just wind speed (such as increased instability near the ground) contributed to the scatter of points at the higher wind speeds. The present analysis is confined to wind-speed considerations because no adequate data on stability are available. Figures 33 and 34 show better continuity of the population of points partly because the wind-speed ranges of these graphs are narrower than that of Fig. 32.

These three graphs are strongly reminiscent of Figs. 28, 29, 30, and 31. It will be recalled that in the pollen count study (Section 4.3) the data for the 1-in. window opening were somewhat disappointing as regards both the correlation of x/m on $\bar{v}$ and the slope of the linear regression. In the present analysis the data have been selected according to the criterion that x = constant for at least two successive samples, and $k_1$ has been computed on the basis of the two successive samples that satisfy the criterion. Generally speaking, Figs. 32 through 35, like Figs. 28 and 29, have too few points to justify computation of regression and correlation coefficients. The dashed lines in these figures are drawn visually through the data. The slopes of these lines steepen as the window opening increases, as should be expected. The selection of data accomplished in computing $k_1$ thus evidently serves to eliminate some extreme cases and, of course, since $k_1$ is computed from two successive samples, some smoothing of individual sample data used to compute x/m is accomplished. So, whereas the regressions of x/m on $\bar{v}$ did not show progressively steepening slopes with increasing window opening, the graphs of $k_1$ against $\bar{v}$ do.

An additional characteristic of these graphs is the apparent tendency of the values of $k_1$ and x/m to increase at an increasing rate with winds above 6-8 mi/hr. A second visually drawn straight line seems to be needed in Figs. 33 and 34. The change of slope in the latter is less marked because the

TABLE VII. VALUES OF k AND ASSOCIATED QUANTITIES

| Test No. | Window Opening (in.) | Sample No. | k | $\bar{v}$ (mi/hr) | $\frac{k}{\bar{v}^2} \times 10^3$ | $\frac{k}{G} \times 10^3$ | $\frac{k}{VE} \times 10^3$ |
|---|---|---|---|---|---|---|---|
| (a) $k_1 = \frac{w}{h}\left(\frac{x}{\bar{m}-x}\right)$ | | | | | | | |
| 4 | 12 | 8-9 | 0.44 | 3.35 | 39.20 | 73.40 | 73.40 |
| | | 9-10 | 0.41 | 3.10 | 42.40 | 135.60 | 136.00 |
| 5 | 12 | 4-5 | 0.52 | 4.90 | 21.50 | 21.60 | 17.90 |
| | | 8-9 | 0.51 | 5.65 | 15.80 | 24.20 | 18.70 |
| | | 11-12 | 0.29 | 4.15 | 16.70 | 38.40 | 36.00 |
| 6 | 3 | 6-7 | 0.34 | 3.70 | 25.20 | 68.80 | 69.00 |
| | | 10-11 | 0.31 | 3.65 | 23.20 | 124.00 | 124.00 |
| 7 | 3 | 4-5 | 0.94 | 5.55 | 30.50 | 110.80 | 94.10 |
| | | 9-10 | 0.36 | 4.45 | 18.00 | 89.40 | 55.00 |
| | | 8-9 | 0.85 | 4.40 | 43.80 | 188.40 | 169.00 |
| 8 | 3 | 3-4 | 0.30 | 3.35 | 26.40 | 9.86 | 2.10 |
| | | 4-5 | 0.27 | 3.20 | 26.20 | 7.88 | 3.01 |
| | | 8-9 | 0.15 | 2.35 | 27.60 | 6.60 | 5.25 |
| | | 9-10 | 0.12 | 2.60 | 17.30 | 5.12 | 3.78 |
| | | 10-11 | 0.09 | 2.35 | 16.70 | 5.74 | 4.00 |
| | | 11-12 | 0.09 | 2.10 | 20.20 | 8.48 | 7.12 |
| 9 | 0 | 2-3 | 3.87 | 14.30 | 18.90 | 29.20 | 10.40 |
| | | 5-6 | 1.14 | 14.00 | 5.82 | 10.24 | 3.70 |
| | | 10-11 | 1.30 | 17.35 | 4.35 | 9.96 | 3.34 |
| 10 | 0 | 1-2 | 0.45 | 12.95 | 2.69 | 4.52 | 1.73 |
| | | 4-5 | 0.38 | 14.15 | 1.88 | 3.42 | 1.10 |
| | | 6-7 | 0.96 | 14.25 | 4.77 | 9.20 | 3.54 |
| 11 | 0 | 2-3 | 1.08 | 9.25 | 12.60 | 17.02 | 7.35 |
| 12 | 1 | 4-5 | 0.52 | 10.05 | 5.16 | 8.14 | 3.36 |
| | | 3-4 | 0.85 | 9.50 | 9.40 | 17.68 | 8.23 |
| 13 | 1 | 2-3 | 0.19 | 8.40 | 2.62 | 2.16 | 0.85 |
| 14 | 1 | 7-8 | 0.29 | 8.80 | 3.74 | 3.48 | 1.42 |
| | | 8-9 | 0.30 | 8.15 | 4.44 | 3.90 | 1.73 |
| | | 10-11 | 1.01 | 10.55 | 9.20 | 1.15 | 4.34 |
| 15 | 1 | 3-4 | 0.40 | 7.80 | 6.66 | 6.86 | 3.18 |

TABLE VII (Continued)

| Test No. | Window Opening (in.) | Sample No. | k | $\overline{V}$ (mi/hr) | $\frac{k}{\overline{V}^2} \times 10^3$ | $\frac{k}{G} \times 10^3$ | $\frac{k}{VE} \times 10^3$ |
|---|---|---|---|---|---|---|---|
| 16 | 1 | 10-11 | 0.45 | 4.40 | 23.20 | 39.20 | 34.60 |
| | | 4-5 | 0.45 | 6.65 | 10.20 | 8.56 | 4.30 |
| 17 | 0 | 4-5 | 0.17 | 5.60 | 5.41 | 2.58 | 1.20 |
| | | 7-8 | 0.15 | 6.80 | 3.25 | 1.55 | 0.66 |
| | | 8-9 | 0.13 | 6.10 | 3.50 | 1.54 | 0.71 |
| | | 10-11 | 0.13 | 5.80 | 3.87 | 1.47 | 0.70 |
| 18 | 0 | 1-2 | 0.16 | 5.50 | 5.28 | 2.38 | 1.32 |
| | | 4-5 | 0.13 | 4.60 | 6.13 | 2.24 | 1.31 |
| | | 6-7 | 0.08 | 4.70 | 3.62 | 1.47 | 0.88 |
| | | 9-10 | 0.06 | 3.10 | 6.24 | 5.72 | 5.45 |
| 19 | 0 | 1-2 | 0.15 | 1.50 | 66.70 | -- | -- |
| | | 5-6 | 0.04 | 2.10 | 9.07 | -- | -- |
| | | 10-11 | 0.07 | 2.10 | 15.90 | -- | -- |
| | | 11-12 | 0.07 | 1.70 | 24.20 | -- | -- |
| 20 | 1 | 2-3 | 0.06 | 2.20 | 12.40 | 120.00 | 120.00 |
| | | 3-4 | 0.08 | 2.30 | 15.10 | 160.00 | 160.00 |
| | | 4-5 | 0.11 | 1.50 | 40.90 | 24.20 | 17.00 |
| 21 | 1 | 1-2 | 1.17 | 3.60 | 90.20 | 3.60 | 27.90 |
| | | 6-7 | 0.13 | 5.40 | 4.45 | 2.10 | 1.11 |
| | | 8-9 | 0.33 | 4.50 | 16.30 | 7.68 | 3.40 |
| 22 | 1 | 1-2 | 0.16 | 5.40 | 5.48 | 2.00 | 1.00 |
| | | 8-9 | 0.11 | 4.40 | 5.68 | 2.86 | 1.51 |
| | | 6-7 | 0.16 | 4.90 | 6.66 | 4.06 | 2.35 |
| | | 7-8 | 0.16 | 4.60 | 7.55 | 3.40 | 1.70 |

(b) $k_2 = \left(\frac{\Delta x}{\Delta t} + \frac{w}{h}\,\overline{x}\right)\frac{1}{m-x}$

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | 12 | 8-9 | 0.46 | 3.35 | 40.99 | 76.34 | 76.34 |
| | | 9-10 | 0.36 | 3.10 | 37.98 | 121.66 | 121.66 |
| 6 | 3 | 8-9 | 0.15 | 3.05 | 15.81 | 36.76 | 36.76 |
| 7 | 3 | 10-11 | 0.23 | 4.05 | 14.02 | 57.50 | 32.86 |
| 8 | 3 | 3-4 | 0.27 | 3.35 | 24.06 | 9.00 | 1.92 |
| | | 7-8 | 0.17 | 2.80 | 21.68 | 6.66 | 3.36 |
| | | 11-12 | 0.10 | 2.10 | 22.67 | 9.04 | 7.60 |

TABLE VII (Continued)

| Test No. | Window Opening (in.) | Sample No. | k | $\bar{v}$ (mi/hr) | $\frac{k}{\bar{v}^2} \times 10^3$ | $\frac{k}{G} \times 10^3$ | $\frac{k}{VE} \times 10^3$ |
|---|---|---|---|---|---|---|---|
| 9 | 0 | 7-8 | -1.66 | 14.65 | -7.73 | -12.86 | -4.32 |
| | | 10-11 | 1.34 | 17.35 | 4.45 | 10.22 | 3.42 |
| 10 | 0 | 1-2 | 0.48 | 12.95 | 2.86 | 4.82 | 1.84 |
| | | 4-5 | 0.38 | 14.15 | 1.87 | 3.42 | 1.10 |
| 11 | 0 | 2-3 | 1.08 | 9.25 | 12.62 | 17.00 | 7.34 |
| | | 3-4 | 0.19 | 10.25 | 1.81 | 2.50 | 1.10 |
| | | 5-6 | 0.72 | 8.55 | 9.85 | 15.48 | 8.42 |
| 12 | 1 | 3-4 | 0.80 | 9.50 | 8.86 | 16.66 | 7.76 |
| 13 | 1 | 6-7 | -1.38 | 9.50 | -15.29 | -17.36 | -7.70 |
| 14 | 1 | 1-2 | 0.81 | 9.75 | 8.52 | 7.98 | 3.20 |
| | | 10-11 | 1.01 | 10.55 | 9.07 | 10.00 | 4.32 |
| 15 | 1 | 1-2 | 2.33 | 8.45 | 32.63 | 32.36 | 13.58 |
| 16 | 1 | 10-11 | 0.45 | 4.40 | 23.24 | 39.14 | 34.62 |
| | | 11-12 | 1.12 | 6.70 | 24.95 | 31.12 | 13.10 |
| 17 | 0 | 4-5 | 0.17 | 5.60 | 5.42 | 2.58 | 1.20 |
| | | 7-8 | 0.16 | 6.80 | 3.46 | 1.64 | 0.70 |
| 18 | 0 | 1-2 | 0.16 | 5.50 | 5.22 | 2.38 | 1.32 |
| | | 8-9 | 0.08 | 3.70 | 5.84 | 3.40 | 2.98 |
| | | 10-11 | 0.03 | 2.40 | 5.21 | 60.00 | 60.00 |
| 19 | 0 | 2-3 | 0.09 | 2.20 | 18.59 | -- | -- |
| | | 11-12 | 0.07 | 1.70 | 25.60 | -- | -- |
| 21 | 1 | 7-8 | 0.22 | 7.30 | 4.13 | 4.80 | 2.28 |
| | | 8-9 | 0.32 | 4.50 | 15.80 | 7.44 | 3.30 |
| 22 | 1 | 7-8 | 0.16 | 4.60 | 7.56 | 3.40 | 1.70 |

TABLE VII (Continued)

| Test No. | Window Opening (in.) | Sample No. | k | $\bar{v}$ (mi/hr) | $\frac{k}{v^2} \times 10^3$ | $\frac{k}{G} \times 10^3$ | $\frac{k}{VE} \times 10^3$ |
|---|---|---|---|---|---|---|---|
| | | (c) | $k_3 = \left(\frac{\Delta x}{\Delta t} + \frac{w}{h}\bar{x}\right)\frac{1}{m-\bar{\bar{x}}}$ | | | | |
| 4 | 12 | 8-9 | 0.44 | 3.20 | 39.20 | 73.40 | 73.40 |
| 5 | 12 | 11-12 | 0.27 | 4.20 | 15.70 | 36.00 | 33.75 |
| 6 | 3 | 1-2 | 0.09 | 3.30 | 8.26 | 25.70 | 22.50 |
| | | 2-3 | 0.41 | 3.40 | 35.40 | 136.70 | 136.70 |
| 7 | 3 | 6-7 | 0.67 | 5.00 | 26.80 | 111.60 | 111.60 |
| | | 10-11 | 0.23 | 4.00 | 14.40 | 57.50 | 32.86 |
| 8 | 3 | 2-3 | 0.31 | 3.90 | 20.40 | 7.05 | 1.79 |
| | | 11-12 | 0.09 | 2.10 | 20.40 | 8.57 | 7.20 |
| 9 | 0 | 4-5 | -4.75 | -14.10 | -24.00 | -40.30 | -13.20 |
| | | 10-11 | 1.34 | 17.40 | 4.46 | 10.20 | 3.42 |
| 10 | 0 | 1-2 | 0.50 | 12.90 | 2.99 | 5.03 | 1.92 |
| | | 3-4 | 5.20 | 15.20 | 22.50 | 41.10 | 13.85 |
| | | 4-5 | 0.38 | 14.20 | 1.91 | 3.49 | 1.11 |
| 11 | 0 | 2-3 | 1.08 | 9.30 | 12.60 | 17.00 | 7.35 |
| | | 5-6 | 0.70 | 8.50 | 9.72 | 15.10 | 8.19 |
| | | 7-8 | 2.00 | 9.30 | 23.10 | 83.40 | 20.40 |
| | | 10-11 | 4.20 | 7.70 | 71.00 | 165.00 | 97.70 |
| 12 | 1 | 11-12 | -4.75 | 10.40 | -44.00 | -49.20 | -20.20 |
| 13 | 1 | 6-7 | -1.38 | 9.50 | -15.35 | -17.40 | -7.71 |
| 14 | 1 | 10-11 | 1.03 | 10.60 | 9.36 | 11.70 | 4.41 |
| 15 | 1 | 6-7 | 7.00 | 8.90 | 88.70 | 99.30 | 46.80 |
| | | 7-8 | -2.30 | 10.40 | -21.30 | -25.20 | -11.00 |
| | | 8-9 | -6.20 | 9.60 | -67.40 | 80.00 | -35.30 |
| | | 10-11 | -1.50 | 10.60 | -13.40 | -20.70 | -8.51 |

## TABLE VII (Concluded)

| Test No. | Window Opening (in.) | Sample No. | k | $\bar{v}$ (mi/hr) | $\frac{k}{\bar{v}^2} \times 10^3$ | $\frac{k}{G} \times 10^3$ | $\frac{k}{VE} \times 10^3$ |
|---|---|---|---|---|---|---|---|
| 16 | 1 | 1-2 | -1.56 | 8.00 | -24.40 | -25.60 | -13.10 |
| | | 6-7 | 2.80 | 7.10 | 55.80 | 51.40 | 26.40 |
| | | 7-8 | -6.20 | 6.70 | -138.50 | -185.00 | -118.00 |
| | | 8-9 | -0.30 | 5.80 | -8.94 | -16.70 | -10.90 |
| | | 10-11 | 0.45 | 4.40 | 23.20 | 39.10 | 34.60 |
| | | 11-12 | 1.15 | 6.70 | 25.60 | 31.90 | 13.45 |
| 17 | 0 | 1-2 | 0.26 | 6.40 | 6.34 | 2.63 | 1.17 |
| | | 3-4 | 0.17 | 6.20 | 4.47 | 1.93 | 0.82 |
| | | 4-5 | 0.18 | 5.60 | 5.74 | 2.72 | 1.27 |
| 18 | 0 | 1-2 | 0.16 | 5.50 | 5.28 | 2.39 | 1.32 |
| | | 10-11 | 0.03 | 2.40 | 5.21 | 60.00 | 60.00 |
| 19 | 0 | 8-9 | 0.06 | 1.90 | 16.70 | -- | -- |
| | | 11-12 | 0.07 | 1.70 | 24.20 | -- | -- |
| 20 | 1 | 5-6 | 0.29 | 0.70 | 5.92 | 64.50 | 44.60 |
| 21 | 1 | 1-2 | 1.09 | 3.60 | 84.20 | 33.60 | 26.00 |
| | | 7-8 | 0.22 | 5.90 | 6.32 | 4.95 | 2.29 |
| | | 8-9 | 0.21 | 4.50 | 10.40 | 4.89 | 2.17 |
| 22 | 1 | 7-8 | 0.16 | 4.60 | 7.55 | 3.40 | 2.00 |
| | | 11-12 | 0.33 | 5.00 | 13.20 | 11.20 | 7.76 |

window opening of 3 in. provides very free ventilation at all wind speeds. The implication of this change of slope is that perhaps the ventilation rate and/or the pollen count ratio (x/m) is more properly a quadratic than a linear function of the average wind speed $\bar{v}$. There seemed little point in attempting the quadratic regression with no greater number of $k_1$ values, but because x/m in a way expresses the ventilation rate, and the graphs of x/m against $\bar{v}$ (Fig. 30) appear very similar to those of $k_1$ against $\bar{v}$ (Figs. 32 through 34), quadratic regressions were computed for x/m as a function of $\bar{v}$. The results are as follows, with x/m expressed as a percentage and $\bar{v}$ in mi/hr:

(a) windows closed, n = 117 sample pairs
$x/m = 16.69 + 1.39\,\bar{v} + 0.32\,\bar{v}^2$

(b) windows open 1 in., n = 88
$x/m = 4.26 + 14.45\,\bar{v} - 0.60\,\bar{v}^2$

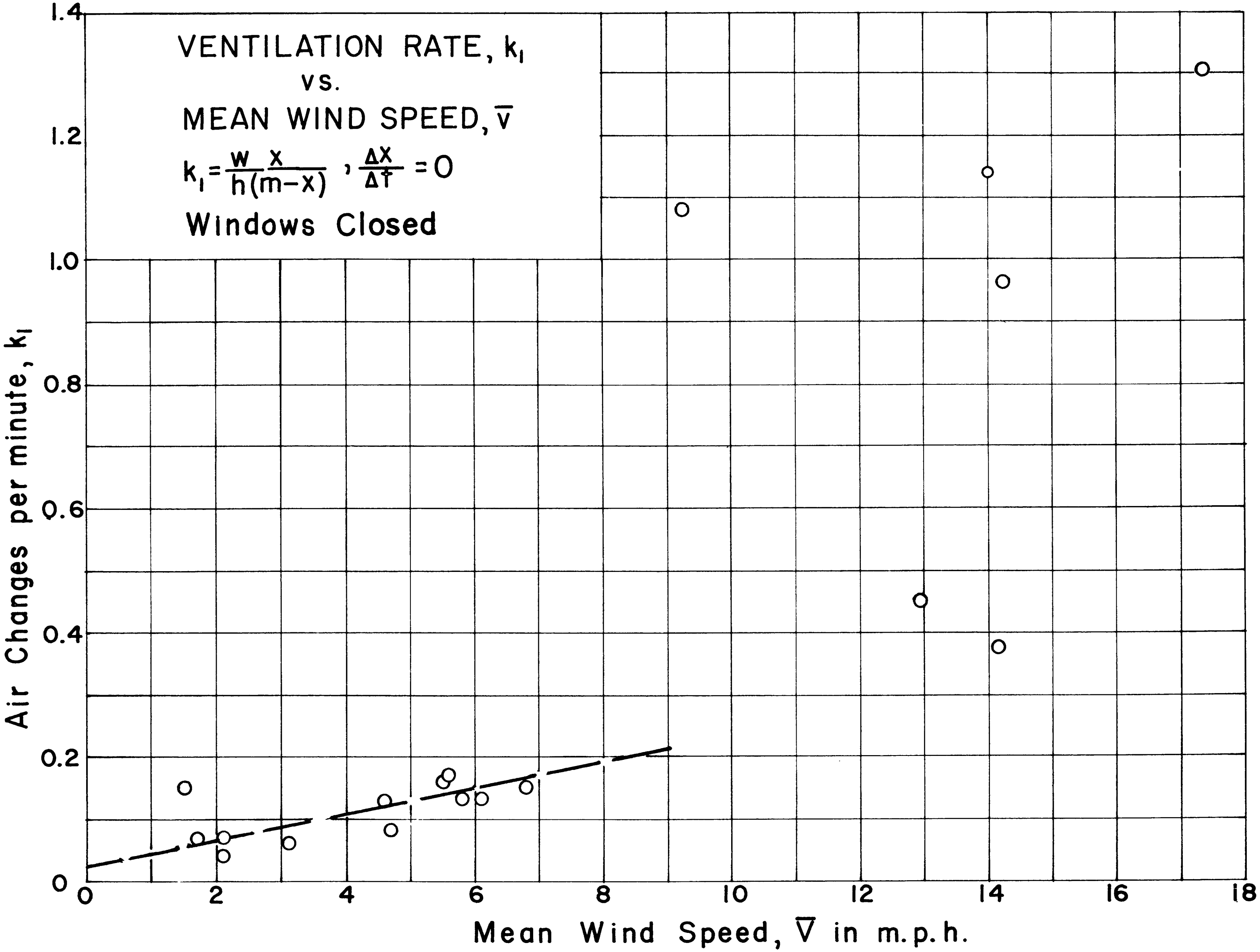

VENTILATION RATE, $k_1$
vs.
MEAN WIND SPEED, $\overline{v}$
$k_1 = \frac{w}{h}\frac{x}{(m-x)}$ , $\frac{\Delta x}{\Delta t} = 0$
Windows Closed
Air Changes per minute, $k_1$
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
2
4
6
8
10
12
14
16
18
Mean Wind Speed, $\overline{V}$ in m.p.h.

Fig. 32.

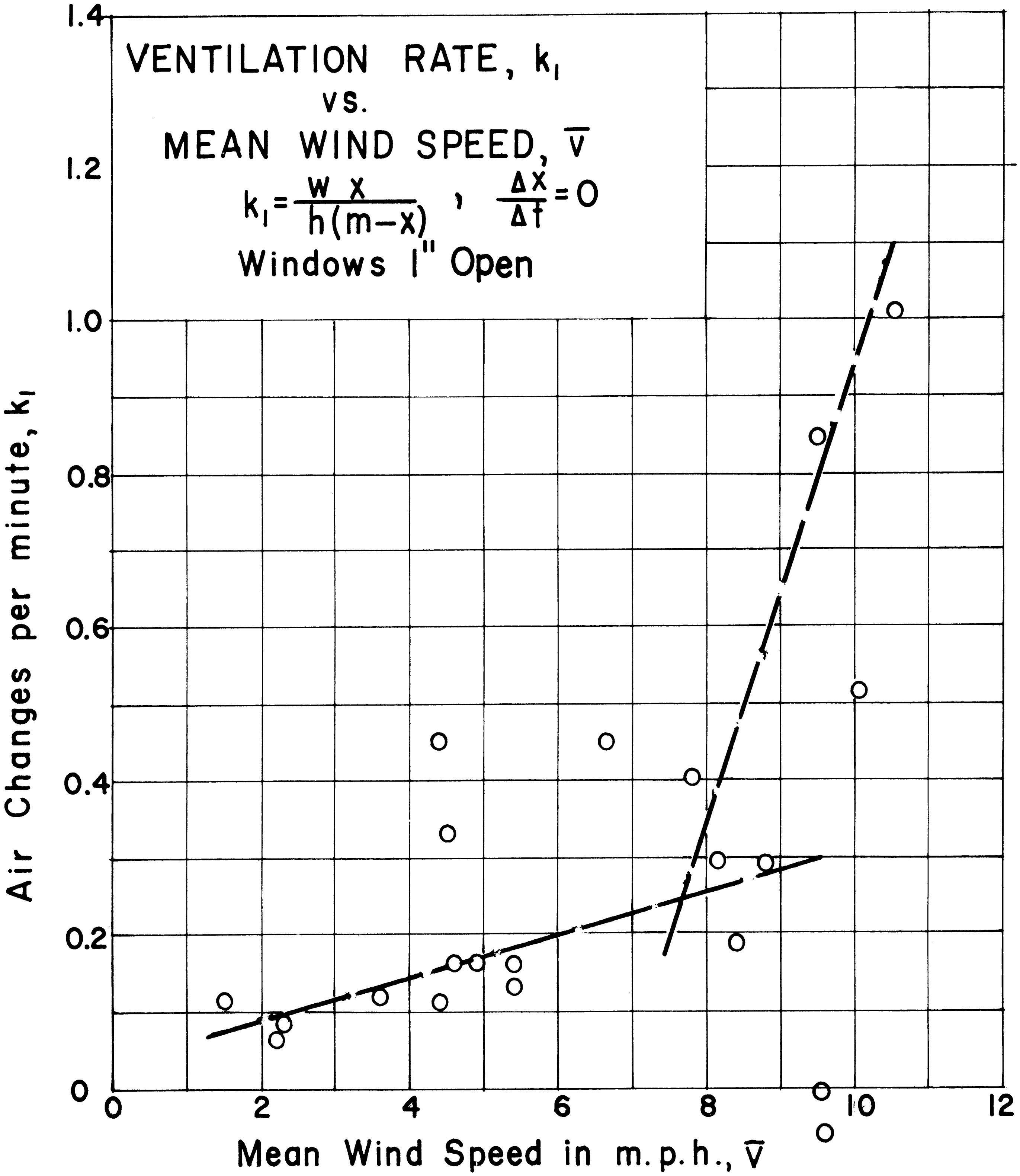

VENTILATION RATE, $k_1$
vs.
MEAN WIND SPEED, $\overline{V}$
$k_1 = \frac{W\ X}{h(m-X)}$ , $\frac{\Delta X}{\Delta t} = 0$
Windows 1" Open
Air Changes per minute, $k_1$
Mean Wind Speed in m.p.h., $\overline{V}$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12

Fig. 33.

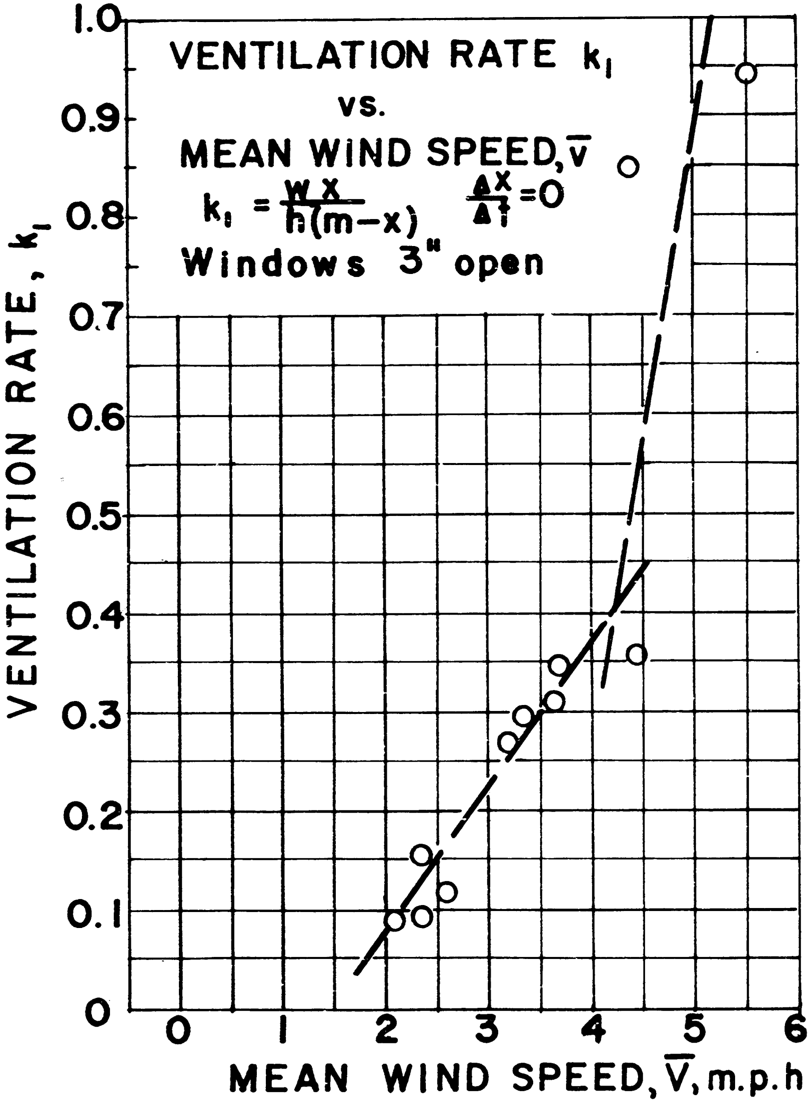

VENTILATION RATE $k_1$
vs.
MEAN WIND SPEED, $\overline{v}$
$k_1 = \frac{wx}{h(m-x)}$ $\frac{\Delta x}{\Delta t} = 0$
Windows 3" open
VENTILATION RATE, $k_1$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
MEAN WIND SPEED, $\overline{V}$, m.p.h

Fig. 34.

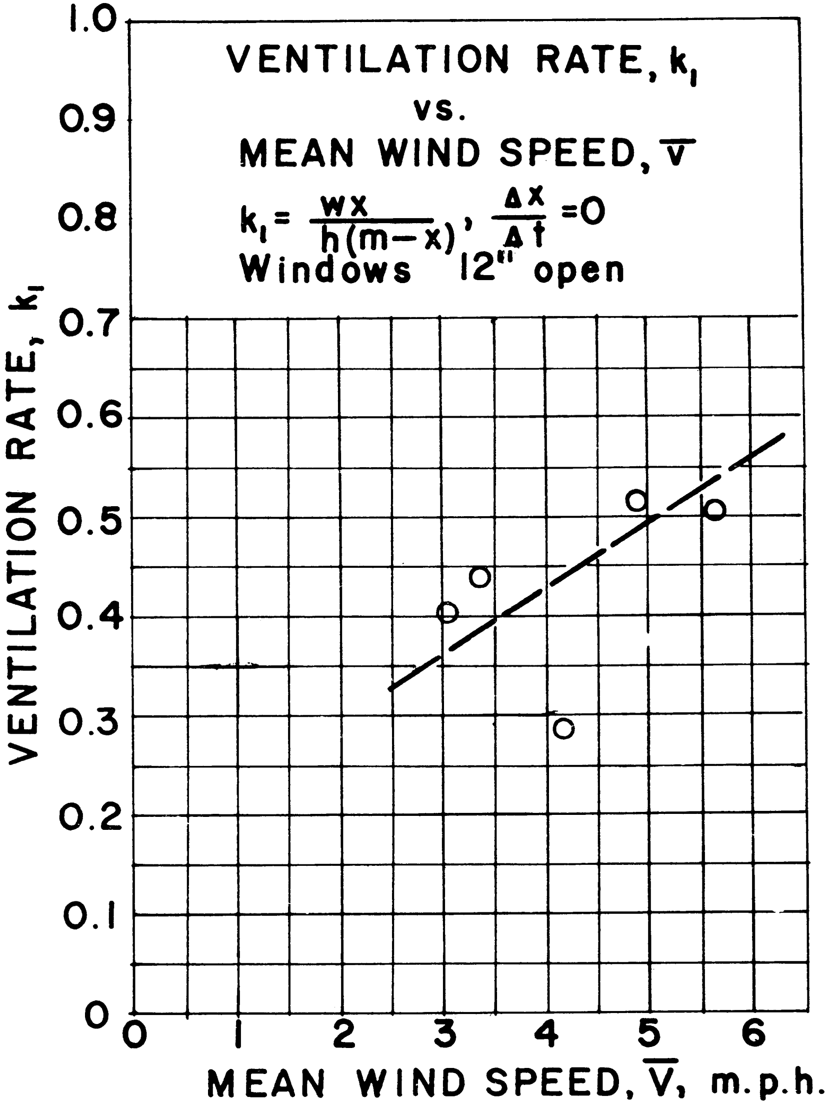

VENTILATION RATE, $k_1$
vs.
MEAN WIND SPEED, $\overline{v}$
$k_1 = \frac{wx}{h(m-x)}$, $\frac{\Delta x}{\Delta t} = 0$
Windows 12" open
VENTILATION RATE, $k_1$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
MEAN WIND SPEED, $\overline{V}$, m.p.h.

Fig. 35.

(c) windows open 3 in., $n = 34$
$x/m = -23.56 + 20.31\ \bar{v} - 0.92\ \bar{v}^2$

The constant terms in these regressions are more properly to be considered indicative, with the coefficient of $\bar{v}$, of the slope of the regression curve at low values of $\bar{v}$ than representative of a hypothetical value of x/m when $\bar{v} = 0$. For case (a) the regression is as anticipated, the slope increasing with increasing values of $\bar{v}$. For the other two cases, the curvature is reversed from that expected, and by virtue of the large coefficients of $\bar{v}$, the effect of $\bar{v}^2$ within the range of wind speeds encountered is quite small. This suggests that the linear equations are probably most appropriate for the range of wind speeds shown when the windows are open 1 in. or more. For the case when windows are closed, the $\bar{v}^2$ term begins to exceed the $\bar{v}$ term at about 4.5 mi/hr and becomes increasingly important thereafter. Under the closed condition, the ventilation is accomplished by virtue of crackage; thus it is inferred that the effective crackage is a function of the wind speed in the range observed, but that it is small compared to a window opening of 1 in. in each window.

It is clear that

$$\lim_{k \to 0} \left(\frac{x}{m}\right) = 0 \quad ,$$

and that

$$\lim_{k \to \infty} \left(\frac{x}{m}\right) = 1 \quad ,$$

so that x/m is not linearly related to $k_1$, and one should expect the behavior of $k_1$ in relation to $\bar{v}$ to be quite different from that indicated by the regressions computed for the more primitive quantity, x/m.

Considering the mechanics of ventilation, reduced to simplest form, the rate of ventilation of the test structure should be directly proportional to the combined areas of window openings and crackage. For the present, let it be assumed that the "crackage" of this structure is invariant and may be expressed as an equivalent amount of window opening. The rate of flow of air through all the openings depends on pressure differences that are generated by the short-period fluctuations of wind speed that are usually called gusts. This dependency is obviously not simple since the ventilating effectiveness of a gust must be related to its intensity. However, the pressure developed by the wind is proportional to the square of the wind speed, so one may try the estimate that k will increase as $\bar{v}^2$. Thus, under these assumptions,

$$k \propto (\text{window opening} + \text{crackage})\ \bar{v}^2$$

from which

$$k/\overline{v}^2 \propto (\text{window opening} + \text{crackage}) \quad ,$$

and a plot of $k/\overline{v}^2$ against window opening should yield an estimate of crackage in terms of the equivalent window opening. Table VIII shows values of $k_1/\overline{v}^2$ listed in order of increasing magnitude for each of the respective window openings. Average and median values are given at the bottom of each column and are plotted against window openings in Fig. 36.

TABLE VIII. ORDERED TABULATION OF $10^3\ k_1/\overline{v}^2$ BY WINDOW OPENINGS

| Window Opening | 0 | 1 in. | 3 in. | 12 in. |
|---|---|---|---|---|
| | 1.88 | 2.62 | | |
| | 2.69 | 3.74 | | |
| | 3.25 | 4.44 | | |
| | 3.50 | 4.45 | | |
| | 3.62 | 5.16 | 16.7 | |
| | 3.87 | 5.48 | 17.3 | |
| | 4.35 | 5.68 | 18.0 | |
| | 4.77 | 6.66 | 20.2 | 15.8 |
| | 5.28 | 6.66 | 23.2 | 16.7 |
| | 5.41 | 7.55 | 25.2 | 21.5 |
| | 5.82 | 9.20 | 26.2 | 39.2 |
| | 6.13 | 9.40 | 26.4 | 42.4 |
| | 6.24 | 10.20 | 27.6 | |
| | 9.07 | 12.40 | 30.5 | |
| | 12.60 | 15.10 | 43.8 | |
| | 15.90 | 16.30 | | |
| | 18.90 | 23.20 | | |
| | 24.20 | 40.90 | | |
| | 66.70 | 90.20 | | |
| Average | 10.75 | 14.70 | 25.01 | 27.12 |
| Median | 5.41 | 7.55 | 25.20 | 21.50 |

Because the data for the 12-in. window openings are very limited (only 5 values of $k_1$), they are omitted from this graph. The y-intercepts of straight lines drawn respectively through the median and average points would provide estimates of the crackage in terms of equivalent window opening. Obviously the distributions of $k_1/\overline{v}^2$ are strongly skewed, so it is difficult to judge the relative significance of the statistics chosen to represent them in

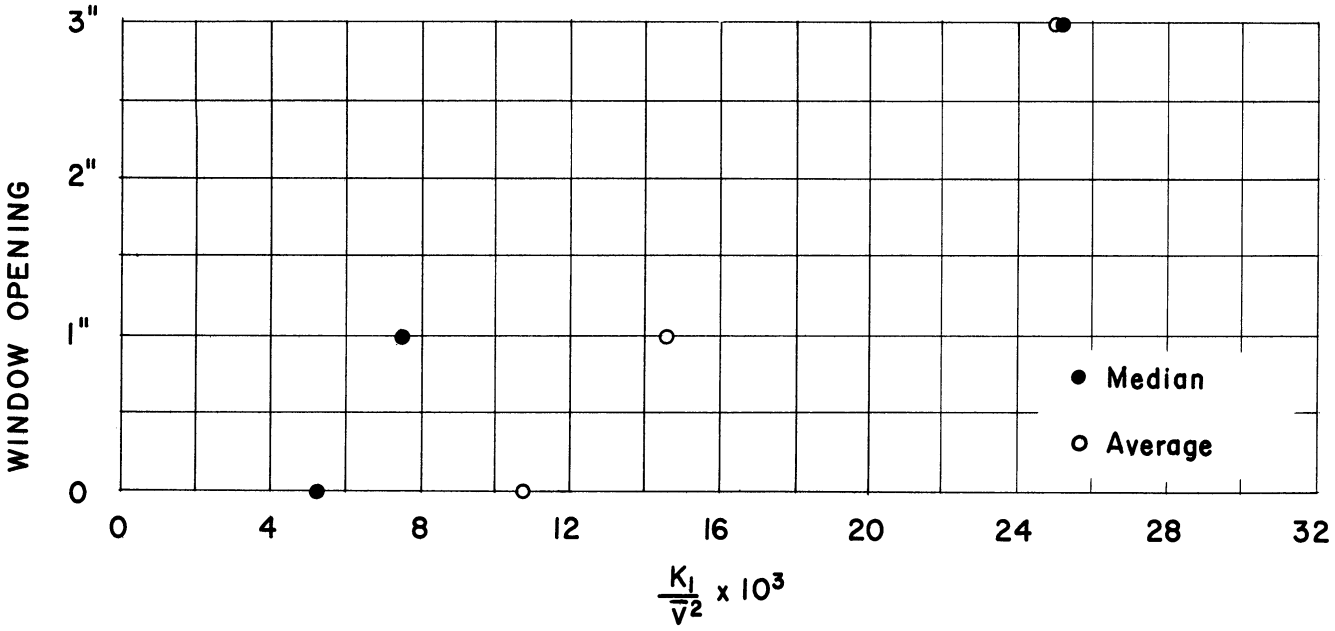


Fig. 36. Median and Average Values of $10^3\ k_1/\bar{v}^2$ vs Window Opening.

the plot. Using the difference between median and average as a criterion, it is clear that the figures for the 3-in. window opening are much less skewed than the others and that this difference (average-median) is remarkably constant for the other three window openings: 6.4, 7.1, and 5.6, respectively.

If instead of using simply $\bar{v}^2$ as a basis for normalization of k, one returns to the gustiness figures and weights them according to the square of the intensity expressed as mi/hr departure from $\bar{v}$, a new index is obtained. This index is designated the "ventilation effectiveness" (V.E.) and is computed according to

$$\text{V.E.} = n_2 + 2.25\ n_3 + 4n_4 + 6.25\ n_5 \quad ,$$

in which the subscripts designate the respective intensity categories (± 2, ± 3, ± 4, ± 5 mi/hr) in which the gusts were counted and n is the number of gusts. This index is thus an expression of the amount of "pumping" action on the test room due to variations from the mean wind speed.

The relation of V.E. to $\bar{v}$ is indicated by the graph, Fig. 37, on which the regression line

$$\text{V.E.} = 28.89\ \bar{v} - 94.31$$

has been drawn, and by the simple correlation coefficient, $r = 0.91$. Thus, referring also to the gust count G (Section 4.2), it appears that $\bar{v}$ is about as appropriate as V.E. or G for use as the independent variable influencing the ventilation rate. This may be regarded as the rule for sampling periods

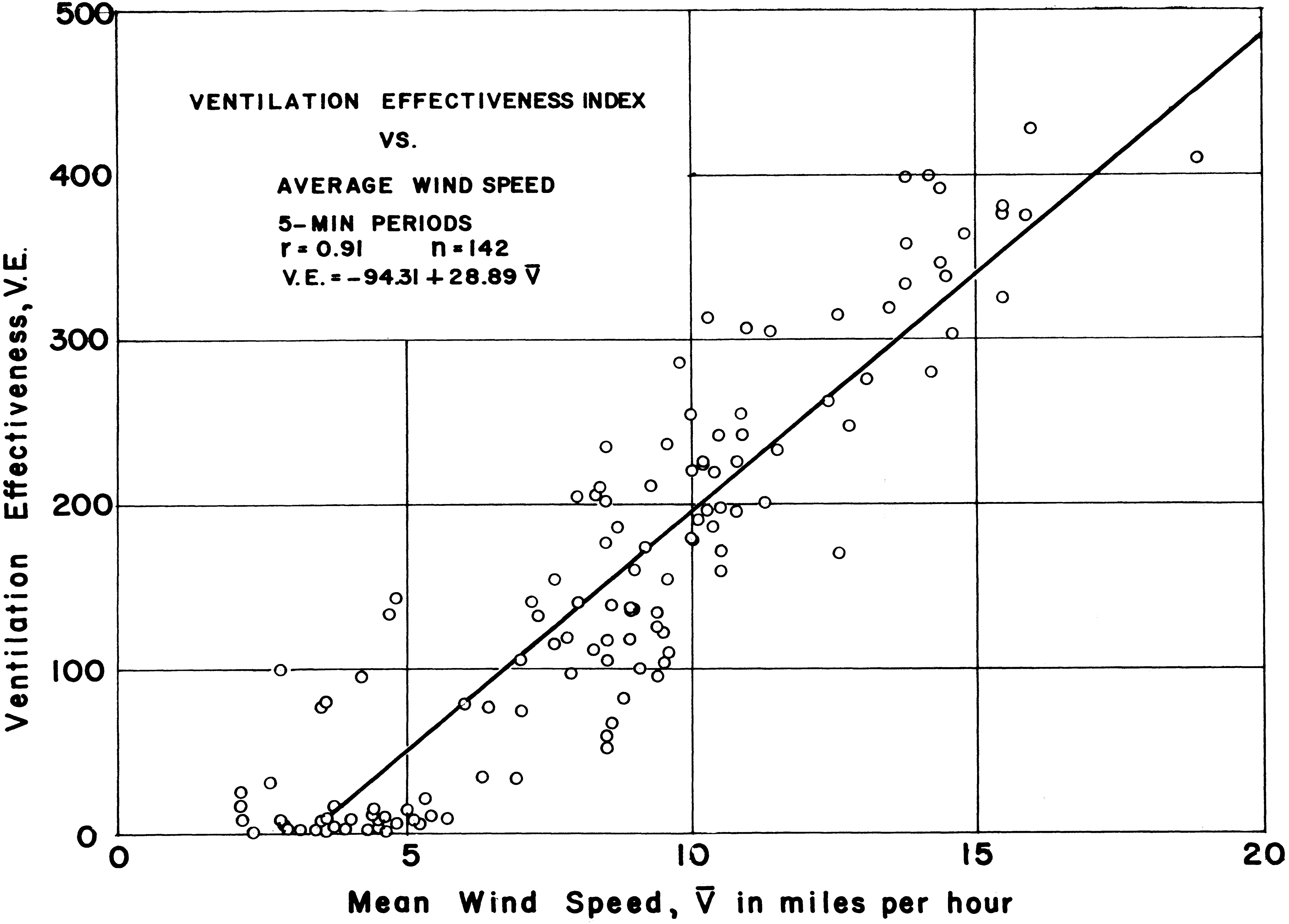

VENTILATION EFFECTIVENESS INDEX
VS.
AVERAGE WIND SPEED
5-MIN PERIODS
r = 0.91 n = 142
V.E. = -94.31 + 28.89 $\overline{V}$
Ventilation Effectiveness, V.E.
0
100
200
300
400
500
0
5
10
15
20
Mean Wind Speed, $\overline{V}$ in miles per hour

Fig. 37.

of 5 to 15 min duration. Further study is needed to verify this rule for other sampling periods. A tabulation of $10^3$ $k_1/V.E.$ is given in Table VII. The median and average values of $10^3$ $k_1/V.E.$ according to window-opening categories are plotted in Fig. 38 against window opening. In this plot it is clear that the median points tend to define one straight line and the average points another. The y intercepts of these two lines are near -3/4 in. and -1/4 in., respectively - suggesting that the crackage of the test house is about equivalent in ventilation effect to opening both windows 1/2 in. Another attempt to estimate the effective crackage was made using $10^3$ $k_1/G$ in a similar way (Fig. 39). The straight lines in this plot are not defined as well as those of Fig. 38, but such lines as are indicated give an estimate of crackage similar to that above.

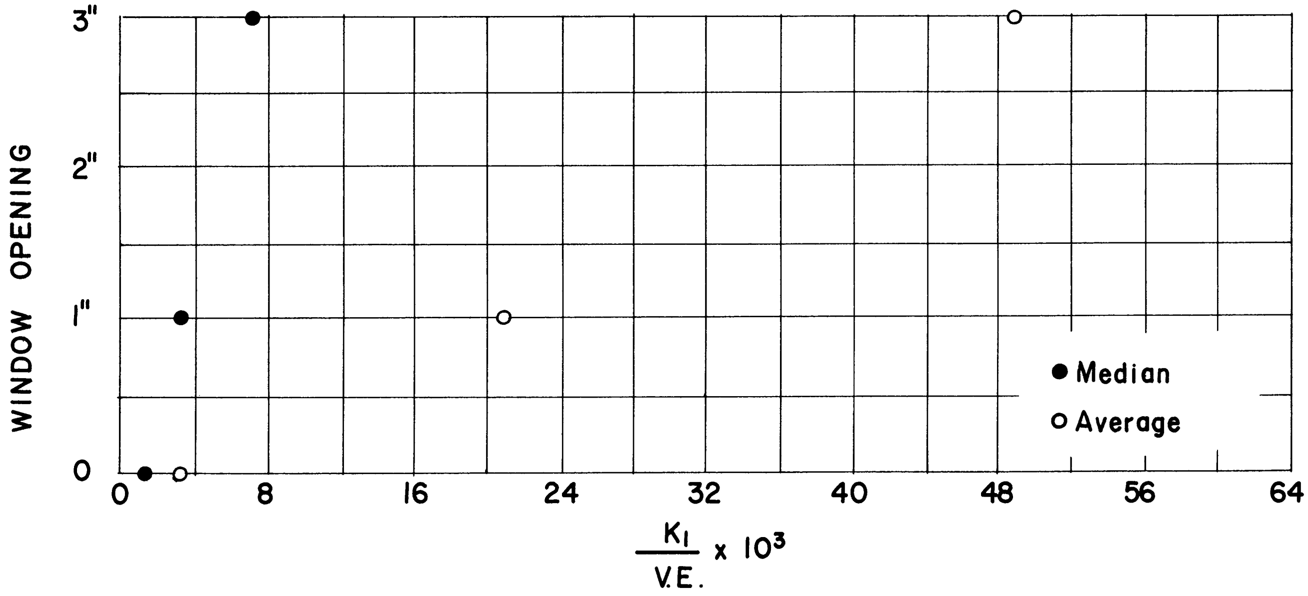


Fig. 38. Median and Average Values of $10^3$ $k_1/V.E.$ vs Window Opening.

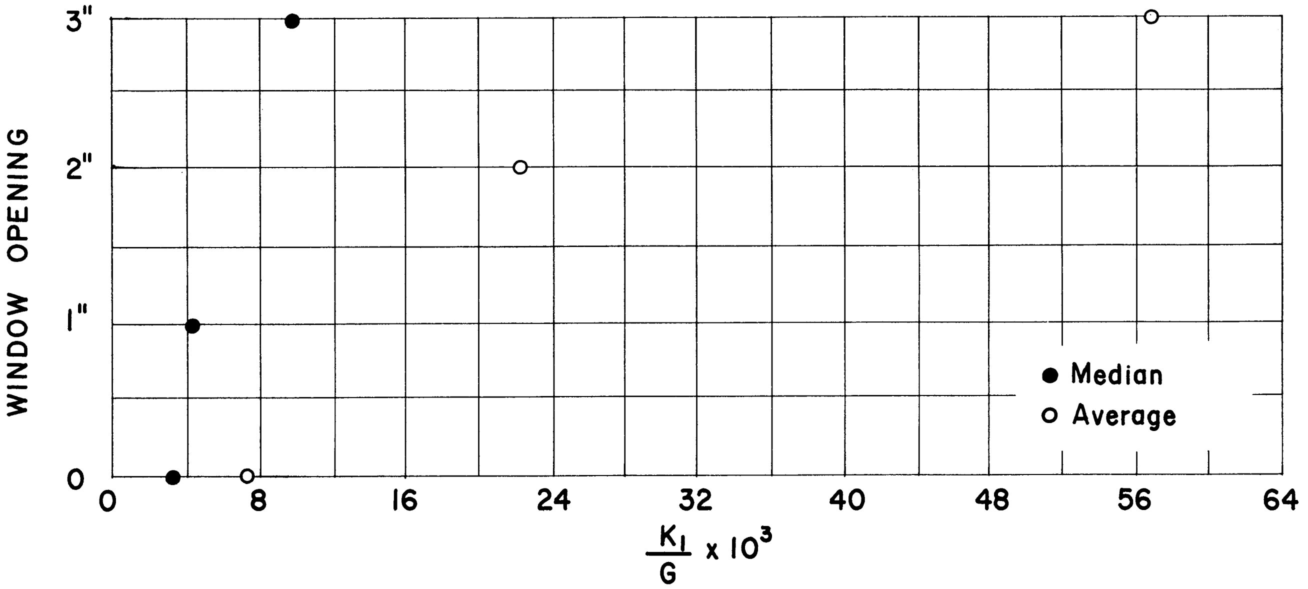


Fig. 39. Median and Average Values of $10^3$ $k_1/G$ vs Window Opening.

One further consideration, namely, that of the relation of V.E. to the kinetic energy of the mean wind, was undertaken. The simple correlation of V.E. and $\overline{v}^2$ gave $r = 0.85$ with the regression line

$$\text{V.E.} = 1.37\,\overline{v}^2 + 31.40 \quad ,$$

which further fortifies the conclusion that as far as the present data are concerned, $\overline{v}$ offers the most simple and direct estimate of the ventilating effect of the wind.

## 4.5 ANALYSIS: VENTILATION DYNAMICS

Because the wind is always variable, the ventilation rate k also varies in time periods much shorter than those used for the present pollen penetration experiments. The general treatment of k as a constant in the analytical procedure is therefore not quite valid. The evaluations obtained by the above methods are obviously not constant from period to period even under conditions that appear to be essentially constant. This must be attributed to the capriciousness of atmospheric turbulence, all the details of which were not measured.

In a few cases it was found that m, the outside pollen count, varied from sample to sample in a way that could be expressed analytically in simple form, particularly as a sine wave. For such cases, it is possible to solve Equation 5 for various assumed values of k and thereby to derive or predict the time variation of x.

Equation 5 may be written in the form

$$x'(t) + A\,x(t) = k\,m(t) \quad , \tag{9}$$

in which $x' = dx/dt$ and

$$A = \left(k + \frac{w}{h}\right) \quad .$$

If m(t) has the form

$$m(t) = C + B \sin \omega t \quad ,$$

and if $x(0) = x_0$, it can be shown (Appendix D) that

$$x(t) = x_0 e^{-At} + \frac{kC}{A}\left(1 - e^{-At}\right) + \frac{k\omega B}{A^2 + \omega^2}\left(e^{-At} - \cos \omega t\right) + \frac{kAB}{A^2 + \omega^2} \sin \omega t . \tag{10}$$

The values of $x_0$, C, B, and $\omega$ were derived from the observed data. A curve of x(t) against time could then be computed for each of several assumed values of k, the ventilation rate. Figures 40, 41, and 42 show the results of this experiment for three selected cases. In Fig. 40 it is seen that the behavior of x (observed) bears almost no relation to the predicted curves. It is true that m (observed) departs from m(t) (assumed) significantly in this case, but this departure does not explain the high values of x obtained in sample Nos. 6, 7, 8, and 9. Since the windows were open during this test (No. 13) and the 5-min average wind speeds ranged from 8.3 to 10.4 mi/hr, one can only judge that the outside sampler (measuring m) did not sample air representative of that which entered the test room during a large part of this test.

Figures 41 and 42 portray somewhat more successful examples of the method. Whereas, in the first 20 min of test No. 14 (Fig. 41), k appears to have been of the order of 1 air change per minute, the latter part of the test (Fig. 42) shows values corresponding to a much lower rate of ventilation (about 0.2 to 0.3 air change per min). The wind speeds (5-min averages) ranged from 8.5 to 11.0 mi/hr in the period represented by Fig. 41 and from 7.6 to 11.5 mi/hr in that represented by Fig. 42. The windows were open 1 in. throughout the test. In those cases for which $k_1$ was computed (Table VII), the values obtained agree very well with the values suggested by Figs. 40, 41, and 42.

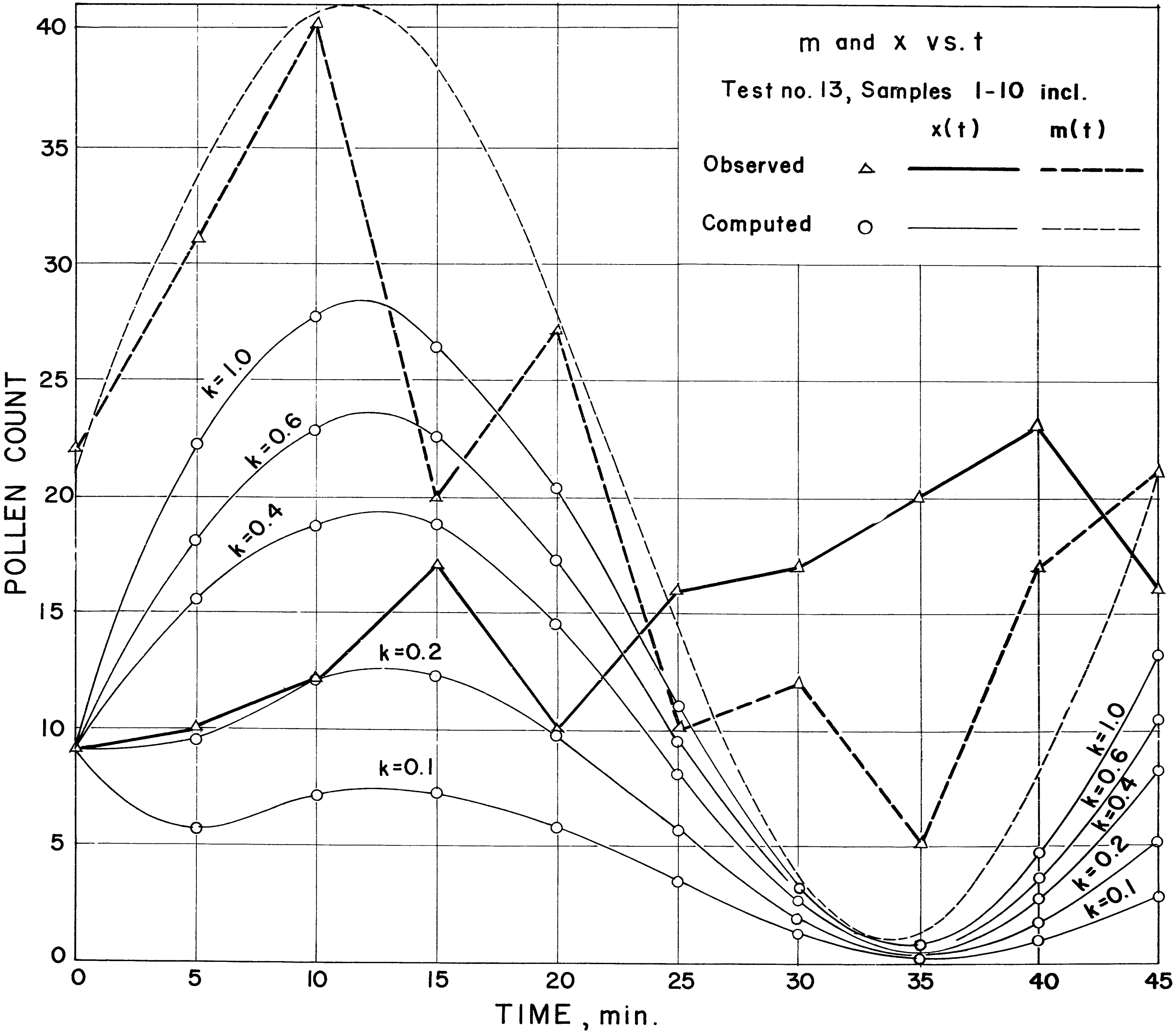

m and x vs. t
Test no. 13, Samples 1-10 incl.
x(t)
m(t)
Observed
Computed
POLLEN COUNT
TIME, min.
0
5
10
15
20
25
30
35
40
0
5
10
15
20
25
30
35
40
45
k=1.0
k=0.6
k=0.4
k=0.2
k=0.1
k=1.0
k=0.6
k=0.4
k=0.2
k=0.1

Fig. 40.

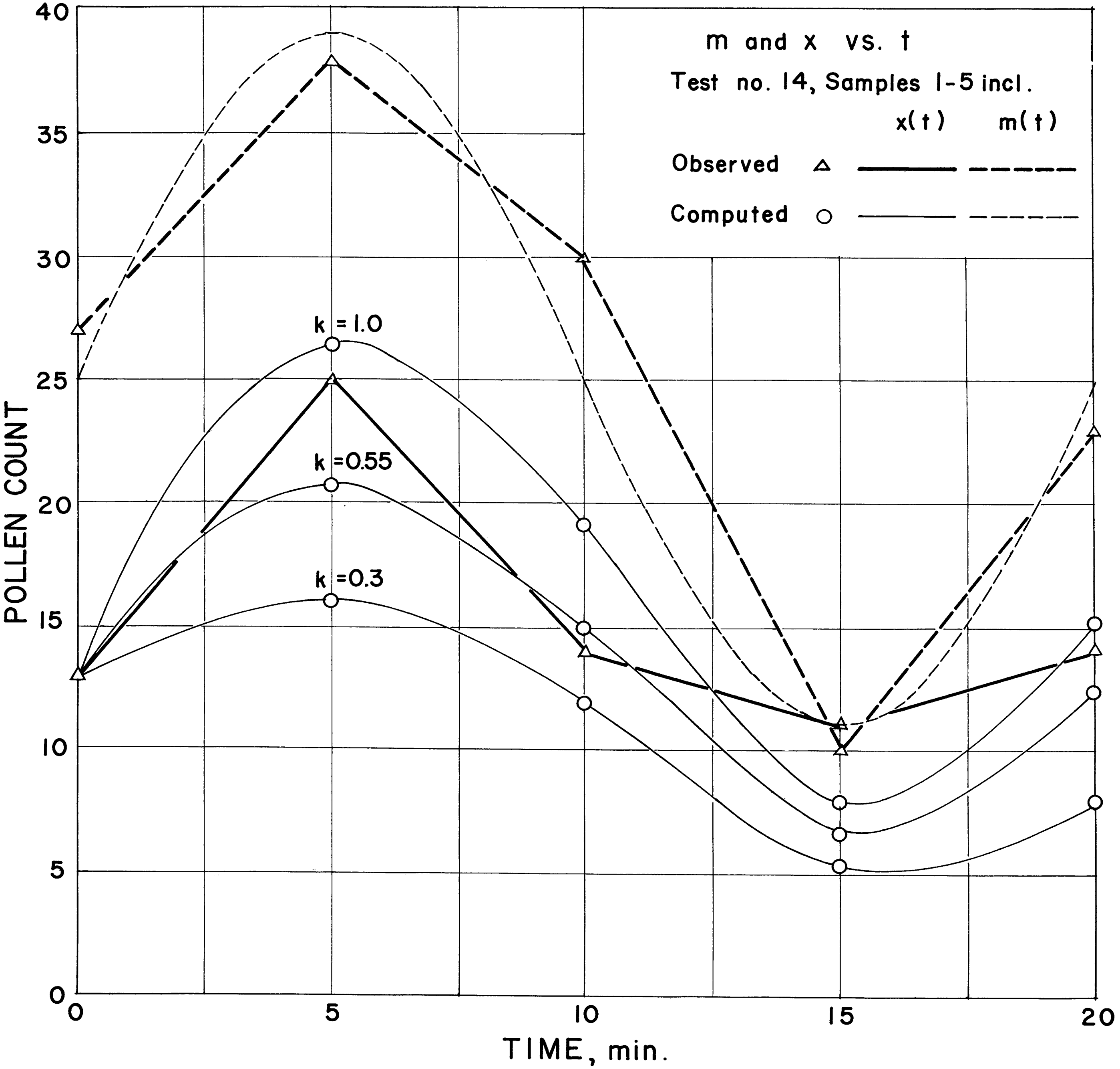

m and x vs. t
Test no. 14, Samples 1-5 incl.
x(t)
m(t)
Observed △
Computed ○
k = 1.0
k = 0.55
k = 0.3
POLLEN COUNT
0
5
10
15
20
25
30
35
40
TIME, min.
0
5
10
15
20

Fig. 41.

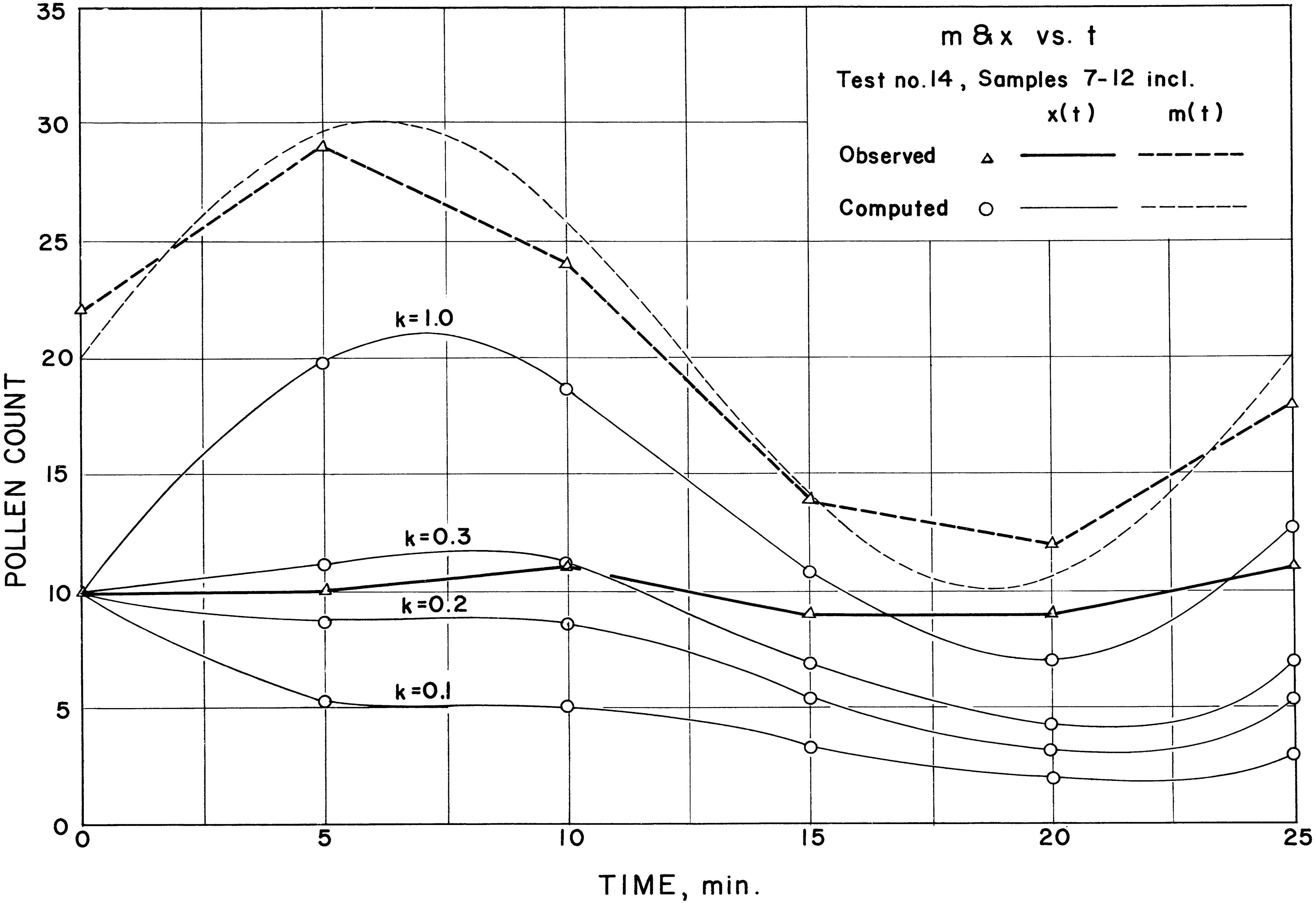

m & x vs. t
Test no. 14, Samples 7-12 incl.
x(t)
m(t)
Observed △
Computed ○
k = 1.0
k = 0.3
k = 0.2
k = 0.1
POLLEN COUNT
0
5
10
15
20
25
30
35
TIME, min.
0
5
10
15
20
25

Fig. 42.

# CHAPTER 5

# SUMMARY, CONCLUSIONS, AND SUGGESTIONS FOR FURTHER RESEARCH

The results of the research described in this report appear to fall naturally into several categories. Those selected for discussion here form the basic outline of the present chapter:

1. The wind in the layer of air near the ground.
2. Penetration analysis by the direct interpretation of inside-outside pollen counts.
3. Penetration analysis by evaluation of the ventilation rate, k.
4. The design of future experimentation.

## 5.1 THE WIND IN THE LAYER OF AIR NEAR THE GROUND

The wind was observed in sufficient detail for analysis only in terms of speed, so the results are based entirely on this scalar representation of wind. On this basis, it was found that if one defines a gustiness index G as the sum total of the number of departures having magnitude 2, 3, 4, and 5 mi/hr from the mean wind speed over a time interval of 5 to 15 min, then G is highly correlated with the mean wind speed, $\overline{v}$ (r is of the order of 0.9). That such a relationship exists appears to have been understood for some time; for example, Giblett (1932) mentions briefly the approximately linear relation of his vector wind deviation to the wind speed, Hewson and Gill (1944) obtained the same result at higher wind speeds, and, in a more general sense, Snedecor (1937) presents the idea that larger quantities tend to have larger variations in his discussion of the "coefficient of variation."

The regressions of G on $\overline{v}$ show that G vanishes for $\overline{v} \approx 2.5$ mi/hr. If smaller deviations than 2 mi/hr were included in G, this threshold would probably decrease.

Of special interest is the evidence presented above (Chapter 4) that the slope of the linear regression of G on $\overline{v}$ is a function of the "degree of nearby obstruction to the wind field." It is suggested that this slope might serve as a "roughness index" for purposes of describing quantitatively the wind structure in the layer of air near the ground.

The relationship of directional shifts of the wind to $\overline{v}$ could not be studied with the present data, but there is some indication in other work

(Smith, 1951; Singer and Smith, 1953) that these fluctuations are more closely related to atmospheric stability than to wind speed.

A short-duration plume of identifiable particulates emitted from a definite source was used to trace the pattern of air movements in a few experiments (Chapter 3). In these tests, coated microscope slides were used, one set facing upward and another set at identical stations facing as nearly upwind as possible. The pollen distributions recorded by these two sets of slides show interesting differences. The labor of counting the large number of samples required proved to be excessive; nonetheless, the line of experimentation appears to have interesting potentialities.

## 5.2 PENETRATION ANALYSIS BY THE DIRECT INTERPRETATION OF INSIDE-OUTSIDE POLLEN COUNTS

The ratio of the volumetric pollen count inside the test room to that outside is useful in the study of the ventilation-penetration process because it eliminates the complex of biological and meteorological factors affecting pollen production and release at the source, etc. Although this ratio correlates positively and fairly significantly with the mean wind speed for the cases treated (Chapter 4), a considerable scatter of points is evident, and the slopes of the respective regressions of $x/m$ on $\bar{v}$ are not entirely consistent with physical expectation. One problem inherent in this type of treatment of the pollen counts is that no distinction is made between cases for which $x$ and $m$ are relatively large and those for which they are small. In the latter case, the error introduced by unit error in counting may become very large. Some selection of data on the basis of a specified minimum acceptable sample is suggested. In the present experiment such selection could only be made "after the fact," and if rigorous enough selection were applied, the number of acceptable samples would be reduced excessively. The statistical problem implicit in these observations can be properly resolved only through further experimentation and study.

The regressions of $x/m$ on $\bar{v}$ for windows shut and windows open 3 in. are reasonably consistent with physical expectation and show that as $\bar{v}$ decreases below 1 mi/hr to about 0.5 mi/hr, $x/m$ vanishes. This threshold should be verified by further experimentation.

## 5.3 PENETRATION ANALYSIS BY EVALUATION OF THE VENTILATION RATE, k

The differential equation for the rate of penetration (Equation 5, Section 4.4) allows evaluation of $k$, under various simplifying assumptions, from consecutive pairs of inside-outside samples. Application of these assumptions to the data as criteria for the selection of cases to be considered tends to reduce the variability of the results as compared to those studied without such selection. It also reduces the number below that necessary for profitable application of statistical methods. The equilibrium case (x = constant) proved to be the most fruitful.

The pollen counts obtained in particular cases proved to be inadequate to give a proper estimate of k. For example, in Test No. 9, Samples 2-3 (Appendix C), x meets the constancy requirement, having values of 21 and 22, respectively, but m has values of 37 and 11, respectively. The result is that m-x is small compared to x, and k computed on this basis is 3.87 changes per minute even though in this test the windows were closed. It appears clear that the low value of m in this case is not representative of the air that was ventilating the room. The relatively high winds of Tests 9, 10, and 11 appear to produce rather erratic fluctuations of the k values computed by this means. Obviously this erratic character is inherent in the pollen counts themselves, depending as they do on the turbulent fluctuations of the local air movement.

Despite the difficulties encountered, the k values in summary form, that is to say, the median and average values of k, taken according to the amount of window opening, provide reasonable estimates of the crackage of the test structure. For this purpose, three different indices of the ventilating effectiveness of the wind were used. In each case the assumption was made that the ventilation rate, k, should be proportional to the product of (amount of window opening + crackage) by the ventilation index. The most successful of the indices tried in this limited experiment is the V.E. index which is described in Section 4.4.2. The gustiness index G (defined in Section 4.2) gave similar results, and both of these indices appeared in this particular test to be superior to $\overline{v}^2$, the kinetic energy of the mean wind, for estimating ventilation effectiveness.

As noted above, the index G correlated very highly with the mean wind speed when both were evaluated for 5-, 10-, and 15-min intervals. The V.E. index correlated about equally well with $\overline{v}$ ($r = 0.9$), but somewhat less satisfactorily with $\overline{v}^2$. Thus, it must be concluded that the most simple and direct index of ventilation effectiveness of the wind is the mean wind speed during the sampling period as far as the present experimentation is concerned.

The values of k, which are uniformly stated in units of $(\text{minutes})^{-1}$, appear inordinately large. It is doubtful whether the assumptions leading to Equation 5, Section 4.4, upon which the computations of k are based, are fulfilled completely for the ragweed-pollen grains. An independent evaluation of k should therefore be used in order that estimates of the effects of impaction and reflotation of the pollen grains could be made.

The effects of nonisotropic distribution of the pollen grains in the outside atmosphere appear prominently in the heterogeneity of the k values. It is pertinent to note that even at the height of the ragweed-pollen season, a concentration of 500 pollen grains per cubic meter is relatively high. The question of the procurement of adequate samples is therefore important, and it is not easily answered because of the relative rarity of airborne pollen grains on the average. Furthermore, the size and mass of this specific particulate militate against its even dispersion with realistic time intervals.

## 5.4 THE DESIGN OF FUTURE EXPERIMENTATION

The work described above indicates clearly that for the study of the penetration of particulate matter of relatively large size (diameters of 10 μ and greater) into structures, the ventilation characteristics of such structures should be evaluated independently of the particulates under study, preferably by the gas-dilution technique. The functional relation of the ventilation rate of the structure in question to the wind speed should be determined in advance, or at least independently.

Because all information about the particulate in question is statistical in nature, it is basic that the distribution of the particulate in the outside air be understood in some measure, and preferably it should be statistically defined. The statistical description of the distribution of ragweed-pollen grains in the atmosphere is a basic prerequisite for obtaining an adequate interpretation of the present data.

Experimental conditions can be controlled artificially within limits, and these techniques may offer the means whereby the penetration problem can most profitably be attacked. They certainly offer a highly effective means of studying dispersion patterns from definite sources, and they should be exploited more fully to this end.

# ACKNOWLEDGMENTS

We are pleased to acknowledge the assistance of a number of persons during the course of the research. Mr. William H. Hansen contributed greatly to the early development of the instrumentation employed, which was fabricated by Messrs. C. Samborski and K. L. Gleason. Dr. V. C. Liu's theoretical studies of the dispersion of dynamic particles in a field of turbulence have been mentioned already in the report; his contribution is greatly appreciated. Mr. G. C. Gill assisted with the experimental program during the 1955 pollen season.

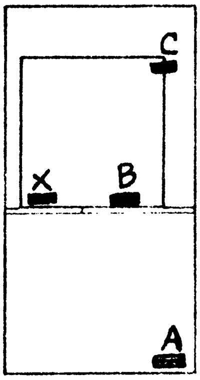
The following Student Assistants in Research have worked on the project: Martin Harwit; Jose F. Asuncion; Gunvant C. Sutaria; Alan H. Molof; F. C. Chang; David A. Lundy; J. A. Ismaili; P. Rangaswamy; and J. W. Hardin.

Finally, we wish to express our deep appreciation of the generosity of Mr. John Armstrong, President of the construction company of Darin and Armstrong in Detroit. Mr. Armstrong supplied the field construction building used in the experiments on penetration at the North Campus site, arranged to have it delivered and set in place at the site, and then had it removed after completion of the experimental program, all without cost to the project.

# APPENDICES

# APPENDIX A: SPOT SAMPLING DATA

KEY: O FACE VIEW OF FILTER
▬ EDGE VIEW OF FILTER
FAN IN PLAN
FAN IN ELEVATION



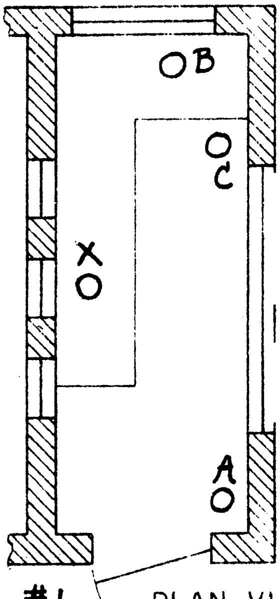
#1 VERTICAL VIEW

TEST #1: 1700 SEP 4 – 1000 SEP 7 (65 HR)

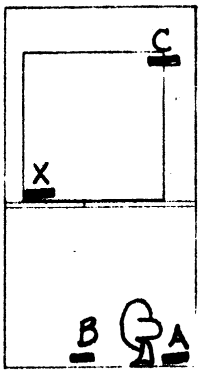
WINDOW OPEN, FAN OFF

| POSITION | COUNT |
|---|---|
| A | 19 |
| B | 9 |
| C | 0 |
| X | 4 |
| AV | 8 |

$\frac{X}{AV} = 50\%$



#1 PLAN VIEW



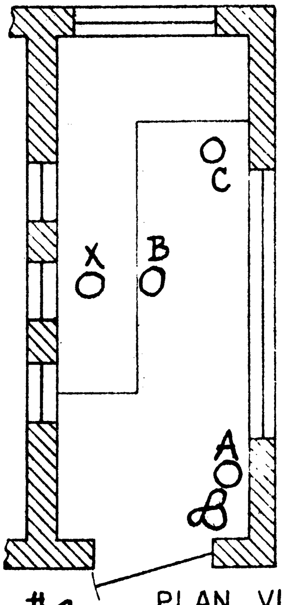
#2 VERTICAL VIEW

TEST #2: 1700 SEP 7 – 0900 SEP 8 (16 HR)

WINDOW OPEN, FAN ON

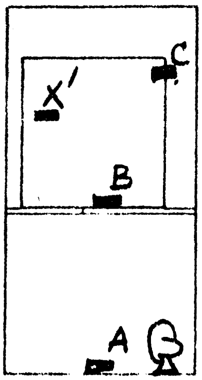
| | |
|---|---|
| A | 13 |
| B | 20 |
| C | 9 |
| X | 12 |
| AV. | 13.5 |

$\frac{X}{AV.} = 89\%$

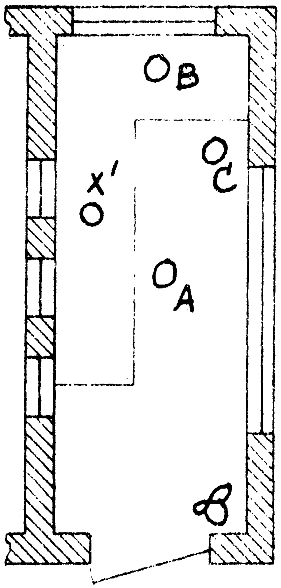


#2 PLAN VIEW

## APPENDIX A, CONTINUED



#3 & #4 VERTICAL VIEW



#3 & #4 PLAN VIEW

### TEST #3: 1700 SEP 10 – 1100 SEP 11 (18 HR)

WINDOW OPEN, FAN ON

| | |
|---|---|
| A | 13 |
| B | 21 |
| C | 4 |
| X' | 10 |
| AV | 12 |

NOTE: X' TAKEN ~ 18" ABOVE THE USUAL X POSITION

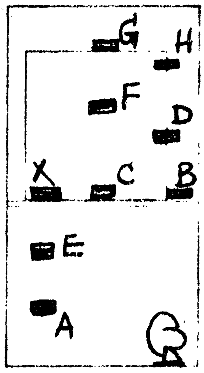
$$\frac{X'}{AV} = 83\%$$

### TEST #4: 1400 – 1600 SEP 11 (2 HR)

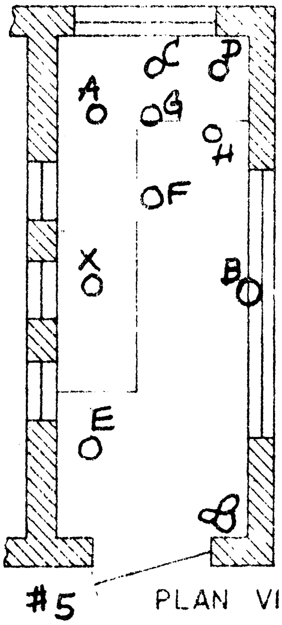
WINDOW CLOSED, FAN OFF

| | |
|---|---|
| A | 2 |
| B | 7 |
| C | 0 |
| X' | 1 |
| AV | 2.3 |

$$\frac{X'}{AV} = 44\%$$



#5 VERTICAL VIEW



#5 PLAN VIEW

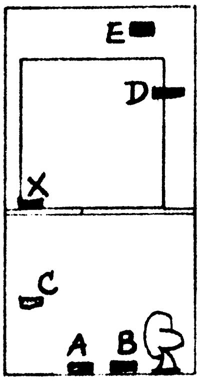
### TEST #5: 0830 SEP 13 – 0830 SEP 14 (24 HR)

WINDOW OPEN, FAN ON

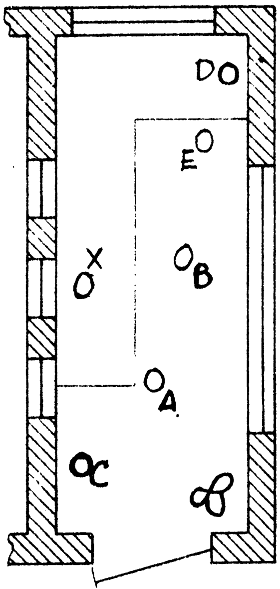
| | | | |
|---|---|---|---|
| A | 9 | F | 13 |
| B | 19 | G | 9 |
| C | 13 | H | 7 |
| D | 9 | X | 10 |
| E | 10 | AV | 11 |

$$\frac{X}{AV} = 91\%$$

# APPENDIX A, CONTINUED



VERTICAL VIEW



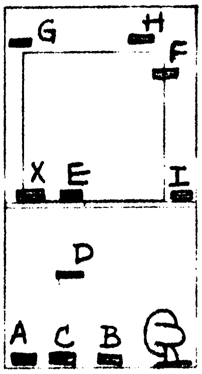
PLAN VIEW

## TEST #6: SEP 16 - ONE HOUR

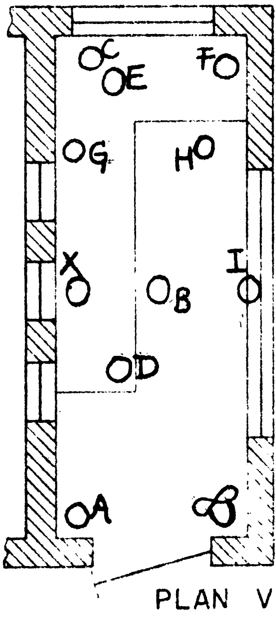
WINDOW OPEN, FAN ON

| | |
|---|---|
| A | 0 |
| B | 2 |
| C | 4 |
| D | 2 |
| E | 1 |
| X | 4 |
| Av | 2.1 |

$\frac{X}{Av} = 190\%$



VERTICAL VIEW



PLAN VIEW

## TEST #7: 1845 SEP 17 - 0945 SEP 18 (15 HR)

WINDOW OPEN, FAN ON

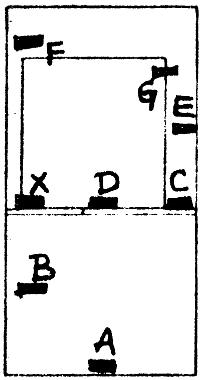
| | |
|---|---|
| A | 7 |
| B | 5 |
| C | 4 |
| D | 3 |
| E | 0 |
| F | 7 |
| G | 2 |
| H | 7 |
| I | 21 |
| X | 5 |
| Av | 6.1 |

$\frac{X}{Av} = 82\%$

# APPENDIX A, CONCLUDED

## TEST #8: 1245 SEP 19 - 1245 SEP 20 (24 HR)

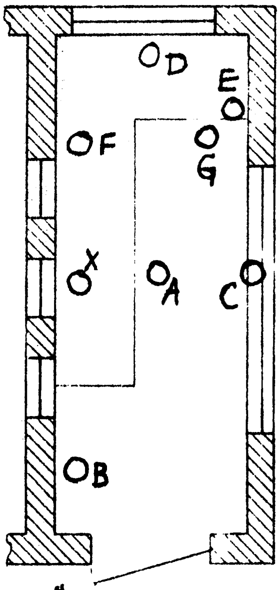
WINDOW OPEN, FAN OFF



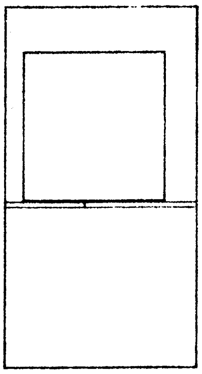
#8 VERTICAL VIEW

| | |
|---|---|
| A | 17 |
| B | 15 |
| C | 16 |
| D | 6 |
| E | 9 |
| F | 7 |
| G | 1 |
| X | 7 |
| Av | 9.8 |

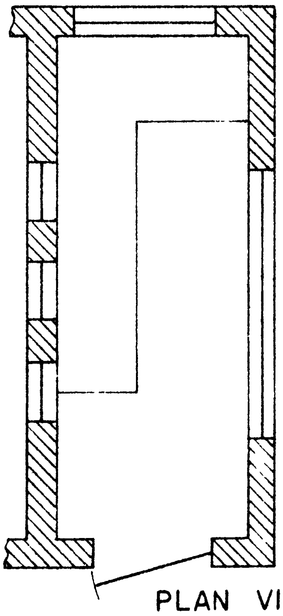
$\frac{X}{Av} = 71\%$



#8 PLAN VIEW



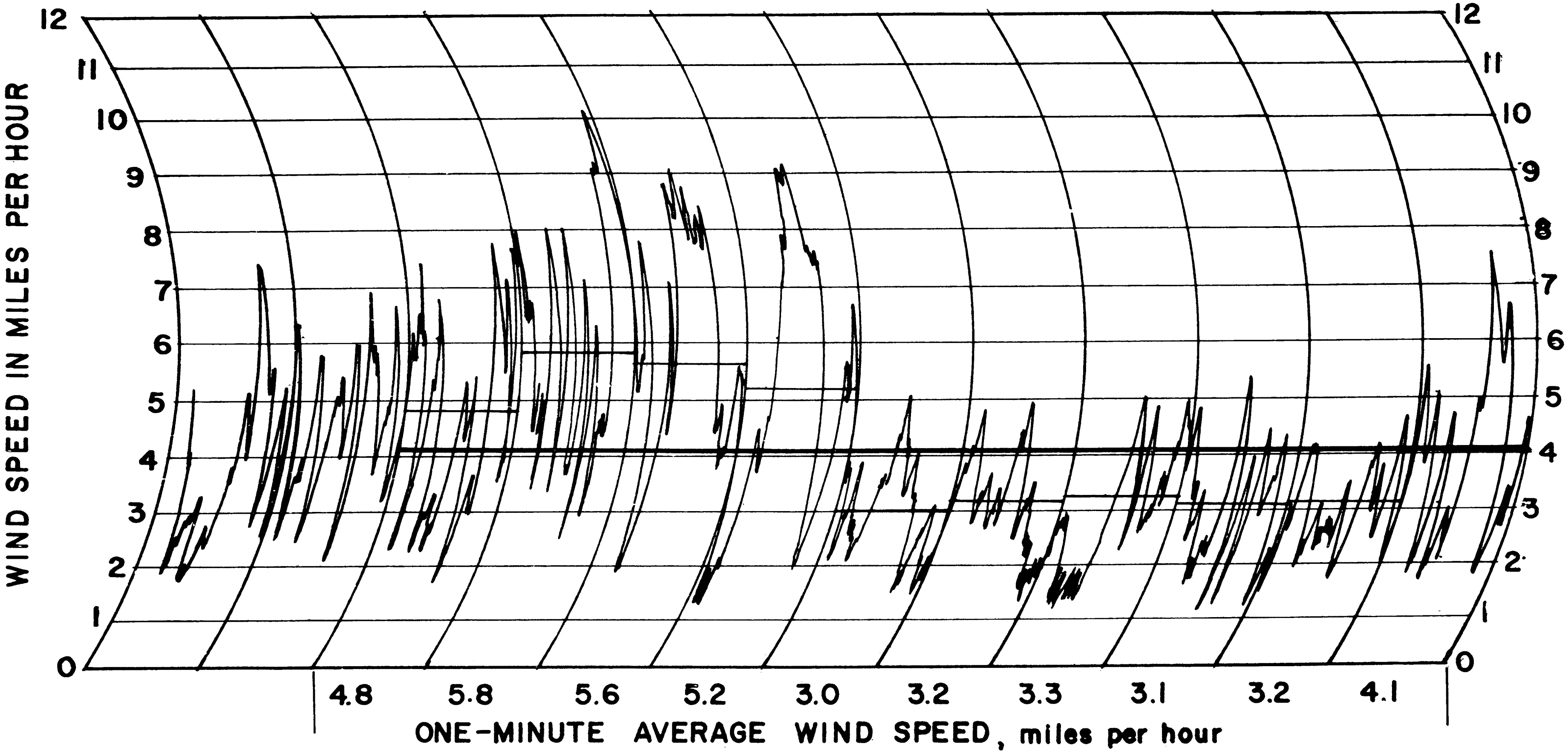
VERTICAL VIEW



PLAN VIEW

## Appendix B. SAMPLE WIND RECORD AND ANALYSIS

(Test no. 18, Sample no. 5, 17:20 – 17:30, Sept. 1, 1955)



| $\bar{v}$ mi/hr. | Gusts mi./hr. | | | | | Total | G |
|---|---|---|---|---|---|---|---|
| | ± 1 | ± 2 | ± 3 | ± 4 | ± 5 | | |
| 4·1 | 54 | 39 | 12 | 6 | 2 | 113 | 59 |

# APPENDIX C

## POLLEN COUNTS FOR INDIVIDUAL SAMPLES, SUMMER,1955

Test No. 1
0930 - 2045, Aug. 20

| Sample | Pollen Grain Counts Inside x | Pollen Grain Counts Outside m |
|---|---|---|
| 1 | 4 | 25 |
| 2 | 13 | 37 |
| 3 | 7 | 5 |
| 4 | 2 | 15 |
| 5 | 5 | 18 |
| 6 | 8 | 8 |
| 7 | 5 | 10 |
| 8 | 5 | 3 |
| 9 | 14 | 9 |
| 10 | 11 | 3 |
| 11 | 7 | 33 |
| 12 | 9 | 21 |

Test No. 2
2230, Aug. 20 - 0945, Aug. 21

| Sample | Pollen Grain Counts Inside x | Pollen Grain Counts Outside m |
|---|---|---|
| 1 | 4 | 19 |
| 2 | 2 | 39 |
| 3 | 3 | 23 |
| 4 | 6 | 34 |
| 5 | 8 | 35 |
| 6 | 3 | 40 |
| 7 | 6 | 51 |
| 8 | 18 | 42 |
| 9 | 2 | 36 |
| 10 | 11 | 43 |
| 11 | 10 | 57 |
| 12 | 4 | 21 |

Test No. 3
1200 - 2315, Aug. 21

| Sample | Pollen Grain Counts Inside x | Pollen Grain Counts Outside m |
|---|---|---|
| 1 | 4 | 27 |
| 2 | 4 | 29 |
| 3 | 6 | 30 |
| 4 | 7 | 27 |
| 5 | 9 | 49 |
| 6 | 4 | 25 |
| 7 | 4 | 41 |
| 8 | 2 | 38 |
| 9 | 4 | 18 |
| 10 | 4 | 23 |
| 11 | 5 | 43 |
| 12 | 3 | 27 |

Test No. 4
1400 - 1500, Aug. 24

| Sample | Pollen Grain Counts Inside x | Pollen Grain Counts Outside m |
|---|---|---|
| 1 | 19 | 124 |
| 2 | 28 | 71 |
| 3 | 138 | 94 |
| 4 | 26 | 84 |
| 5 | 31 | 96 |
| 6 | -- | -- |
| 7 | 32 | 136 |
| 8 | 44 | 91 |
| 9 | 48 | 95 |
| 10 | 38 | 86 |
| 11 | 23 | 96 |
| 12 | 15 | 16 |

APPENDIX C
(Continued)

| Sample | Pollen Grain Counts | |
|---|---|---|
| | Inside | Outside |
| | x | m |
| Test No. 5 | | |
| 1630 - 1830, Aug. 24 | | |
| 1 | 35 | 197 |
| 2 | 22 | 85 |
| 3 | 45 | 130 |
| 4 | 76 | 110 |
| 5 | 69 | 161 |
| 6 | -- | -- |
| 7 | -- | -- |
| 8 | 34 | 75 |
| 9 | 38 | 61 |
| 10 | 44 | 20 |
| 11 | 23 | 52 |
| 12 | 18 | 53 |

| Sample | Pollen Grain Counts | |
|---|---|---|
| | Inside | Outside |
| | x | m |
| Test No. 6 | | |
| 1000 - 1100, Aug. 26 | | |
| 1 | 6 | 57 |
| 2 | 10 | 54 |
| 3 | 32 | 58 |
| 4 | 16 | 64 |
| 5 | 13 | 89 |
| 6 | 19 | 54 |
| 7 | 20 | 36 |
| 8 | 7 | 52 |
| 9 | 15 | 59 |
| 10 | 10 | 38 |
| 11 | 10 | 11 |
| 12 | 16 | 70 |

| | | |
|---|---|---|
| Test No. 7 | | |
| 1400 - 1500, Aug. 26 | | |
| 1 | 16 | 62 |
| 2 | 27 | 68 |
| 3 | 20 | 49 |
| 4 | 24 | 42 |
| 5 | 22 | 26 |
| 6 | 29 | 40 |
| 7 | 21 | 39 |
| 8 | 34 | 47 |
| 9 | 30 | 51 |
| 10 | 31 | 87 |
| 11 | 28 | 86 |
| 12 | 23 | 57 |

| | | |
|---|---|---|
| Test No. 8 | | |
| 1600 - 1700, Aug. 26 | | |
| 1 | 11 | 39 |
| 2 | 20 | 43 |
| 3 | 16 | 41 |
| 4 | 17 | 44 |
| 5 | 17 | 47 |
| 6 | 10 | 23 |
| 7 | 4 | 40 |
| 8 | 14 | 49 |
| 9 | 13 | 58 |
| 10 | 12 | 63 |
| 11 | 12 | 78 |
| 12 | 14 | 79 |

## APPENDIX C
(Continued)

| Sample | Pollen Grain Counts | |
|---|---|---|
| | Inside | Outside |
| | x | m |
| Test No. 9 | | |
| 1450 - 1550, Aug. 30 | | |
| 1 | 33 | 18 |
| 2 | 21 | 37 |
| 3 | 22 | 11 |
| 4 | 25 | 20 |
| 5 | 17 | 18 |
| 6 | 16 | 28 |
| 7 | 11 | 17 |
| 8 | 17 | 12 |
| 9 | 26 | 22 |
| 10 | 14 | 19 |
| 11 | 15 | 20 |
| 12 | 12 | 14 |
| Test No. 11 | | |
| 1830 - 1930, Aug. 30 | | |
| 1 | 3 | 13 |
| 2 | 6 | 8 |
| 3 | 6 | 9 |
| 4 | 1 | 4 |
| 5 | 5 | 11 |
| 6 | 8 | 12 |
| 7 | 6 | 5 |
| 8 | 2 | 4 |
| 9 | 3 | 9 |
| 10 | 1 | 3 |
| 11 | 5 | 4 |
| 12 | 6 | 10 |

| Sample | Pollen Grain Counts | |
|---|---|---|
| | Inside | Outside |
| | x | m |
| Test No. 10 | | |
| 1640 - 1740, Aug. 30 | | |
| 1 | 6 | 12 |
| 2 | 7 | 14 |
| 3 | 12 | 8 |
| 4 | 5 | 10 |
| 5 | 5 | 12 |
| 6 | 7 | 17 |
| 7 | 8 | 5 |
| 8 | 19 | 14 |
| 9 | 4 | 7 |
| 10 | 3 | 10 |
| 11 | 4 | 6 |
| 12 | 6 | 11 |
| Test No. 12 | | |
| 1105 - 1205, Aug. 31 | | |
| 1 | 16 | 28 |
| 2 | 19 | 51 |
| 3 | 26 | 41 |
| 4 | 23 | 34 |
| 5 | 24 | 54 |
| 6 | 27 | 35 |
| 7 | 32 | 19 |
| 8 | 34 | 14 |
| 9 | 25 | 23 |
| 10 | 17 | 37 |
| 11 | 20 | 22 |
| 12 | 25 | 19 |

## APPENDIX C
## (Continued)

| Sample | Pollen Grain Counts<br>Inside<br>x | <br>Outside<br>m |
|---|---|---|
| Test No. 13<br>1300 - 1400, Aug. 31 | | |
| 1 | 9 | 22 |
| 2 | 10 | 31 |
| 3 | 12 | 44 |
| 4 | 17 | 20 |
| 5 | 10 | 27 |
| 6 | 16 | 10 |
| 7 | 17 | 12 |
| 8 | 20 | 5 |
| 9 | 23 | 17 |
| 10 | 16 | 21 |
| 11 | 12 | 9 |
| 12 | 11 | 26 |

| Sample | Pollen Grain Counts<br>Inside<br>x | <br>Outside<br>m |
|---|---|---|
| Test No. 14<br>1500 - 1600, Aug. 31 | | |
| 1 | 13 | 27 |
| 2 | 25 | 38 |
| 3 | 14 | 30 |
| 4 | 11 | 10 |
| 5 | 14 | 23 |
| 6 | 12 | 40 |
| 7 | 10 | 22 |
| 8 | 10 | 29 |
| 9 | 11 | 24 |
| 10 | 9 | 14 |
| 11 | 9 | 12 |
| 12 | 11 | 18 |

| Sample | Inside x | Outside m |
|---|---|---|
| Test No. 15<br>1645 - 1745, Aug. 31 | | |
| 1 | 4 | 5 |
| 2 | 8 | 10 |
| 3 | 4 | 13 |
| 4 | 5 | 6 |
| 5 | 3 | 16 |
| 6 | 4 | 7 |
| 7 | 8 | 6 |
| 8 | 5 | 5 |
| 9 | 7 | 6 |
| 10 | 7 | 3 |
| 11 | 5 | 5 |
| 12 | 7 | 12 |

| Sample | Inside x | Outside m |
|---|---|---|
| Test No. 16<br>1830 - 1930, Aug. 31 | | |
| 1 | 7 | 4 |
| 2 | 5 | 5 |
| 3 | 4 | 11 |
| 4 | 3 | 4 |
| 5 | 3 | 8 |
| 6 | 4 | 3 |
| 7 | 3 | 5 |
| 8 | 7 | 4 |
| 9 | 1 | 2 |
| 10 | 4 | 9 |
| 11 | 4 | 7 |
| 12 | 5 | 6 |

## APPENDIX C
(Continued)

| Sample | Pollen Grain Counts | |
|---|---|---|
| | Inside | Outside |
| | x | m |
| Test No. 17 | | |
| 1206 - 1501, Sept. 1 | | |
| 1 | 9 | 37 |
| 2 | 17 | 39 |
| 3 | 5 | 49 |
| 4 | 12 | 48 |
| 5 | 14 | 46 |
| 6 | -- | 43 |
| 7 | 7 | 32 |
| 8 | 10 | 36 |
| 9 | 7 | 39 |
| 10 | 12 | 67 |
| 11 | 14 | 46 |
| 12 | 19 | 83 |
| Test No. 19 | | |
| 2000 - 2255, Sept. 1 | | |
| 1 | 11 | 39 |
| 2 | 13 | 56 |
| 3 | 3 | 43 |
| 4 | 5 | 5 |
| 5 | 5 | 55 |
| 6 | 3 | 43 |
| 7 | 6 | 8 |
| 8 | 8 | 33 |
| 9 | 2 | 35 |
| 10 | 4 | 24 |
| 11 | 4 | 33 |
| 12 | 5 | 32 |

| Sample | Pollen Grain Counts | |
|---|---|---|
| | Inside | Outside |
| | x | m |
| Test No. 18 | | |
| 1620 - 1915, Sept. 1 | | |
| 1 | 7 | 25 |
| 2 | 6 | 24 |
| 3 | 11 | 62 |
| 4 | 8 | 48 |
| 5 | 9 | 29 |
| 6 | 5 | 35 |
| 7 | 6 | 41 |
| 8 | 4 | 28 |
| 9 | 5 | 34 |
| 10 | 4 | 38 |
| 11 | 1 | 36 |
| 12 | 3 | 56 |
| Test No. 20 | | |
| 0623 - 0918, Sept. 2 | | |
| 1 | 4 | 25 |
| 2 | 2 | 12 |
| 3 | 2 | 20 |
| 4 | 3 | 11 |
| 5 | 2 | 15 |
| 6 | 9 | 16 |
| 7 | 4 | 6 |
| 8 | 7 | 14 |
| 9 | 4 | 29 |
| 10 | 4 | 67 |
| 11 | 4 | 29 |
| 12 | 5 | 108 |

## APPENDIX C
(Concluded)

| Sample | Pollen Grain Counts<br>Inside<br>x | <br>Outside<br>m |
|---|---|---|
| Test No. 21<br>0950 - 1245, Sept. 2 | | |
| 1 | 12 | 19 |
| 2 | 14 | 18 |
| 3 | 17 | 29 |
| 4 | 10 | 37 |
| 5 | 5 | 16 |
| 6 | 8 | 45 |
| 7 | 9 | 33 |
| 8 | 12 | 33 |
| 9 | 17 | 35 |
| 10 | 9 | 20 |
| 11 | 31 | 8 |
| 12 | 85 | 13 |

| Sample | Pollen Grain Counts<br>Inside<br>x | <br>Outside<br>m |
|---|---|---|
| Test No. 22<br>1324 - 1619, Sept. 2 | | |
| 1 | 11 | 35 |
| 2 | 10 | 43 |
| 3 | 12 | 15 |
| 4 | 8 | 20 |
| 5 | 6 | 11 |
| 6 | 9 | 38 |
| 7 | 8 | 27 |
| 8 | 7 | 29 |
| 9 | 7 | 44 |
| 10 | 20 | 29 |
| 11 | 5 | 18 |
| 12 | 9 | 17 |

# APPENDIX D

## DETAILS OF SOLUTION OF DIFFERENTIAL EQUATION

The differential equation

$$x'(t) + A\,x(t) = k\,m(t) \qquad (9)$$

may be solved for the condition that m(t) has the form

$$m(t) = C + B \sin \omega t$$

and

$$x(0) = x_o = \text{constant}$$

by the use of the appropriate Laplace transform. If the transform of x(t) is X(s) and that of m(t) is M(s), then the transformation of Equation 9 is

$$\begin{aligned} sX(s) - x(0) + A\,X(s) &= k\,M(s) \\ &= k\left(\frac{C}{s} + B\,\frac{\omega}{s^2 + \omega^2}\right) . \qquad (D.1) \end{aligned}$$

Therefore,

$$X(s) = \frac{x_o}{s+A} + \frac{kC}{s(s+A)} + \frac{kB\omega}{(s+A)\,(s^2+\omega^2)} . \qquad (D.2)$$

Using the Heaviside partial fractions expansion, the inverse transforms of the terms on the right side of Equation D.2 are formed individually as follows:

$$L^{-1}\left\{\frac{x_o}{s+A}\right\} = x_o\,e^{-At} \qquad (D.3)$$

$$\begin{aligned} L^{-1}\left\{\frac{kC}{s(s+A)}\right\} &= \frac{kC}{A} - \frac{kC}{A}\,e^{-At} \\ &= \frac{kC}{A}\,(1 - e^{-At}) . \qquad (D.4) \end{aligned}$$

The quadratic factor in the denominator of the third term transforms to

$$\frac{1}{\omega}\,(\psi_2 \cos \omega t + \psi_1 \sin \omega t) , \qquad (D.5)$$

in which $\psi_1$ and $\psi_2$ are respectively the real and imaginary parts of the complex number $\psi(i\omega)$. The expression $\psi(s)$ is the remainder left after removing $(s^2 + \omega^2)$ from the denominator. Thus,

$$\psi(s) = \frac{kB\,\omega}{s+A} \tag{D.6}$$

and

$$\psi(i\omega) = \frac{kB\,\omega}{A+i\omega} = \frac{kB\,\omega A}{A^2+\omega^2} - i\,\frac{\omega^2\,kB}{A^2+\omega^2} \quad . \tag{D.7}$$

Hence,

$$\psi_1 = \frac{kB\,\omega A}{A^2+\omega^2} \quad \text{and} \quad \psi_2 = -\frac{\omega^2\,kB}{A^2+\omega^2}$$

so that expression D.5 becomes

$$-\frac{\omega kB}{A^2+\omega^2}\cos\omega t + \frac{kBA}{A^2+\omega^2}\sin\omega t \quad . \tag{D.8}$$

The linear factor of the denominator transforms as above, and the complete inverse transform of the third term is

$$L^{-1}\left\{\frac{kB\,\omega}{(s+A)(s^2+\omega^2)}\right\} = \frac{k\omega B}{A^2+\omega^2}e^{-At} - \frac{k\omega B}{A^2+\omega^2}\cos\omega t$$

$$+ \frac{kAB}{A^2+\omega^2}\sin\omega t \quad . \tag{D.9}$$

Finally, addition of D.3, D.4, and D.9 gives the complete inverse transform:

$$L^{-1}\left\{X(s)\right\} = L^{-1}\left\{\frac{x_0}{s+A} + \frac{kC}{s(s+A)} + \frac{kB\,\omega}{(s+A)(s^2+\omega^2)}\right\} \quad .$$

Therefore,

$$x(t) = x_0e^{-At} + \frac{kC}{A}(1 - e^{-At})$$

$$+ \frac{k\omega\,B}{A^2+\omega^2}(e^{-At} - \cos\omega t)$$

$$+ \frac{kAB}{A^2+\omega^2}\sin\omega t \;, \tag{D.10}$$

which is Equation 10 of Section 4.5.

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