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"Experiments on Wind-Pressure."

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METHODS OF OBSERVATION.

THE experiments described in this Paper form the second part of the research on the distribution and intensity of the pressure of the wind on structures, which was proposed by the Committee of the National Physical Laboratory as the first investigation to be undertaken in the Engineering Department, and was commenced by the Author in 1902.

The first part of this research, of which the results were communicated to The Institution in December 1903, was the investigation of the resultant pressure and the distribution of pressure on flat plates normal or inclined to the direction of a uniform current of air.[1]

The chief reason for this preliminary work was to determine, if possible, the effect of the form and dimensions of the plate upon its resistance, since it appeared to be commonly recognized that geometrical form, or possibly actual dimensions, had considerable influence on the intensity of pressure. As it was seen that this determination would involve a large number of experiments made under precisely similar conditions, which would be very difficult to obtain in the open air, it was decided to make the experiments on small plates placed in a current of air artificially produced. For this purpose a vertical channel 24 inches in diameter was used, and

[1] "On the Resistance of Plane Surfaces in a Uniform Current of Air." Minutes of Proceedings Inst. C.E., vol. clvi, p. 78.

plates and models up to 4 square inches in area were exposed in this channel to a downward current of air produced by a fan.

The results obtained in that investigation indicated that, in a uniform current of air, and within the range in dimensions obtained, the resistance of geometrically similar plates was strictly proportional to the area of the plates, but that for dissimilar plates, such as long rectangles and circular plates, the resistances per unit area differed considerably. The value of the resistance so found, for round and square plates, was somewhat lower than that determined by Dines, Froude and Langley in their experiments, as will be seen from the following table, in which the values of the coefficient k in the formula

$$P = k V^2$$

are tabulated.[1]

Experimenter.	Method.	Value of k.
Dines	Whirling table	0·0029
Froude	Moving carriage	0·0036
Langley	Whirling table	0·0032
Stanton	Plate in uniform current	0·0027

In the discussion on the Author's previous Paper the feeling was expressed that experiments on a much larger scale in the open air should be made, because, although the resistance of similar plates in a uniform current might be proportional to the area, general experience tended to show that in actual winds, whose velocity was not uniform over either time or space, the mean pressure per square foot on a large surface was considerably less than on a small one. It was therefore decided to make observations on flat surfaces, of areas ranging up to 100 square feet, when exposed to the wind.

Previous Work on the Subject.—Records of the pressure exerted by the wind on flat plates 1 or 2 square feet in area have been made continuously for many years at various English meteorological stations. These records are made by instruments in which a pen, moving in accordance with, and proportionally to, the pressure on the plate, traces a curve on a rotating drum: in this way the time variation of the pressure of the wind on the plate is obtained. This record can then be compared with the curve of time variation of the velocity of the wind, taken from an instrument such as the Robinson cup anemometer, in order to deduce, if possible, the corresponding values of the pressure and velocity at any instant.

It is generally admitted by meteorologists that the records of pressure-plate anemometers leave much to be desired in point of

[1] P = pressure in pounds per square foot.
V = velocity of current in miles per hour.

accuracy, owing to the inertia of the plate and the other moving parts of the instrument, which renders them liable to register pressures greatly in excess of the true value. There appears, however, to be some probability that in many cases these instruments have been wrongly condemned, owing to imperfect knowledge of the motion of the air in winds.

The only experiments, so far as the Author is aware, which have been made on a plate of considerable dimensions, are those made at the Forth Bridge in 1882 and the following years. These were on a plate 300 square feet in area fixed in direction, and there were also two small plates, each 1½ square foot in area, one fixed in direction and the other free to revolve.

In his lecture [1] on the Forth Bridge to the British Association at Montreal in 1884, Sir Benjamin Baker summarized the readings of these gauges for 2 years by taking the mean of the maximum daily readings of the three gauges between 0 and 5 lbs., 5 and 10 lbs., etc., per square foot, and tabulating the results (Table I).

In all these cases it was found that each of the mean readings of the two small gauges was considerably higher than the corresponding mean reading for the large gauge. Taking the whole of the readings, the ratio of the revolving-gauge indications to those of the large-gauge indications is 1·5.

TABLE I.—OBSERVATIONS AT THE FORTH BRIDGE.

Range of Pressures.	Mean of Gauge Indications.		
	Revolving Gauge.	Small Fixed Gauge.	Large Fixed Gauge.
Lbs. per Sq. Ft.	Lbs. per Sq. Ft.	Lbs. per Sq. Ft.	Lbs. per Sq. Ft.
0 to 5	3·09	2·92	1·90
5 „ 10	7·58	7·70	4·75
10 „ 15	12·40	13·20	8·26
15 „ 20	17·06	17·90	12·66
20 „ 25	21·00	22·75	19·00
25 „ 30	27·00	28·50	18·25
30 „ 35	32·00	38·50	21·50
Above	65·00	41·00	35·25

Experiments on the relative resistances of moderately large plates in the wind have been made by Mr. W. H. Dines by the method of balancing the pressure on one plate by the pressure on a similar and

" [1] The Forth Bridge." London, 1884. Also *Engineering*, vol. xxxviii, p. 213.

smaller plate.[1] In these experiments a rotating shaft with its axis vertical carried the two plates, which were attached to the opposite arms of a light cross piece with an arrangement for varying the distance of the plates from the vertical axis. In taking observations the plates, which were in one plane, were set normal to the wind, and the distance of one of them from the vertical axis varied until approximate balance of the two wind-pressures about the vertical axis was obtained. Using two plates, one 42 square feet and the other 9 square feet in area, Mr. Dines found that, in spite of considerable difficulty in adjusting the equilibrium, the pressure on the large plate was only 78 per cent. of that on the smaller one. Using plates 9 and 2½ square feet in area respectively, he found that the pressure on the large plate was 89 per cent. of that on the smaller one.

The results of both the Forth Bridge experiments and those of Mr. Dines appear therefore to indicate that the wind-pressure on a large plate is of smaller mean intensity than that on a small plate. In discussing these experiments, however, it must be carefully noted that there is an essential difference between them. Sir Benjamin Baker's figures are the daily maximum indicated pressures of three gauges, which pressures may or may not have been indicated at the same instant. Mr. Dines's results give the relative mean intensities of pressure on two plates at any instant when there was an approximate balance.

Sir Benjamin Baker's explanation[2] of his results is that near the surface of the earth uniform velocity cannot obtain, and unsteady motion must be the rule, so that the threads of the currents moving at the highest velocity will strike an obstruction successively rather than simultaneously, and hence the mean pressure per square foot on a large area must be less than on a small area.

This variation in velocity in winds at the same instant of time has been verified experimentally by Mr. Dines,[3] who, by means of two velocity instruments of the same type, placed 11 feet apart, has found that the simultaneous velocities at these points bear a ratio to each other which may vary from 0·75 to 1·25. Mr. Dines also noticed, as an instance of widely varying conditions at these points 11 feet apart, that the liquid in one of his gauges would often be rising when that in the other was falling.

Further experiments fully confirming the observations of Mr.

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[1] Quarterly Journal of the Royal Meteorological Society, vol. xvi (1890), p. 205.
[2] Lecture at British Association Meeting, Montreal, 1884.
[3] Quarterly Journal of the Royal Meteorological Society, vol. xx (1894), p. 183.

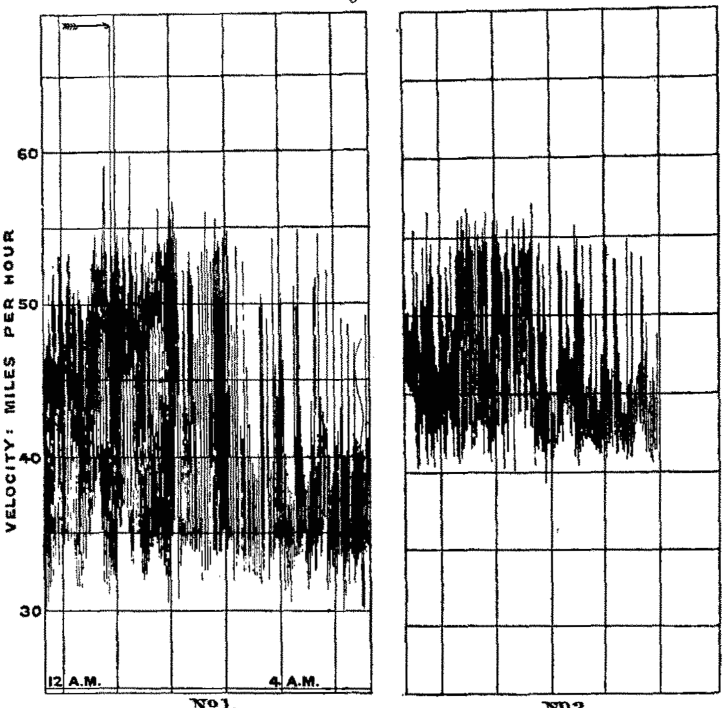
Dines have been made by the Author, who has found that very appreciable differences of velocity may exist at the same instant at points whose horizontal distance apart is only 2 feet, but that in general the slope of the velocity-gradient is small enough to justify the assumption of practically uniform intensity of pressure over any single square foot.

It will be seen that Sir Benjamin Baker's explanation of his results is strictly limited to the conditions under which his experiments were made, *i.e.*, that the pressures are the maximum pressures which have been registered in certain intervals of time; and further, it is assumed that the maximum wind-velocity which is attained in each of these intervals occurs at all points in the region of the pressure-plates, although not necessarily at the same instant. Under these conditions it is obvious that the small plate will register a pressure whose mean intensity is practically the maximum intensity attained in the interval, and also that the greatest mean intensity registered by the large plate will be less than this maximum value, owing to the varying intensity of pressure over its surface.

The importance of the foregoing assumption will be readily seen by considering the not impossible case of a gust of wind of short duration, whose intensity is much greater than the intensities of the gusts which precede or follow it in the given interval of time. Such a case is shown in *Fig. 1*, No. 1, which is a copy of the record made by the bridled anemometer at Holyhead on the 5th October, 1904, and is here reproduced by kind permission of Dr. W. N. Shaw, the Director of the Meteorological Office. According to this record the velocity of the maximum gust was approximately 68 miles per hour, or 13 per cent. higher than the next highest. Owing to the smallness of the time-scale it is not possible to determine the duration of this gust, but assuming it to be of a momentary character, as common experience tends to show, it is quite possible that in this gale the greatest pressure on a small gauge might be less per unit of area than the greatest pressure on a large gauge. The case of a sudden gust of this description is not a common one, but evidence of its occurrence is to be seen in one of the later records of the Forth Bridge experiments kindly furnished to the Author by Sir Benjamin Baker. On the 17th March, 1891, the maximum mean intensity of pressure on the large plate was 14½ lbs. per square foot, whereas the maximum mean intensity on the small revolving plate was only 11½ lbs. per square foot.

The common case, however, as proved by Sir Benjamin Baker's experiments, is that in which the maximum gust is not greatly in excess of others which occur in the given interval. Thus a moderately steady gale will consist of a series of squalls, each squall being made up of a succession of gusts which gradually increase in intensity up to a maximum and then decay, but no single squall

Figs 1.



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RECORDS OF BRIDLED ANEMOMETER AT HOLYHEAD.

reaches an intensity greatly in excess of the others. Such a case is shown in *Figs. 1*, No. 2.[1]

It may be concluded from the foregoing evidence that the excess of the maximum recorded mean intensity of pressure on the small

[1] The bridled anemometer at Holyhead was designed by the late Sir George Stokes, and consists of five hemispherical cups attached to a vertical spindle by short arms, and so arranged that no cup acts as a screen to the others. The mechanism is designed so that the moment of the wind-pressure on the cups about the vertical axis is recorded on a drum. The records of this instrument have been chosen for illustration because it is more sensitive to momentary gusts than any of the other recording instruments in common use.

plate over that on the larger plate in Sir Benjamin Baker's experiments is not necessarily due to a purely dimensional effect of the plates, that is, an effect which would be equally apparent if the velocity of the wind were perfectly uniform.

Under the same conditions of variable velocity as discussed above, a large and a small plate, which were fitted with appliances for recording the minimum pressures in any interval of time, would give results in which the minimum mean intensity of pressure on the small plate would be considerably below the value of that on the large plate. This is evident, since the minimum mean intensity on the large plate will certainly be higher than the minimum pressure on any square foot of its surface. But if, instead of the recorded maximum and minimum pressures in any interval, the simultaneous pressures at any instant on two plates are considered, the result may be of a different character. In such a case the mean intensity of pressure on the small plate may be greater or less than that on the large plate, and apart from any purely dimensional effect, it may be assumed that, taking the mean of a sufficiently large number of observations, the average pressure for the two plates will be the same in value. Now, turning to the consideration of Mr. Dines's experiments, which consisted of simultaneous observations on two plates, it appears that the mean intensity of pressure on the small plate was always greater than that on the large plate. Under the above assumption it is evident that the explanation of those results cannot be found in the unequal distribution of the velocity of the wind at any instant. The cause of the apparent preponderance in intensity of pressure of the small plate over the large one must therefore be sought in other directions, and may be :—

(1) A real dimensional effect ; or

(2) The possibility of eddies from the large plate affecting the pressure on the small plate, or the proximity of the ground affecting the large plate.

With regard to (1), it may be assumed that if a purely dimensional effect exists it will be found in the negative pressure set up by the eddies at the back of the plate, as it is difficult to suppose that the distribution of pressure in front of the board will be affected by the scale of the experiment. Its existence should in this case be easily detected.

With regard to (2), the Author's experience tends to prove that the pressure on a plate is considerably influenced by the pressure of any large area in its vicinity. This has been shown by balancing a small plate in a uniform current, in the manner of the Author's previous experiments, and then moving another larger surface, which was already in the plane of the other plate, nearer to it. The result is always to increase the pressure on the small plate.

An examination of previous work would therefore appear to indicate that the existence of a purely dimensional effect in the resistance of plates cannot be regarded as certain, since Sir Benjamin Baker's results can be entirely explained apart from such an effect, and those of Mr. Dines may be due to other causes. The evidence of the Author's previous experiments in a uniform current is against the existence of any effect of this kind, which varies continuously with the dimensions of the plate.

As the further investigation of this matter seemed to be of the greatest importance, it was decided to make the determination of the existence or non-existence of the purely dimensional effect on the intensity of pressure the chief feature of the present research. As a consequence of this it became necessary to attempt either—

(1) The simultaneous determination of the pressures on two similar plates of different sizes; or

(2) The determination from a large number of experiments of the relation between intensity of pressure and velocity of the wind for each of a number of similar plates. The values of the constants so obtained would indicate the existence and magnitude of the dimensional effect sought.

As the first method appeared to offer a comparatively simple solution of the problem, some preliminary experiments were made on two similar plates, which were 50 and 5 square feet in area respectively, by attempting to balance the wind-pressure on one of them by that on the other, as in Mr. Dines's experiments. The plates were attached to a light frame on the top of a steel windmill tower 50 feet from the ground, and were arranged so that their centres of gravity were in a vertical line. The framework carrying the plates rested on a pair of knife-edges which could be adjusted in a vertical direction relative to the plates, which were at a fixed distance apart. It was hoped that, when the plates were set normal to the direction of the wind, it would be possible to adjust the knife-edge to a definite position in which the wind-pressure on one plate would balance that on the other.

Several sets of observations were made with this arrangement but without obtaining satisfactory results, it being impossible to determine any definite position of the knife-edges so that even approximate balance was ensured. The general effect was that several positions could be obtained in which sometimes the pressure on the small plate would predominate and sometimes that on the large plate. In order to investigate the cause of this failure to secure a balance a number of pressure-holes were drilled in the two plates at corresponding points. Any two corresponding points, one in each plate, were then connected to the extremities of a delicate water-gauge and the difference of pressure was measured. It was found in this way that the wind-pressures at corresponding points were rarely the same in value, sometimes one predominating and sometimes the other. This result, which might have been predicted from the known variation in velocity of the wind, fully accounted for the difficulty in obtaining a balance between the resultant pressures on the two plates.

The method was therefore abandoned and the research was carried out on the lines of the second method, namely, determination of the pressure-velocity relation for each plate.

Description of the Experimental Appliances.—For the purposes of the experiments a steel windmill tower was erected in the grounds of the National Physical Laboratory in such a position that the prevalent winds, which are westerly and south-westerly, should encounter as few obstacles as possible immediately before reaching the pressure-boards. The situation was not particularly favourable for wind-pressure experiments, as it is more or less surrounded by the trees in Bushy Park; but in the above-mentioned directions there was practically open ground for a distance of 700 yards in front of the tower, with the exception of a wall $2\frac{1}{2}$ yards high and 15 yards in front of it. As the lowest edge of the largest pressure-board used was 38 feet above the top of this wall, it was not considered likely that the eddy from the wall would affect the pressure.

The tower was 50 feet in height from the ground to the cap, and consisted of four legs made of 2-inch by 2-inch by $\frac{5}{16}$-inch angles well braced together, and carrying a platform 5 feet 6 inches square 3 feet below the cap (Fig. 2, Plate 3). The framework of the tower was chosen as light as possible, in order to reduce the disturbances from eddies due to it, and it proved sufficiently stiff for the work, its only weakness being a liability to torsional oscillations about its vertical axis.

The tower was 10 feet square at the base, and the lower part, as shown in Fig. 2, was roofed in and used as an observing-station. A cross girder with a foot-step working in ball-bearings about a vertical axis was fitted to the cap of the tower, and to this was attached the frame carrying the pressure-board. This frame, also made as light as possible, was 15 inches deep and 10 feet square. The pressure-board rested on knife-edges fixed to the front of the frame so as not to be affected by the eddies from the tower. Two handwinches were placed one on either side of the tower, in order to raise and lower the frame when the pressure-boards were changed.

For the experiments on plane surfaces with normal impingement, three pressure-boards were used, one 10 feet square, one 10 feet by 5 feet, and one 5 feet square.

In order to reduce the weight as much as possible, the boards were made of mahogany $\frac{5}{16}$ inch thick, with a plane surface facing the wind and with stiffening ribs $1\frac{1}{2}$ inch deep at the back, so that the total thickness round the edges of the boards was approximately $1\frac{3}{4}$ inch. The 100-square-feet board was made in three parts, having a central portion 10 feet by 5 feet and an upper and lower leaf 10 feet by 2 feet 6 inches, which were hinged to the central part so that when observations were not being made these leaves could be folded over the central part, leaving an exposed area of 50 square feet. This was done because the tower was not considered strong enough to resist the severe pressure which might otherwise come on it in the event of a heavy gale arising.

Estimation of the Velocity of the Wind.—In the Author's previous experiments in a uniform current of air, the velocity of the air was calculated from the difference of pressure in two tubes placed in the current, one measuring the velocity head of the current—that is, it was an ordinary Pitot tube—and the other the static pressure of the current. The latter was a tube placed with its axis in the current, the end being stopped and small holes drilled in the side.[1]

The same arrangement was tried in the open-air experiments, but it was found that, owing to the rapid fluctuations in direction of the wind, the pressure in the static-pressure tube was by no means constant. For this reason this type was abandoned and the form adopted by Mr. Dines in his experiments was used. In this form the low-pressure tube is placed at right angles to the direction of the wind with its axis vertical, and there are holes drilled at short intervals all round it, so that any change in the direction of the wind will not affect the pressure in this tube. The arrangement of the two tubes used is shown in Fig. 3, Plate 3, and as the dimensions differ considerably from those of the one used by Mr. Dines, it was necessary to calibrate it in a current of known speed. This was done by putting it in the 24-inch experimental channel side by side with the form of Pitot tube and static pressure-tube used in the previous experiments, and whose constant was known. Simultaneous observations on both forms of gauge were taken at varying speeds of the current, and it was found that the ratio of the pressure-

[1] Minutes of Proceedings, Inst. C.E., vol. clvi, p. 82.

difference in the modified Dines gauge to the corresponding pressure-difference in the gauge previously used was fairly regular and equal to 1·54. By direct calibration from an air-meter [1] the velocity of the current in miles per hour by the gauge used in the previous experiments was found to be

$$V = 11 \cdot 90 \sqrt{R},$$

where R is the reading of the tilting gauge used for measuring the pressures. The corresponding relation for the modified Dines gauge here used is therefore

$$V = 9 \cdot 62 \sqrt{R}.$$

This agrees fairly well with the determination which Mr. Dines made for his own gauge by calibration on a whirling table.[2] In these experiments he found that at 40 miles per hour the difference of pressure in his tubes was

1·169 inch of water.

Put in terms of the tilting-gauge reading this relation would be

$$V = 9 \cdot 44 \sqrt{R},$$

which shows that the difference of pressure indicated by the original tubes of Mr. Dines and the tubes made for these experiments differ by less than 2 per cent. of the indications.

Method of Estimating the Pressure on the Board.—As the methods which have been previously used for obtaining the resultant wind-pressure on a plate have been much criticized on account of the possibility of their being affected by the inertia of the plate and its attached mechanism, it was considered very important to devise a method in which these inertia-effects would be so small as to be negligible. There was the further difficulty of transmitting the pressure-indications through a distance of 50 feet to the observing-table at the foot of the tower.

In order to overcome the difficulty of the inertia-effects the use of a thin steel diaphragm suggested itself, as in that way the actual movement of the pressure-board in a strong wind could be restricted to a few hundredths of an inch. After some preliminary experiments it was considered that the change in pressure of a given quantity of air contained behind the diaphragm in a cylinder and pipe leading to a delicate pressure-gauge at the foot of the tower could be estimated

[1] Minutes of Proceedings Inst. C.E., vol. clvi, p. 86.

[2] Quarterly Journal of the Royal Meteorological Society, vol. xviii (1892), p. 170.

and utilized as a measure of the pressure on the board by the following device. If two closed cylinders are connected, one to each leg of a U tube containing water, this water-gauge will not be sensitive to changes of temperature which are common to the whole system, but will respond to changes of pressure set up by the expansion or contraction of one of the cylinders.

The arrangement finally adopted is shown in Fig. 4, Plate 3, in which D is the casting forming the two cylinders bolted to the frame F, which carries the knife-edges on which the pressure-board B rests. The cylinders are divided by a partition-wall, each cylinder being bounded on the outside by diaphragms made of hard steel plate 0·03 inch thick.

The pressure-cylinder diaphragm carries a conical socket which faces a similar socket fixed to the pressure-board. The pressure is transmitted from the board to the diaphragm by the hardened steel pin P with small hemispherical ends. The object of this arrangement is to secure a perfectly direct central pressure on the diaphragm unaffected by small lateral and vertical displacements of the board, owing to lack of rigidity in the frame or oscillations of the tower in gales.

The whole casting is well lagged, and a pair of lead pipes T, from the pressure- and compensating-cylinders respectively, are carried down one leg of the tower, being carefully lagged with asbestos along their whole length. At the foot of the tower they are connected one to each of the auxiliary cylinders, C, which are also embedded in asbestos. From these auxiliary cylinders rubber pipes lead to the tilting water-gauge on which the pressures are measured.

The object of the auxiliary cylinders is two-fold : first, to allow the total volume of the air contained in the pipes and cylinders to be varied in accordance with the dimensions of the pressure-boards ; and secondly, for the purpose of checking the calibration of the upper diaphragm from time to time after the first determination, and to detect the presence of leaks in the pipes. To enable this to be done, these cylinders also are provided with diaphragms, and to one of them pressure can be applied by a pin from the hand-wheel above, so that when once the gauge-reading for a given pressure on the upper diaphragm has been determined, the amount of the deflection of the lower diaphragm to produce the same gauge-reading can be read off from the hand-wheel and used for future calibrations. The gauge G is a simplified form of the one used in the Author's previous experiments on air-pressure.[1] Its principle is that of a U tube in

[1] Minutes of Proceedings Inst. C.E., vol. clvi, p. 82.

which the difference of pressure on the surfaces of the water in the limbs of the tube is measured by tilting the gauge through a small angle, so that there is no displacement of the water along the tube. In the original form of the gauge the observations were made on the surface of separation of the water and some oil contained in the horizontal limb of the U tube, but this arrangement, which rendered the gauge extremely sensitive, was not suitable for the rapid fluctuations in the pressure of the wind, which could not be followed by the wheel sufficiently quickly to prevent rupture of the surface of separation of the oil and water. For this reason a plain U tube was mounted on the tilting platform of the gauge, and during observations the hair-line of the microscope was kept as near as practicable on the surface of the water in one limb, and readings were taken only when the two were in coincidence.

It will be readily understood that the use of this arrangement was entirely dependent on the nearness in equality of the temperatures in the two sets of cylinders and pipes, since a quite small difference of temperature would be sufficient to mask the pressure-effects. By taking great care with the lagging it was found possible to make these temperature-effects small, and to obtain an estimate of their magnitude in the following manner. The effect of the slight differences in temperature showed itself in a gradual change in the zero of the water-gauge. The method of observation adopted was to take frequent zero-readings between short sets of pressure-readings noting the times of all the observations. At the end of the experiments a time-curve of zero-readings was plotted, from which the value of the zero for each separate pressure-observation could be scaled off. It was found that the amount of the correction varied considerably with the atmospheric conditions. In uniform cloudy weather the correction was quite small and it was only during intervals of sunshine that the zero-displacements were important.

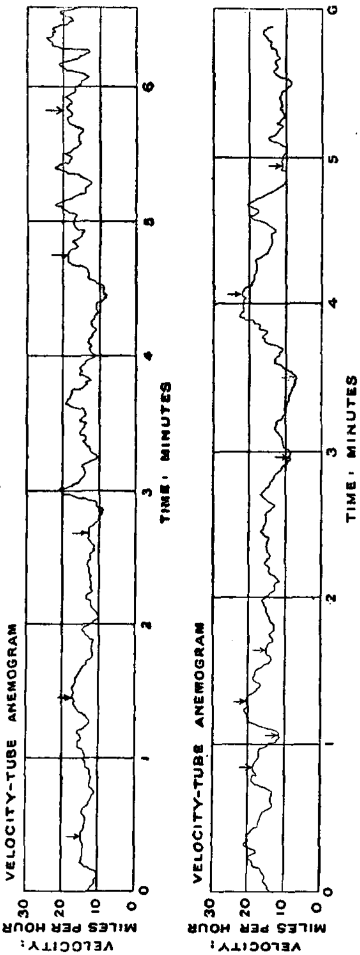
Calibration of the Diaphragm.—For the purpose of calibration known pressures were applied to the upper diaphragm, either by disconnecting it from the frame and loading it with weights when in a horizontal position, or by means of a spiral spring when fixed to the frame. The excess of pressure due to the deflection of the diaphragm was measured on the tilting gauge for each additional load, and was repeated several times up and down the scale until consistent readings had been obtained. The calibration-curve was then plotted (Fig. 5, Plate 3) and was used for the pressure-estimations in the actual wind-experiments.

Method of making Simultaneous Observations of the Velocity of the Wind and the Resultant Pressure on the Board.—With the arrangements for the measurement of these two quantities on the two tilting water-gauges described above, the difficulties of making reliable simultaneous observations were as follows:—

(1) The possibility of a "damping" of the pressure- and velocity-indications owing to the length and small diameter of the connecting pipes.

(2) The existence of a time-lag in the indications of the gauges and the possibility that the amount of the time-lag might be different in the two sets of tubes.

(3) The possibility of a sufficiently rapid adjustment of the gauges not being made under the rapid fluctuations of wind-velocity which are known to obtain.



Figs. 6.

With reference to these difficulties it will be seen that they are all dependent on the time rate of variation of velocity of the wind: that is, if the velocity-conditions could be relied upon to remain steady for say 3 or 4 seconds, these difficulties could be successfully met. Now although the fluctuations in velocity of the wind in what is called a steady breeze are considerable in magnitude and take place with great rapidity, from a study of the available records of time variation in wind-velocity[1] and from observations made for the present research, it was considered that such intervals of practically steady conditions occurred sufficiently often to enable simultaneous observations of the kind required to be made with the apparatus described above. For the purpose of

[1] Quarterly Journal of the Royal Meteorological Society, vol. xx, p. 180, and vol. xviii, p. 175.

illustrating the existence of these steady intervals a record of the Dines anemometer at Kew Observatory was taken on a specially devised open time-scale, by permission of the Director of the Meteorological office, and is shown in *Figs. 6*. It will be seen that in those parts of the curve indicated by the arrows practically steady conditions obtained for intervals exceeding 3 seconds, and that these steady intervals occurred on an average about once a minute.

The difficulties mentioned in (2) and (3) were therefore considered to be successfully met by taking the simultaneous observations required in those approximately steady intervals; for although a small time-lag in the indications of the gauges was detected, its duration did not apparently amount to 1 second.

It was also found that the damping effect due to the long length of small tube was not appreciable when steady conditions had been maintained for 2 or 3 seconds.

A further difficulty in making the observations lay in the fact stated by Mr. Dines, that in two instruments situated 10 feet apart the velocity would be occasionally rising at one point and falling at the other at the same instant. This was met by the observers at the two water-gauges signalling to each other when the steady interval had been reached. It was only when the steady intervals coincided for the two gauges that readings were taken. In this method three observers were required, two at the table at the foot of the tower, who were continually watching the gauges and following the fluctuations of velocity and pressure as quickly as possible, so that the hair-line of the microscope was in approximate coincidence with the surface of the water, and one on the platform of the tower to carry out the periodical adjustment of the pressure-board to the mean direction of the wind, and to relieve the diaphragm of the pressure of the board when the zero observations were taken.

Results of the Experiments.

Experiments on the Pressure-Boards placed Normal to the Direction of the Wind.—In order to obtain a reliable value of the constant in the pressure-velocity relation it was found necessary to make about two hundred simultaneous observations of pressure and velocity for each board. The observations for the three boards used are plotted in Figs. 7, 8 and 9, Plate 3, the co-ordinates being the resultant pressure on the board and the pressure-difference in the velocity-tubes stated in divisions of the tilting-gauge scale. As the latter quantity is proportional to the square of the velocity of the wind, these points should be approximately symmetrically grouped about a straight line passing through the origin. For the purpose of illustrating the extent to which this is fulfilled, the means of every ten observations in ascending order of velocity are indicated by the large circles, and it will be seen that the approximation is remarkably close considering the extreme divergence of the individual observations from the mean line. It will be noticed that the divergence is least marked in the case of the 50-square-feet pressure-board. This is perhaps due to the favourable wind-conditions under which the experiment on this board was made, and to the fact that the whole of the observations on this board were made in a single day, which was not the case with the other boards. No observations were rejected on account of possible errors in reading the gauges. The mean line was obtained by dividing the whole of the observations on each board into two groups of high-velocity and low-velocity readings respectively, and drawing the line through the two centres of gravity of the points in each group. This was considered preferable to joining the centre of gravity of the whole of the points to the origin, as this assumed an exact balance of the board about the knife-edges at zero velocity, which it was not possible to check, as there was always a certain amount of wind on the calmest days. These lines were found to pass through the origin in the cases of the 25- and 50-square-feet boards, but the line for the 100-square-feet board indicates a negative pressure of 3 lbs. at zero velocity, showing that the centre of gravity of the board was apparently overhanging the knife-edges by $\frac{3}{4}$ inch.

Correction for Difference in Elevation of Velocity-Tubes and Pressure-Boards.—As the centre of the pressure-board was 50 feet from the ground, and that of the velocity-tubes 15 feet higher, it was anticipated that there would be a correction to be applied to the readings of the velocity-tubes in order to reduce them to the corresponding values at the centre of the board. Owing to the importance of a fairly accurate determination of this correction, the arrangement of the two sets of velocity-tubes shown in Fig. 10, Plate 3, was devised for obtaining its value. The upper set of tubes was that used for the actual pressure-observations, and the lower set were placed at the same elevation as the centre of the board and sufficiently in front of the frame to prevent any effect from eddies set up by it. About two hundred simultaneous observations were taken from these two sets of tubes and the results are plotted in Fig. 10. The mean of sets of ten, in ascending order of magnitude, have also been plotted, to show more clearly the agreement of the results for all parts of the scale. The deviation of the mean line drawn through these plotted points from the line drawn through the origin at an inclination of 45° to the base-line gives the effect due to difference in elevation, and indicates that the velocity of the wind at the velocity-tubes is 3 per cent. greater than that at the centre of the board. In the reductions of the experimental results which follow the values of the wind-velocity derived from the velocity-tube readings are corrected for the difference shown in Fig. 10.

From the positions of the mean lines in Figs. 7, 8 and 9 the values of the constant in the pressure-velocity relation,

$$P = KV^2$$

where P = pressure in pounds per square foot,
V = velocity of the wind in miles per hour

have been calculated for each of the three boards and are given in the following Table:—

Pressure-Board.	Value of K.
5 feet by 5 feet	0·00320
10 ,, ,, 5 ,, (long axis horizontal)	0·00318
10 ,, ,, 10 ,,	0·00322

In addition to the determination of the resultant pressure, an independent estimation was made by measuring the intensities of the pressure at various points of the 10-by-5 board, on both windward and leeward sides; and the calculated pressures on the whole board from these data were found to agree with the results obtained from the diaphragm. Since the value of the constant in the pressure-velocity relation is practically the same for each of the three boards, it is evident that, for this range in size, any purely dimensional effect in the resistance, if it exists, is a very small one. This conclusion is further strengthened by comparing the results given in the above Table with the mean of the open-air experiments of Dines, Froude, and Langley on plates of much smaller dimensions, which is almost identical with the value given in the Table.

There appear, therefore, to be good reasons for supposing that the mean intensity of pressure on similar surfaces of areas greater than 1 square foot, exposed to the wind, is independent of their actual dimensions.

The only observations here cited which conflict with this view are those of Mr. Dines, whose combined experiments indicated that the pressure on a plate 42 square feet in area was only 70 per cent. of that on a plate of 2½ square feet. Now the value of the constant in the pressure-velocity relation, for plates whose dimensions are of the order of the small plate here referred to, has been found by

Mr. Dines to be 0·0029. The value of the constant for the large plate would therefore be 0·0020. Comparing this with the value 0·0032, determined in the present experiments for a plate of slightly larger dimensions, the Author ventures to think that, in the experiments of Mr. Dines, either the eddies from the large plate affected the small one, or the large plate was partially screened by adjacent objects or by the surface of the ground. As the lower edge of the large plate appears to have been only 8 or 9 feet from the ground, this latter influence may have been considerable.

There remains the comparison of the present results with those obtained in the Author's previous experiments on plates ranging from ½ inch to 2 inches in diameter in a uniform current of air. As the value of the constant in these experiments was 0·0027, the increase in resistance in the open air is somewhat marked, the ratio of the two constants being 1·18.

In discussing the two cases it will be convenient to make comparisons

(1) Between the pressures on the windward sides.
(2) Between the pressures on the leeward sides.

With reference to the windward pressures, it was found in the experiments in a uniform current on the distribution of pressure on the plates that the pressure in the centre of the windward side was approximately

$$\frac{1}{2}\,\rho\,V^2,$$

where ρ = density of current,
V = velocity of current,

and equal in value to the pressure in the Pitot tube. Corresponding observations on the 10-by-5 board showed that the pressure at its centre on the windward side was also approximately equal to the pressure in the Pitot tube of the velocity-gauge, and, further, the distribution of the pressure on the windward side was found not to differ very appreciably from that on a small model in the uniform current.

From this it appears that the difference in the resistances is not, in the main, due to the intensity or distribution of the pressure on the windward side, so that the explanation must be sought in the relative value of the pressures on the leeward sides. It was not found possible to make this determination directly, owing to the unknown value of the static pressure in the open air, which could not be estimated with sufficient accuracy for the purpose. For this reason it was decided to measure the difference of pressure between the centre of the windward side and the centre of the leeward side, both in the open air and in the experimental channel. In order to obtain a comparison of these centre-pressure differences, a series of observations were made on the velocity-tubes and large board in the open air, and on the same tubes and a small plate in the experimental channel. The following are the mean results:—

	In Open Air.	In Channel.
Ratio of velocity-tubes indications to centre-pressure differences	0·94	1·08

These results indicate that for the same velocity of air and wind the centre-pressure difference in the open air exceeds that in the experimental channel in the ratio 1·15.

Since the pressures on the windward side are approximately the same, it is evident that the suction effect due to eddies is considerably greater in the open air than in the channel, which points to the existence either of a purely dimensional effect of the plates of the kind described above, or of some peculiarity in the flow of the air in the channel due to the mechanical arrangements for securing uniformity of flow. Against the latter supposition there is the evidence of the Author's calibration of the Dines tubes in the channel, which agrees with that made by Mr. Dines in his whirling machine. Assuming, therefore, that there is a purely dimensional effect, it appears, both from the Author's previous experiments and the present research, that this effect does not increase uniformly with the dimensions, as is seen in the steady value of the constant in the two cases. The following experiment throws some light on the problem. A plate 6 inches long and 0·3 inch wide was placed in the channel, and the pressures were measured on the leeward side at two points in its central line, one 0·15 inch from the end and one 2 inches from the end. It was found that the intensity of the negative pressure in the latter case was more than 50 per cent. greater than the negative pressure near the end of the plate, which was approximately the same in value as that on the leeward side of a square plate 0·3 inch by 0·3 inch.

This may be taken as an illustration of the marked increase in the suction-effect due to the long dimension of the plate. It appears most probable that the greater resistance of the large pressure-boards in the wind is due to this dimensional effect, although the present experiments and those of previous observers show that the increase in this effect with the area of the plate must be very small for plates exceeding 1 square foot in area.

Experiments on a Model Girder.—Owing to the marked difference in resistance between flat plates and lattice-work such as braced girders, it was considered desirable to make experiments on a model girder of this kind. The one made for the purpose was 29 feet in length and 3 feet $7\frac{1}{2}$ inches deep, and consisted of two equal flanges 9 inches by 1 inch, connected by a double system of lattice bars and verticals, as shown in Fig. 11, Plate 3. The total area exposed to the wind was 56·3 square feet. The model was mounted on the knife-edges used for the previous experiments, and about two hundred observations of pressure and wind-velocity were made in the same manner as for the rectangular boards. The results are plotted, together with the means of the observations, in sets of ten in Fig. 11. From the inclination of the mean line drawn in the figure, the value of the constant in the pressure-velocity relation is found to be K = 0·00405.

For the purpose of comparing the resistance of this model in the wind with that of a very small similar model in the experimental channel, the latter was made in brass, the ratio of its linear dimensions to those of the original being $\frac{1}{42}$, so that its area was 0·032 square foot. This was placed in the channel, and from a set of experiments upon it, the value of the constant in the pressure velocity relation was found to be 0·00338. Now the value of this constant determined in the channel for round and square plates was[1] 0·0027, so that the ratio of the resistance of the small model to that of the small plate in the uniform current is 1·25, and the ratio of the resistance of the large model to the large boards in the wind is 1·26, which shows that the relative resistances of dissimilar surfaces are the same in the two cases.

Experiments on Roof Models.—In the experiments in a uniform current of air described in the Author's previous Paper, the intensity of the pressure at certain points in the central plane perpendicular to the ridges of small roof-models was measured, and the results were tabulated. These pressures were estimated on the outside of the roof only, and were stated relatively to the static pressure of the air in the current, higher pressures than this being stated as positive, and lower pressures as negative. The reason for this was that the models were completely closed on all sides, so that the pressure on the inside of the roof was independent of the velocity of the current, and could be taken as equal to the static pressure of the latter. It will thus be seen that the results given were applicable only to the case of a building so closed as to be unaffected in its interior by the velocity of the wind. The experiments showed that in such a case for all angles between 30° and 60° the suction on the leeward side of the roof was considerable, as had been previously pointed out by Mr. J. O. V. Irminger.[2]

[1] Minutes of Proceedings Inst. C.E., vol. clvi, p. 94. [2] *Ibid*, vol. cxviii, p. 468.

These experiments on small models were not carried further, chiefly on account of the difficulty of measuring the resultant pressure on the roof of such small models without interference from the other parts; and it was thought that sufficient evidence had been obtained of the suction-effects on the leeward sides of roofs to justify experiments on a larger scale in the open air.

The model which was constructed for these experiments is shown in Fig. 12, Plate 3, and consists of two mahogany boards each 8 feet by 7 feet, mounted on two pairs of steel principals, so constructed that the two sides of the model could be set at any angle between 30° and 60° to the horizontal. One of these boards was bolted to the framework, and the other, on which the pressure-observations were to be made, was attached in such a way as to be free to rotate about an axis perpendicular to the ridge under the action of gravity and the force of the wind. As the actual movement about this axis would be very small, the component of the weight in the plane of the board was taken by the two flexible steel strips SS, and the position of the axis was fixed by attaching steel knife-edges to the board, working on **V** blocks bolted to the frame and held in contact by the spiral springs KK.

The axis was made perpendicular to the ridge instead of parallel to it, because of the unknown position of the centre of pressure of the wind relatively to the ridge. It was considered that its position could safely be regarded as being in the line perpendicular to the ridge bisecting the board, and therefore its distance from the axis of the knife-edges was known. The centre of the board was fitted with a hardened steel cone and pin bearing upon a diaphragm of the same kind as that used for the experiments on normal pressure, and the observations were made in precisely the same way.

In the first series of experiments made on this model the two vertical boards shown in Figs. 13, Plate 3, were attached to the framework, extending downwards from the eaves for a distance of 30 inches. The spaces between the two boards at the ridge and those at the eaves were made practically air-tight by means of canvas strips so connected as to leave the pressure-board free from constraint. The ends of the model were also closed by canvas sheets as indicated in Figs. 13, the part underneath being left perfectly open.

In making the experiments the pressure-board was used alternately as the windward side and as the leeward side, by rotating the model through 180°. This necessitated the use of two sets of velocity-tubes to avoid the delay due to re-erecting the pipes whenever a change in the side observed was made. These were situated at a height of 9 feet above the ridge and 14 feet in front of it (Figs. 13).

Sets of observations were made at three inclinations—30°, 45° and 60° to the horizontal, for both windward and leeward sides, and the means of them, in sets of ten, are plotted in Figs. 13.

In these experiments the total pressure on the diaphragm was the sum of that due to the weight of the board, which depended on the inclination of the roof, and that due to the wind. The pressures on the diaphragm due to the weight of the board were carefully determined in the workshop before erection on the tower, in order to obtain a check on the plotted results. The points plotted in Figs. 13 have as ordinates the total pressures on the diaphragm at the corresponding wind-velocities, so that for any particular set of observations, the mean line through these points should cut the line of zero velocity at a point whose ordinate is the pressure due to the weight of the board. It was found that in all cases the pressure so determined agreed very well with the pressures measured before erection. It will be noticed that the deviation of the means of the observations from the mean line is rather more marked than in the experiments on normally exposed plates, but this is to be expected from the known instability of the pressure on inclined surfaces.

The mean results may also be conveniently represented as pressure per square foot of the roof-surface at a wind-velocity of 20 miles per hour, as given in the following Table:—

Inclination of Roof to Horizontal.	Pressure in Pounds per Square Foot of Roof Surface at 20 Miles per Hour.	
	Windward Side.	Leeward Side.
60°	+1·35	+0·15
45°	+1·13	0·0
30°	+0·61	−0·16

With reference to the pressures on the windward sides, it may be noticed that at 60° inclination the pressure is somewhat in excess of the corresponding pressure for normal impingement of the wind, a fact which is in accordance with previous experiments on inclined plates. Even at an inclination of 45° the pressure is not greatly diminished.

The pressures on the leeward side are seen to be comparatively small and to consist of a small pressure effect at 60°, a small suction-effect at 30°, and practically zero effect at 45°. The explanation of these low values of the *resultant* pressure on the leeward board is to be found in the reduction of the pressure on the inner side of the leeward board caused by the eddies from the windward board. The interior of the roof-model, as stated above, was protected from the action of those eddies at the ridge and at the sides, but was exposed to their action from the lower edge of the short, vertical board attached to the windward side of the frame. The reduction of pressure set up inside the roof-model by these eddies is greater than that which obtained in the outer surface of the leeward board when inclined at 60°, is equal to it at 45°, and less at 30°, as will be seen by inspection of the Table.

The foregoing results may be taken to apply to roofs supported on columns through which the air is free to pass, and in such cases there does not appear to be any necessity for taking into account the effect of the wind on the leeward sides.

In order to obtain results which might be applicable to roofs supported on walls, the roof-model was altered in the manner indicated in Figs. 14, Plate 3. The vertical board at the eaves on the windward side was taken away, and that on the leeward side was lengthened to a depth of 6 feet. In this way it was hoped that the reduction of pressure inside the model due to the eddies from the windward side would be prevented.

The results of the experiments on this arrangement by taking the means of every ten readings are plotted in Figs. 14. It will be seen from the results given in the following Table that this device had the effect of producing resultant negative pressures of high intensity on the leeward board :—

Inclination of Roof to Horizontal.	Resultant Pressures in Pounds per Square Foot of Leeward Surface at 20 Miles per Hour.
64°	−0·36
48°	−0·68
36°	−0·82

These suction-effects are of the same order as those observed in the Author's previous experiments on small models, and it may be pointed out that at the smallest inclination the suction-effect is greater than the pressure-effect on the windward side. Doubtless, still greater suction-effects could have been obtained by extending the vertical plate attached to the eaves on the leeward side still lower, but it was considered that sufficient evidence had been obtained to lay down the approximate wind-effects which a roof may be called upon to resist.

The conditions of wind-pressure in the foregoing case may be taken as roughly approximating to those of the roof of a building in which the windows and doors are open on the windward side and closed on the leeward side, so that there will be a pressure set up inside the building and acting on the inside of the roof, the magnitude of which is unknown but which may be assumed to be a large fraction of the pressure experienced by the windward side of a plate upon which the wind impinges normally. There will also be a negative pressure on the leeward side of the roof, due to the eddies from the ridge and ends of the building.

The determination of the pressure inside a building due to open windows and doors would have been a matter of considerable difficulty with the roof-model used for these experiments, but as the value of the fraction stated above could be equally well obtained from a small model in the experimental channel, a set of observations of such a kind was made. The effect of openings in the leeward wall of the model was also observed and is here tabulated. In the latter case, as would be expected, the pressure inside the building depends on the ratio of the areas of the openings on the leeward and windward walls. The area of the openings in each wall was approximately 4 per cent. of its surface.

Angle of Roof.	State of Openings.		Ratio of Intensity of Pressure Inside Model Building to Maximum Intensity on the Windward Side of a Plate on which the Wind Impinges Normally.
	Windward Side.	Leeward Side.	
60°	Open	Closed	1·00
60°	,,	Half-open	0·67
60°	,,	Open	0·20
30°	,,	Closed	0·82
30°	,,	Half-open	0·49
30°	,,	Open	0·20

Further, since the negative pressure due to eddies on the outside is approximately the same as that on the leeward side of a plate upon which the wind impinges normally, it appears that the maximum suction-effect on the leeward side of a roof inclined at 60° may be equal to the resultant pressure on a board of the same area placed normal to the wind. In the case of a roof inclined at 30°, the maximum effect may be roughly 70 per cent. of this amount. These estimations were further checked by observations of the difference of pressure between the two sides of the leeward plate in the small model used.

The results of the experiments on roof models here described are, in the Author's opinion, too complicated to be expressed in terms of the inclination of the roof, but the maximum values of the constant in the pressure-velocity relation may be conveniently stated for the actual cases treated :—

(*a*) Roof mounted on columns through which the wind can pass.

	Values of *k*.		
	60°.	45°.	30°.
Windward side	+0·0034	+0·0028	+0·0015
Leeward side		Negligible.	

(*b*) Roofs of buildings in which the pressure on the interior may be affected by the wind.

	Values of *k*.		
	60°.	45°.	30°.
Windward side	+0·0034	+0·0028	+0·0015
Leeward side	−0·0032	..	−0·0022

General Conclusions.

With reference to the experiments as a whole, the individual observations here recorded may be taken as illustrating the extremely complicated nature of the motion of the air in winds, which had been previously detected by other observers. There can be no doubt that a correct appreciation of the actual distribution of velocity in winds will go far to remove the suspicions which have been entertained about many of the published records of wind-velocity and pressure. As an example, it has been the custom to allude to as manifestly inaccurate[1] the Bidston Observatory records of the gales of 1871 and 1877, in which the maximum velocities of the wind as recorded by an anemometer, and the maximum pressures of the wind as recorded by a pressure-plate were, 79 miles per hour and 90 lbs. per square foot on the 9th March, 1871, and 80 miles per hour and 64 lbs. per square foot on the 23rd November, 1877.

As the Author has previously pointed out,[2] it is not sufficiently recognized that these are the records of two instruments placed 10 feet apart, and that it is quite conceivable that, during the maximum gust on the 9th March, the velocity of the wind at the anemometer may have been 9 per cent. less than that at the pressure-plate, and on 23rd November, 9 per cent. greater, which would account for the apparent discrepancies.

It will be noticed that these experiments have been made at quite moderate wind-velocities ranging from 5 to 30 miles per hour. This was due partly to the locality in which the observations were made, and partly to the large number of observations required, which rendered necessary the use of the prevailing type of wind which had an average speed of 20 miles per hour. Assuming that the

[1] *E.g.*, *see* Minutes of Proceedings Inst. C.E., vol. clxv, p. 95.

[2] *Ibid.*, p. 124.

relation between pressure and velocity here determined holds for the strongest gales—which there seems no reason to doubt—the Author is of opinion that these experiments indicate a fairly simple and accurate method of estimating the force exerted on any structure by wind-pressure. This method is based on the fact brought out in the experiments, that the ratio of the wind-pressure on a complicated structure such as a braced girder to that on a square board of the same area is the same as the ratio of the resistance of a small scale model of the structure to a square plate of the same area when placed in an experimental channel in a uniform current of air. The fact that the resistance per unit area in the wind is not the same as in the uniform current is comparatively unimportant, for when once the resistance of any surface of simple form in the wind is known, the correction to be applied to the results obtained in the experimental apparatus can be determined for all subsequent observations.

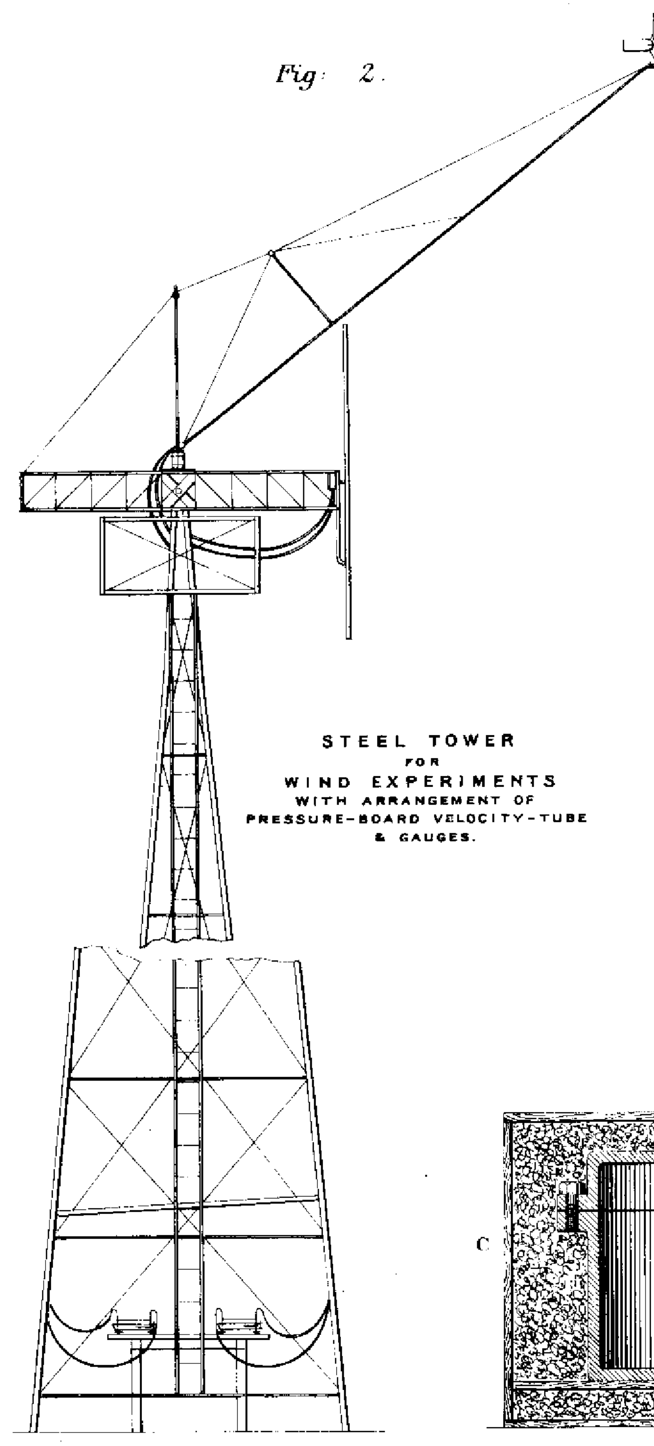
Thus, adopting this method in the design of structures, when once the resistance of a small model of the structure had been determined, and that of the structure itself had been deduced from it, there would only remain the estimation of the maximum wind-velocity which might likely be attained on the site of the structure. This estimation would be made from the records of a reliable anemometer on or near the site. In the case of a very large and important structure in an exposed situation, where the maximum record of a single anemometer might be considered to give an excessive estimate of the total wind-force on the structure, the simplest and best method would seem to be to erect several sets of pressure-tubes at certain points in the area considered, and to connect all these tubes in parallel to the same recording instrument. In this way a reliable estimate of the mean velocity over the area might be made.

In conclusion, the Author desires to express his great indebtedness to his colleague, Mr. Leonard Bairstow, for his invaluable help in carrying out and reducing the experiments, and in overcoming the not inconsiderable practical difficulties which have arisen in the course of the work. He also begs to thank Dr. R. T. Glazebrook, F.R.S., for the facilities which he has given for the purpose of the research and for the interest which he has taken in it.

The Paper is accompanied by an Appendix containing Tables of the numerical values of the separate observations which may be referred to in the Library of The Institution, and by twelve sheets of drawings and two photographs, from which Plate 3 and the Figures in the text have been prepared.

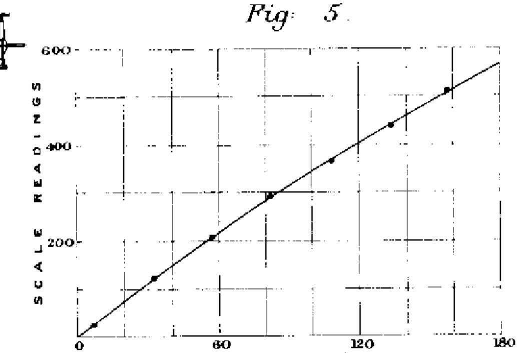
EXPERIMENTS ON WIND-PRESSURE.

Fig: 2.



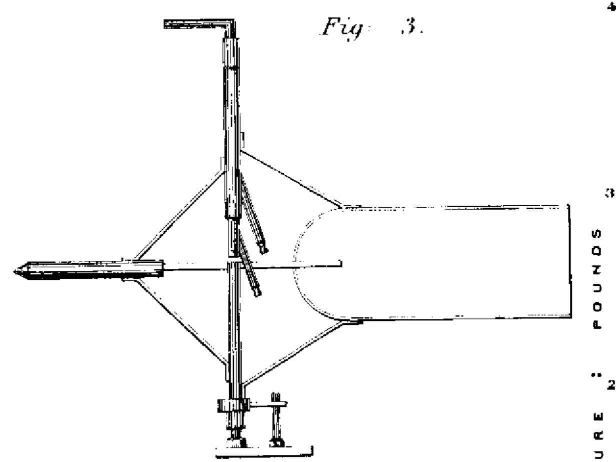
STEEL TOWER FOR WIND EXPERIMENTS WITH ARRANGEMENT OF PRESSURE-BOARD VELOCITY-TUBE & GAUGES.

Fig: 5.



CALIBRATION-CURVE FOR DIAPHRAGM.

Fig: 3.

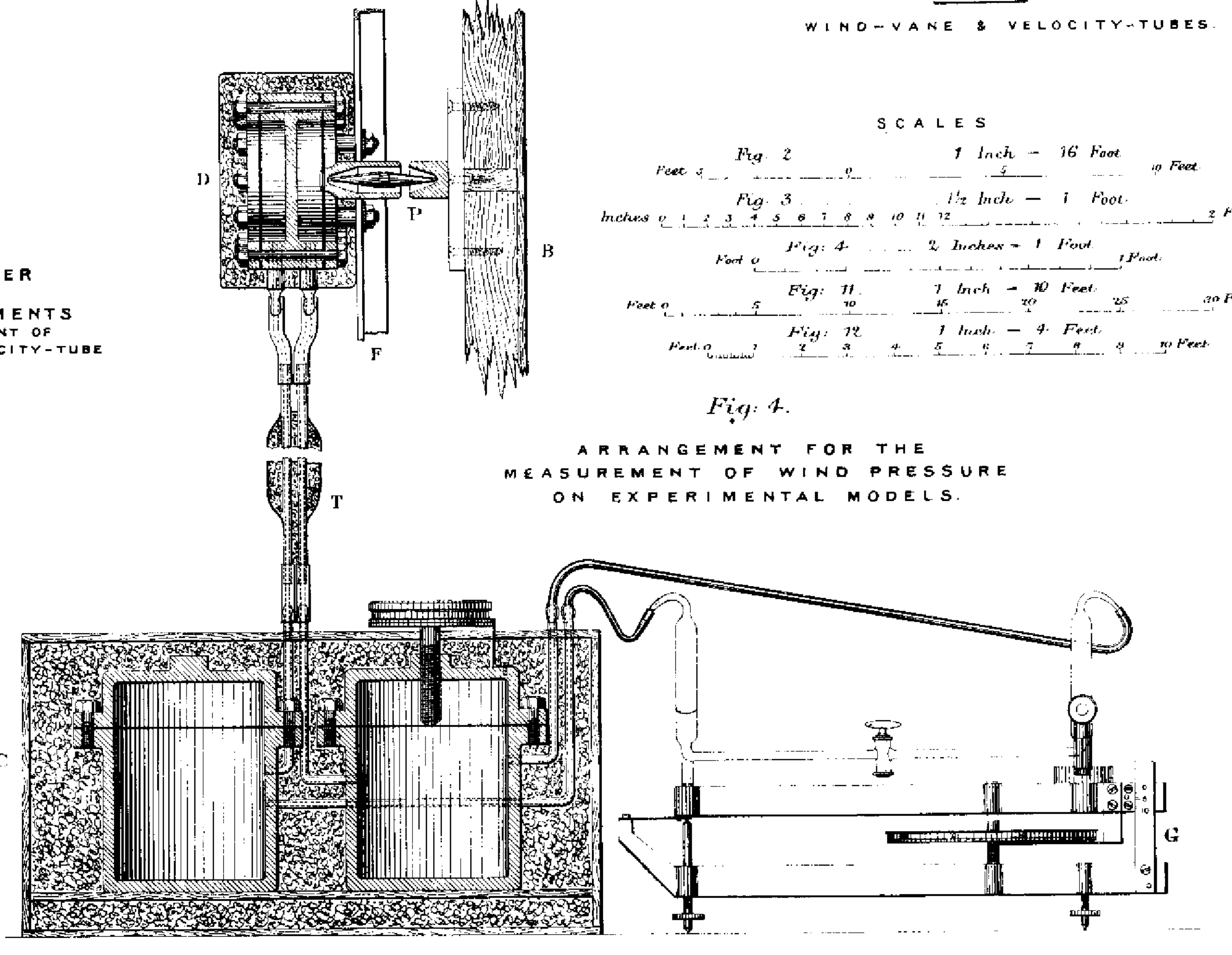


WIND-VANE & VELOCITY-TUBES.

SCALES

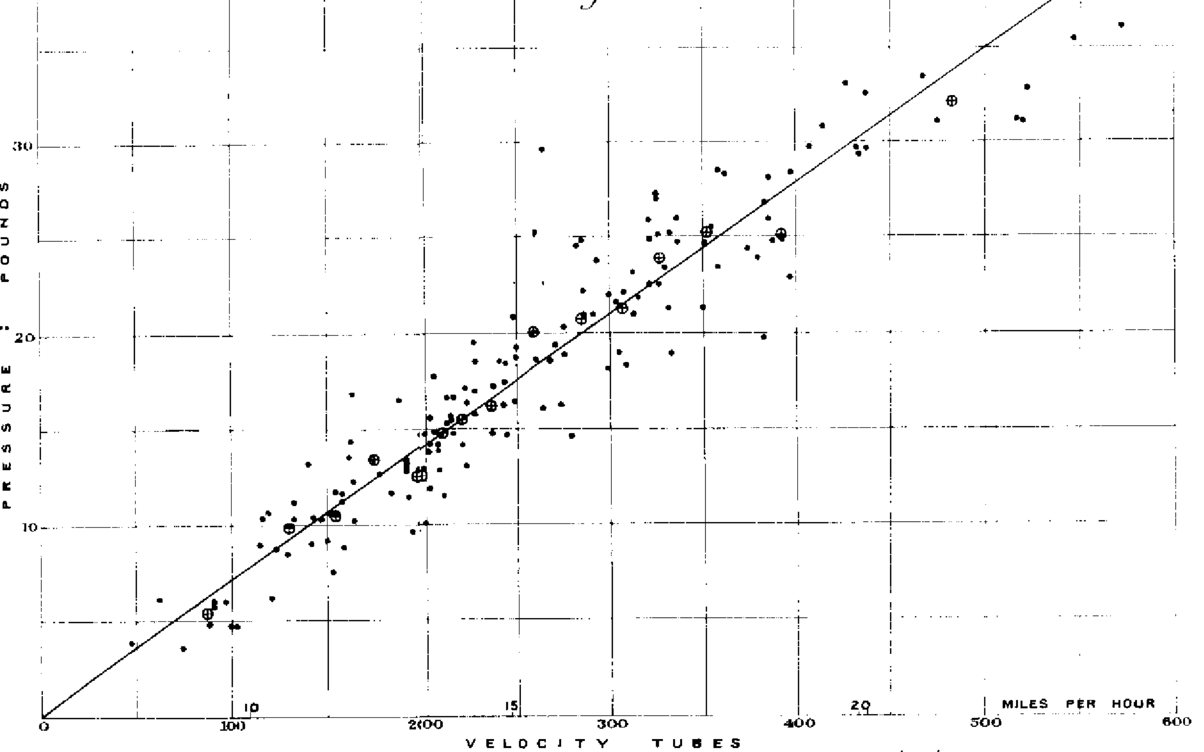
Fig. 2 — 1 Inch = 16 Feet
Fig. 3 — 1½ Inch = 1 Foot
Fig: 4 — 2 Inches = 1 Foot
Fig: 11 — 1 Inch = 10 Feet
Fig: 12 — 1 Inch = 4 Feet

Fig: 4.



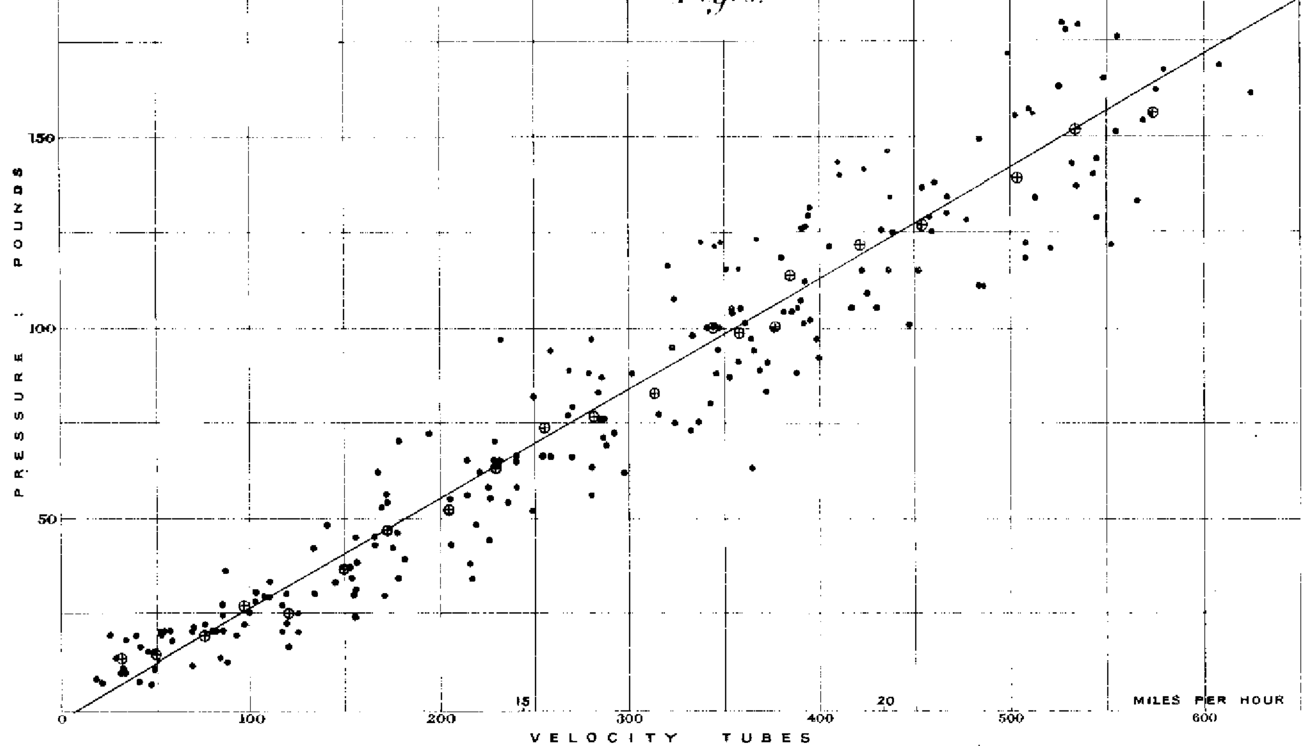
ARRANGEMENT FOR THE MEASUREMENT OF WIND PRESSURE ON EXPERIMENTAL MODELS.

Fig: 7.



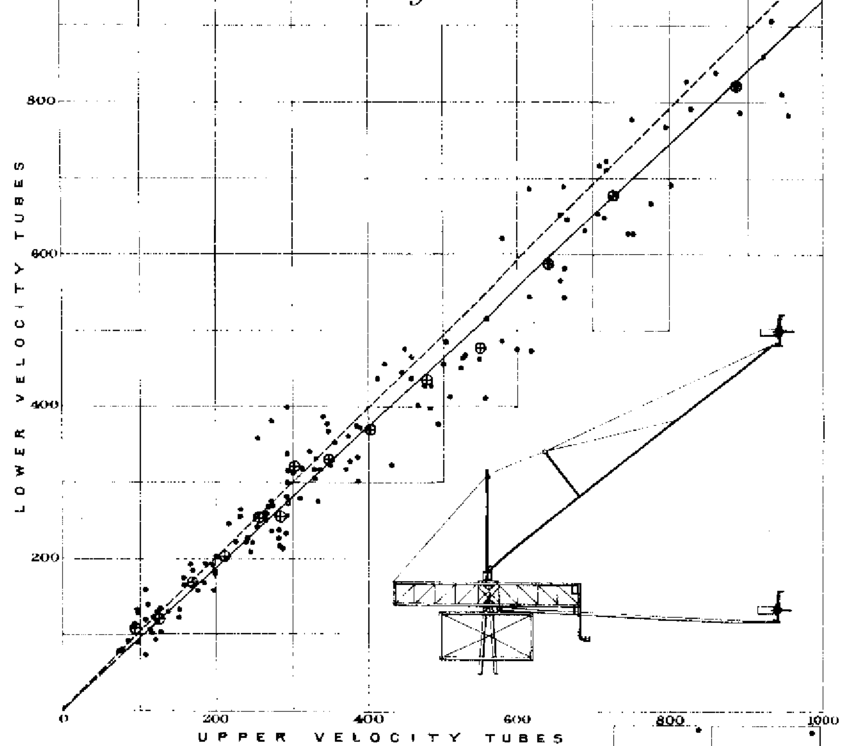
EXPERIMENTS ON PRESSURE-BOARD 5'×5'.

Fig: 9.



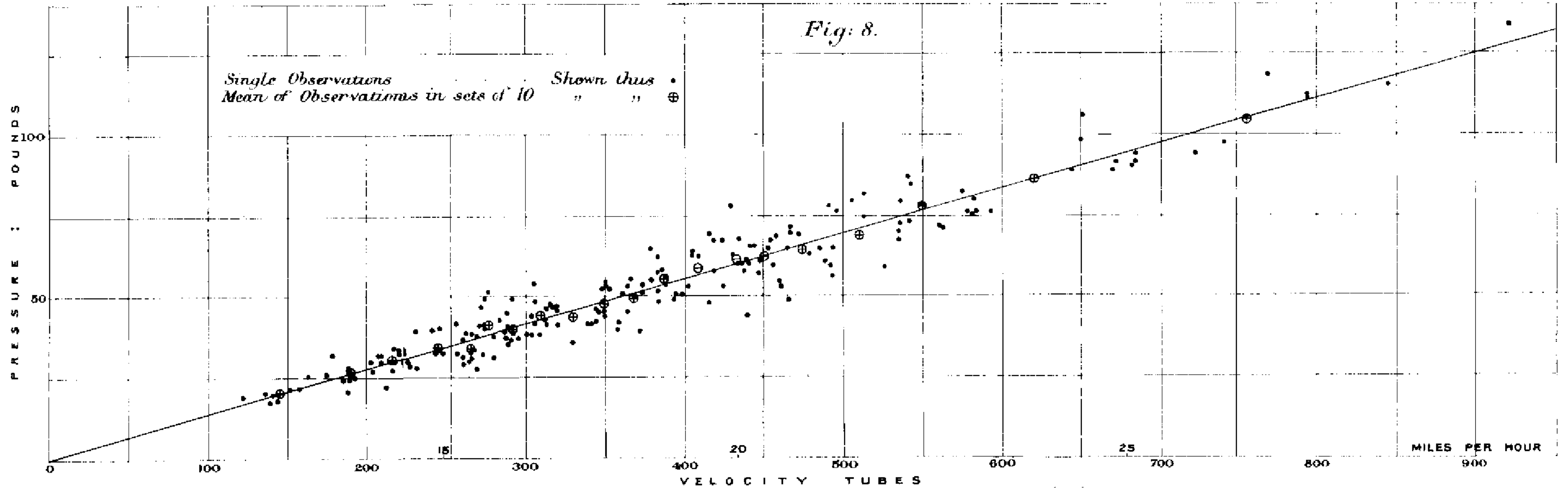
EXPERIMENTS ON PRESSURE-BOARD 10'×10'.

Fig: 10.



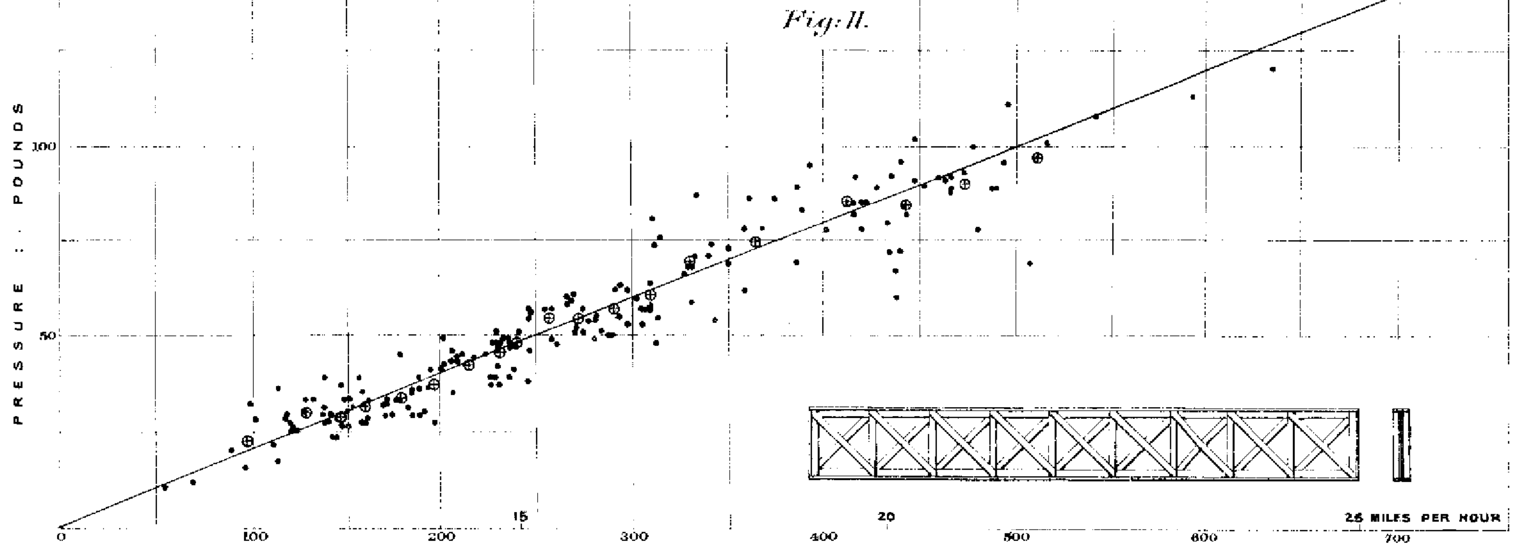
COMPARISON OF WIND VELOCITIES AT VANE & CENTRE OF PRESSURE-BOARD.

Fig: 8.



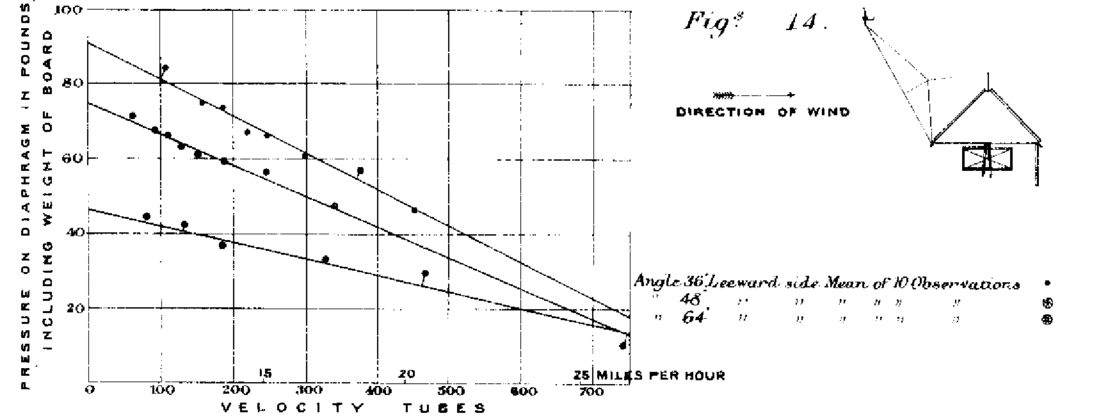
EXPERIMENTS ON PRESSURE-BOARD 10'×5'.

Fig: 11.



EXPERIMENTS ON MODEL GIRDER 29'×3'.6".

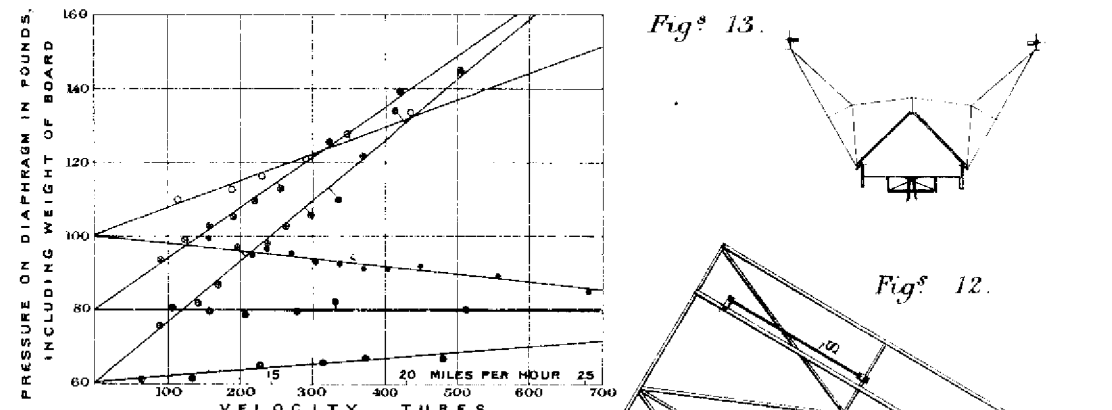
Figs 14.



EXPERIMENTS ON ROOF-MODEL.

Angle 36° Leeward side Mean of 10 Observations •
" 48° " " " " " ⊗
" 64° " " " " " ⊕

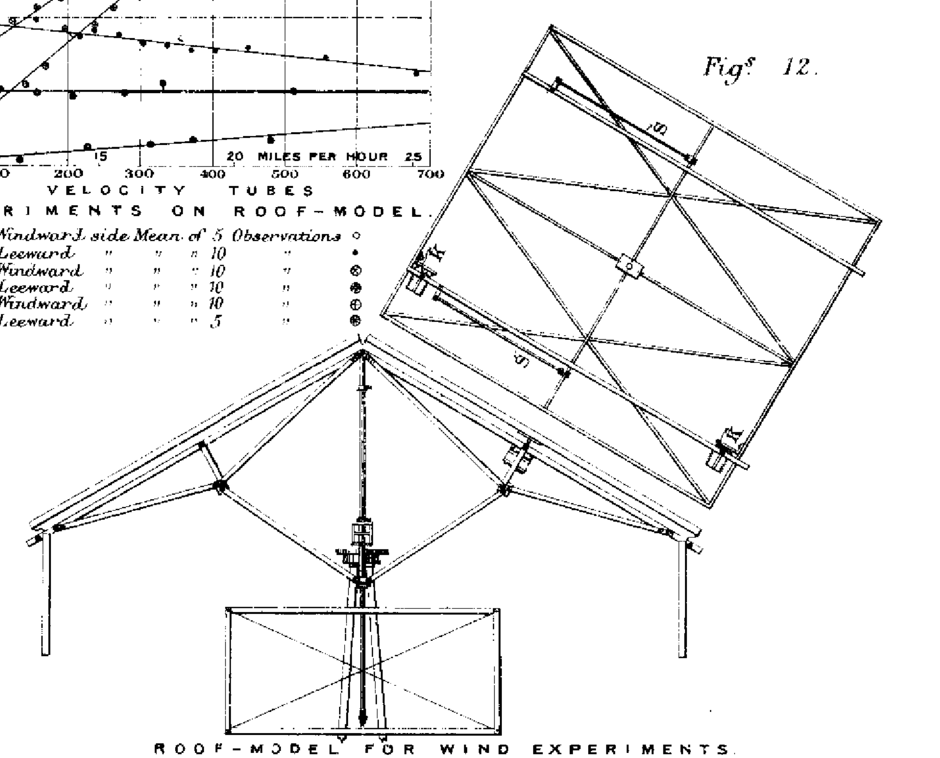
Figs 13.



EXPERIMENTS ON ROOF-MODEL.

Angle 30° Windward side Mean of 5 Observations ○
" 30° Leeward " " " 10 " •
" 45 Windward " " " 10 " ⊗
" 45 Leeward " " " 10 " ⊕
" 60° Windward " " " 10 " ⊕
" 60° Leeward " " " 5 " ⊛

Figs 12.



ROOF-MODEL FOR WIND EXPERIMENTS

TROS. KELL & SON, LITH. 40 KING ST. COVENT GARDEN