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A Survey of Measuring Instruments For Low-Velocity Winds

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PREFACE

Contract DA-11-022-ORD-1048 between the University of Minnesota, St. Anthony Falls Hydraulic Laboratory; and the Department of the Army, Ordnance Corps, Ballistic Research Laboratories, provided for a survey of literature and correspondence contact to determine the basic nature and limitations of existing systems or components intended for or adapted to the precision measurement of low-velocity winds near the earth's surface. This report constitutes a summary of the above survey study, together with a description of the limited confirming or pilot physical tests carried out at the St. Anthony Falls Hydraulic Laboratory in support of the evaluations offered herein. A continuation of the effort applied under the above Contract is provided for under Evans Signal Laboratory Contract DA-36-039 SC-56694.

This report was prepared by John F. Ripken, assisted by John M. Killen, who conducted the physical tests and guided the electrical interpretations; and Loyal A. Johnson who edited the manuscript.

The program was under the general direction of Dr. Lorenz G. Straub, Director of the Laboratory.

Dr. W. W. Berning represented the Ballistic Research Laboratories and Mr. A. Arnold represented the Evans Signal Laboratory in the technical aspects of the work.

ABSTRACT

Knowledge of the speed and direction of low-velocity winds near the earth's surface was deemed necessary in providing a solution to certain ordnance-firing problems.

This paper attempts to review and assess all pertinent existing instruments or methods which might be practically employed to measure the desired wind velocity. The assessment was based on a review of the available literature and limited physical tests, both of which were conducted at the St. Anthony Falls Hydraulic Laboratory.

In general the assessments relate to the accuracy, sensitivity, and responsiveness of the sensory instrument, together with a discussion of the related accessory and field use problems.

A brief discussion of the general problem and the nature of the wind's structure is followed by a detailed appraisal of dynamic pressure, and thermal and ionization types of anemometers, together with a lesser treatment of other special devices.

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A SURVEY OF MEASURING INSTRUMENTS FOR LOW-VELOCITY WINDS

I. INTRODUCTION

A. The General Problem

Unguided missiles launched from the ground and directed at distant targets will have a target accuracy dependent on the compensating steering settings which are applied to the missile before it is launched. The ability to fully compensate the device for all of the many deviating forces to which it may be exposed is determined by the adequacy of knowledge of these forces at the time that the compensations are applied to the launching device or the missile.

Among the deviating forces at work on the missile in flight are the forces produced by the existent winds of nature. In the case of projectiles fired from guns, where the body achieves its major speed while in the guiding influence of the gun barrel, the deviating action of low-velocity horizontal winds near the earth's surface is insignificant in the general steering problem. However, in the case of missiles which are moving slowly and experiencing their major acceleration while in an unguided launching system, the deviating force of a horizontal wind may be quite significant. While the actual magnitude of such a deviating force may be very small, the missile tends to weather vane into the wind when such a force is applied to its large, lateral, unbalanced areas. Even minute angular deviation at this phase can result in major errors of target accuracy, consequently it is necessary to clarify this wind force for appropriate pre-launching compensation.

It is the purpose of this report to examine and appraise the merits and limitations of wind-measuring devices which might be employed to supply data on existent wind conditions for use in the compensating mechanism.

It is desired that this instrumentation be capable of supplying data on the wind direction and magnitude from the earth's surface to an elevation of about 300 ft for winds ranging in speed from about 1 to 30 fps, or possibly to 50 fps, with a desired accuracy of 1/2 fps in the lower range and 1 fps in the upper range.

B. The Nature of the Pertinent Wind Structure

The winds of the earth are extremely complex in structure. They vary in speed from zero at the earth's surface to high values in the upper atmosphere. The speed is seldom steady in either magnitude or direction for any appreciable length of time and may as a normal thing be expected to fluctuate both widely and rapidly in a pattern of gustiness.

A given general wind is the adjusting fluid flow that accompanies the pressure differences induced by atmospheric density changes resulting from the continually changing seasonal and daily solar heating effects together with force effects contributed by the earth's rotation. The general wind is in turn modified by the local thermal influences contributed by cloud cover, ground cover, land and water masses, humidity, topography, etc. The end result of this intricate play of variables is a random, unpredictable wind structure which has as yet failed to yield to any consistent and orderly analytical determination except in a general simplified statistical treatment of long-time averages which do not necessarily apply with any accuracy to individual instances.

The great bulk of available wind data has been obtained at meteorological weather stations for the purpose of establishing the general weather pattern and has utilized instruments capable of supplying data for 5-min or 1-hr average winds. Since man's interest in the weather is usually associated with its extremes and the harm that may result therefrom, the standard instruments have been built to measure the medium to high expected winds with scant concern for the lower values which are of interest in this particular study. In addition, for practical reasons, the bulk of the data has been obtained from instruments mounted about 30 ft or 10 m above the ground, thus it throws little light on the values above or below this level.

In the field of micrometeorology in recent years, an increasing amount of wind data has been accumulating which is concerned with conditions in the lower layer of the atmosphere in which man lives and grows his food. This layer is restricted by some investigators to the lower 6 ft of atmosphere, while others extend it several hundred feet to include the factors associated with air pollution of an industrial, atomic, or military nature. These latter data are illuminating but serve principally to emphasize the extreme variability and the difficulties associated with an attempt to predict the wind values at any particular point or time.

In attempting to sift existing wind data for some guide as to the probable nature of values which the proposed instrumentation may be expected to measure, two primary wind variables appear to be evident. These are the wind profile, or mean wind velocity variations with height; and the gustiness, turbulence, or eddies which may be superimposed on the mean profile.

Numerous attempts have been made to systematize the available data to show the probable nature of the wind speed profile that may be expected. These efforts have not been highly successful but have served to demonstrate certain trends which do exist. Among these trends is evidence of a laminar boundary layer existing immediately above the ground surface. In this layer the speed varies from zero at the surface through values which increase rapidly with height in a nearly linear manner. This steep linear variation in the lower few feet then swings into a profile which is approximated by a power law of the form, velocity = K $(\text{height})^{\alpha}$.

In analyzing extensive data, Carruthers [1]* concluded that α was widely variable with thermal conditions, having been observed to vary from 0.1 to 0.6 with a mean value of about $\alpha = 0.17$. This variation is noted as being in general accord with Prandtl's 1/7-power law for the velocity in a boundary layer. Some idea of the relative values involved may be obtained from the following, which lists the ratio of (velocity at height h)/(velocity at 10-m height) against the height h in meters for a value of $\alpha = 0.17$.

h in meters	1	3	5	10	15	20	30	40	50	75	100
h in feet	3.3	9.8	16	33	49	66	98	131	164	246	328
V_h/V_{10}	0.68	0.81	0.89	1.00	1.02	1.13	1.21	1.27	1.31	1.41	1.48

Sutton [2] indicates that the range of α may be even greater, extending from 0.01 to 0.77. Carruthers [1] concluded that the α-value was somewhat affected by the height h and the velocity V, but was primarily influenced by the temperature conditions together with the roughness of the ground surface. The latter condition gave an α which was smaller over a rough than over a smooth surface because of the mixing influence of the mechanical turbulence.

In general, the power law equation appears to be susceptible to fitting measured data from an elevation of a few feet up to some 1500 to 2000 ft. Above this value the ground frictional and local thermal effects seem to lose

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*Numbers in brackets refer to references at end of each section.

influence. The wind becomes a "gradient wind" which is of a different character primarily influenced by the large-scale barometric pressure gradients and the earth's rotational forces. Some idea of the relation between the ratio of surface wind to gradient wind, and the influence of exposure is evident in the following hour-average observations made in the British Isles and listed by Carruthers [1].

Exposure	$\frac{\text{Velocity at 31 ft}}{\text{Gradient Wind Velocity}}$	α
Open sea	0.60	0.13
Low islands	0.55	0.15
Windward coast	0.50	0.18
Leeward coast	0.40	0.23
Open land unsheltered to the west	0.40	0.23
Land sheltered to the west, and townsites	0.30	0.31

Figures 1 and 2 represent further indications of the nature of velocity profiles extending up to the gradient wind. Figure 1 shows Sherlock's [3] application of Ekman's theoretical logarithmic spiral to storm wind data recorded between elevations of 50 and 250 ft. The curves also show the influence of various arbitrary time averages and Prandtl's 1/7-power boundary layer profile. Figure 2 shows a comparison of the Ekman spiral, the Prandtl 1/7-power law, the power law with a power of 0.157 as discussed by Pagon [4], and the curve of Wing [5] which results from a statistical analysis of U. S. Weather Bureau data. It is apparent from these figures that they contain no consistent theoretical treatment to describe the velocity profile accurately.

The problem is further complicated, moreover, by the superposition of turbulence oscillations on the above-described mean wind profile, and a considerable effort has been devoted in the literature to defining this eddy pattern. Fluctuations which pass in a few seconds are known as gusts. Turbulence fluctuations are believed to be reducible to three basic causes which are as follows:

1. A mechanical turbulence exists near the ground as a result of flow past local physical irregularities of terrain, vegetative cover, or artificial structures. The size of such eddies is of the order of the size of the form which produces them, and their time frequency is usually a matter of seconds or fractions thereof. Since the eddies are produced by relatively

fixed geometric forms, they are usually less variable than thermal turbulence in the upper layers.

2. Thermal turbulence is the result of a vertical temperature gradient and consequent density instabilities and rising air currents. The condition of instability usually arises from solar heating of the ground, or from a cold air mass moving in over warm ground or overrunning a warm air mass. On the other hand, thermal stability occurs in the absence of solar heating, or when a warm air mass moves in over cold ground or overruns a cold air mass. If the thermal instability is high, the upper air is brought toward the ground with considerable vertical speed. (Sherlock [3] found evidence of vertical speeds as great as 40 fps at a 200-ft elevation.) If the upper air or horizontal gradient wind is of high speed at the time of the vertical instability, the violence of the turbulence working into the lower layers may be considerable. Such turbulence eddies may be quite small and rapid or may have a lateral extent of several thousand feet and require minutes of time to pass an anemometer station. Since thermal conditions are subject to a wide variety of influences, thermal turbulence is markedly variable. In general, though, the gustiness will increase with the temperature instability.

3. Barometric pressure systems produce large oscillations whose passage across an anemometer station may be measured in days.

In view of the random nature of turbulence, it is quite apparent that physical tests will show wide variations in data; consistent, precise relations are continually being obscured. However, despite this condition, certain trends and effects have been detected. Some of these include the following:

1. The turbulence near the ground appears to be nonisotropic; the oscillations of velocity horizontal and perpendicular to the mean wind direction are somewhat greater than the oscillations in the direction of the wind and about twice as much as the vertical component. For heights in excess of 75 ft, the three components appear to be about equal.

2. The gradient of the velocity profile is an indicator of the degree of turbulence, since the momentum exchange accompanying turbulence will tend to flatten the profile.

3. The gustiness factor, which is defined in many ways, is commonly the ratio between the difference of minimum and maximum gust velocity and the

mean wind velocity. With few exceptions this factor increases slightly with mean velocity when the velocity is low, but it is quite constant in the higher range. The factor also appears to decrease with increasing height and is primarily a function of the unstable temperature gradient, showing marked variation with seasonal and daily temperature changes. Some indication of the nature of gustiness variation with height and the daily thermal cycle is evidenced in Fig. 3 as taken from Poppendiek [6]. A vertically tilting wind vane was used to take these readings from a tower on the California desert. Values of the arbitrary gustiness parameter employed in this figure are given by the absolute mean vertical angular displacement of the vane tilt from the horizontal, expressed in radians.

4. Gustiness is frequently related to the direction of the wind wholly apart from the directional variations of local mechanical turbulence. This fact is evidenced by a lesser gustiness with the stable winds of polar origin, as opposed to the instability accompanying the winds of equatorial origin.

5. Some measurements indicate that the greater part of all atmospheric turbulence is associated with eddy periods of about 1 sec or less and that at least two-thirds of the eddy energy is associated with eddy periods of less than 5 sec.

6. There is evidence that the components of turbulence pulsations in the lower layers produce an effect of slightly upward rather than horizontal wind direction.

7. The variation of atmospheric variables is usually much larger in the vertical direction than in the horizontal.

The end effect of a natural combination of the foregoing tendencies is not precisely predictable, but recent micrometeorological studies [7] show definite evidence that the general level and type of turbulence can be quite readily predicted by the proper forecast procedures applied to readily obtainable standard-type meteorological data. The exact prediction of the more random eddies that are superimposed on the general gustiness structure is not possible. However, the detailed observations of Sherlock [3] do offer some very interesting evidence as to the probable range of certain values of a superimposed gust. Sherlock's data were recorded as shown in Fig. 17 with the normal pressure plate anemometer shown in Fig. 15. A large number of these anemometers was mounted vertically on a spaced row of towers so that simultaneous measurements of a substantial cross section of the wind could be recorded. A portion of the wind pattern of a storm as interpreted from data recorded at one of these towers is shown in Fig. 4. For the purpose of this report, it is unfortunate that Sherlock's data relate to storm winds rather than to more normal winds. However, his observations as to trends are believed to constitute useful information on maximum variations that may be expected and his following findings on gust values are believed noteworthy:

1. A gust factor, which Sherlock arbitrarily defined as (fastest gust velocity within a 5-min period)/(5-min-average velocity), was found to be a useful parameter.

2. The maximum value of the gust factor was not usually associated with selection of the fastest 5-min-average data for a storm but was more nearly approximated by the average 5-min average for the storm. This is shown by the curves of Fig. 5.

3. The maximum value for the gust factor increased as the time duration of the individual gust decreased. This also is shown in Fig. 5 in which a maximum gust factor of 1.8 is obtained with the shortest observed gust duration of 1/2 sec.

The force exerted by a wind acting on the exposed area of a body is usually a function of the square of the wind velocity. If the wind is gusty or variable, the force on the exposed body will also vary and the magnitude of the force for body control or design purposes must be estimated accordingly. It is apparent that gusts of small size relative to the body dimensions cannot exert a total force measurable by the highest peak of the gust velocity. Rather, the force must be measured by a mean gust velocity which exists for a time sufficient to envelop the body completely. In other words, if the velocity oscillates between V_1 and V_2, the attending forces can be expressed as $F_1 = f(V_1)$, $F_2 = f(V_2)$ only if the values V_1 and V_2 exist for a span of time which exceeds some minimum body response period. This means that a sufficient time must be available to permit the flow pattern to adjust itself completely to the new velocity value. While relatively little experimental data are available for the determination of this time period, it would appear from aerodynamic tests on aerfoils that a long vertical cylinder might be expected to attain a full force response from a wind-velocity change if the velocity exists for a period of time sufficient for the new flow stream to attain a steady length of at least eight times the cylinder diameter.

While this study is directed toward bodies of no specific dimension, it is conceivable that effective cylinder body diameters of interest might vary from a few inches to several feet. If a body of 2-in. diameter, for example, were exposed to a wind of 50 fps (the latter value has previously been indicated as the maximum limit of interest in this study), any new exposure would need to exist for a period of 0.027 sec ($T = D/V = 2/12 \times 8/50 = 0.027$) before a complete shift in force could be achieved. If the body diameter is considered to be 2 ft and the top velocity is designated as 30 ft, the time period will increase to 0.53 sec.

Although none of the foregoing data on the magnitude and rate of wind change are necessarily anything more than a rough guide as to what may happen to the deviating wind forces acting in a given missile launching, the data do indicate the following:

1. An approximate prediction of the general wind conditions as related to the average velocity and gustiness level can be made on the basis of general meteorological observations with standard instruments.

2. The wind (this includes both direction and speed) may readily have rapid gust oscillations which vary plus and minus from 100 to around 200 per cent of the average value and the greater part of the gust energy is contained in eddies with a period of 1 sec or less. These gusts are not predictable, and more or less instantaneous measurements must be made locally to ascertain the nature of a particular structure.

3. A wind gust exerts a variable deviating force on body areas exposed to it. The velocity of a gust does not become fully effective as a dynamic pressure force unless the extent of the gust is sufficient to envelop the body. For small ordnance bodies and strong surface winds, the bodies could be subjected to as much as a 400 per cent change in the deviation force in a period as short as about 1/30 sec. The per cent of change in force will usually be much less than this, and for larger ordnance bodies the change will require a considerably longer time period.

C. The Anemometer Problem

In view of the foregoing, it would appear that the wind velocity instrumentation should preferably be capable of a speed and directional time response to a small fraction of a second. Because most data-computing systems and steering mechanisms are electrically motivated, it is further desirable that the output of the wind instrument be electrical in nature.

It has already been established (see Figs. 2 and 3) that both the general wind and the gust pattern will vary widely with height and time. Therefore, if knowledge of the variation is to be transmitted to the compensation mechanism, a sufficient number of anemometer stations must be established along a vertical to determine either the details of the profile or some integrated average of this pattern. The sensitivity of the ordnance operation to the gradient or pattern of the wind is not within the scope of this study, but it would appear that at least two and possible as many as ten stations might be required in the approximately 300 ft of elevation which are believed to be of concern.

While most anemometers and anemometer studies of the past have utilized fixed mounting conditions, it is apparent that serious practical problems would be involved in providing such a mounting to a 300-ft elevation under the various field operating conditions which might be encountered. For this reason the anemometers discussed in this report will be evaluated on the basis of whether they must be rigidly supported and oriented or whether a nonrigid suspension such as a tethered balloon cable will suffice.

The individual anemometer discussions herein deal only with the ability of the device to measure the wind at the point where the instrument is located. Since it is impractical for the ordnance body to be launched along the vertical line on which the instruments may be located, it must be launched along some line which is offset therefrom. A study of data such as is shown in Fig. 4 makes it quite apparent that the entire velocity pattern can change very rapidly with distance and that separation of the measuring instrument and the launch axis will introduce substantial uncertainties. It is not within the scope of this study to predict the tolerable limits of the offset distance or the optimum placement pattern of the one or more instrument strings which might be employed to predict the wind pattern on the launch axis.

It is quite apparent that adherence to any substantial offset distance will greatly nullify any high order of accuracy or response time that may be indicated at the instrument proper.

In view of the above secondary difficulties, the remainder of this report will be devoted to a discussion and evaluation of the possible sensory measuring devices which might be employed for the problem, but no attempt will be made to extend the findings to a design level.

The instruments have been grouped in the following sections of this report in accord with an arbitrary selection of basic physical actuating forces. The survey on which this summary is based is the result of a literature study and correspondence. While it is believed to be a quite complete treatment of the current status of pertinent wind instrumentation, it is very possible that other promising devices do exist.

D. References

[1] Carruthers, N. "Variations in Wind Velocity Near the Ground." Quarterly Journal of the Royal Meteorological Society, Vol. 69, pp. 289-301. 1943.

[2] Sutton, O. G. Atmospheric Turbulence. London: Methuen and Company, 1949.

[3] Sherlock, R. H. "Variation of Wind Velocity and Gusts with Height." Proceedings of the American Society of Civil Engineers, Vol. 78, April, 1952.

[4] Pagon, W. W. "Wind Velocity Variations with Height." Engineering News-Record, Vol. 114, pp. 742-745. 1935.

[5] Wing, S. P. "Wind Bracing in Steel Buildings." Proceedings of the American Society of Civil Engineers, p. 1103. August, 1932.

[6] Poppendiek, H. F. "Gustiness Profiles in the Lower Layers of the Atmosphere." Meteorological Monographs, Vol. 1, No. 4, pp. 36-38. November, 1951.

[7] Smith, M. E. "The Forecasting of Micrometeorological Variables." Meteorological Monographs, pp. 50-55. November, 1951.

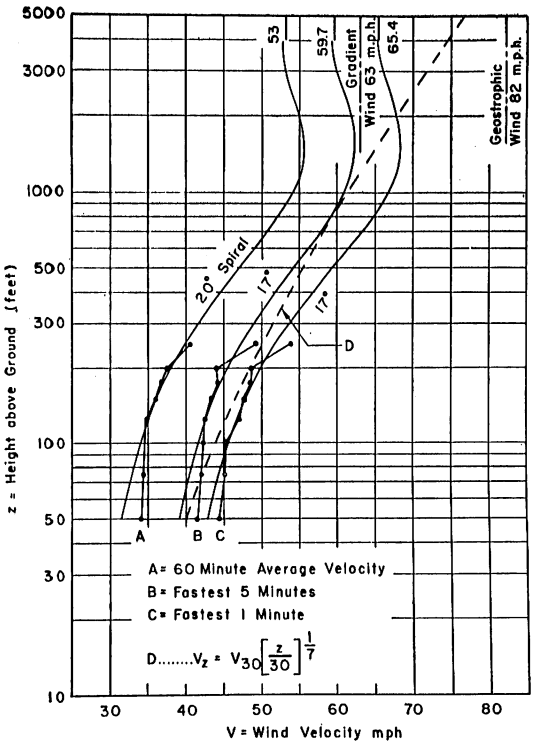

Fig. 1 - Theoretical Wind Profiles Based on Ekman's Spiral as Fitted to Observed Wind Velocities and Compared with Computed Gradient Wind [3]

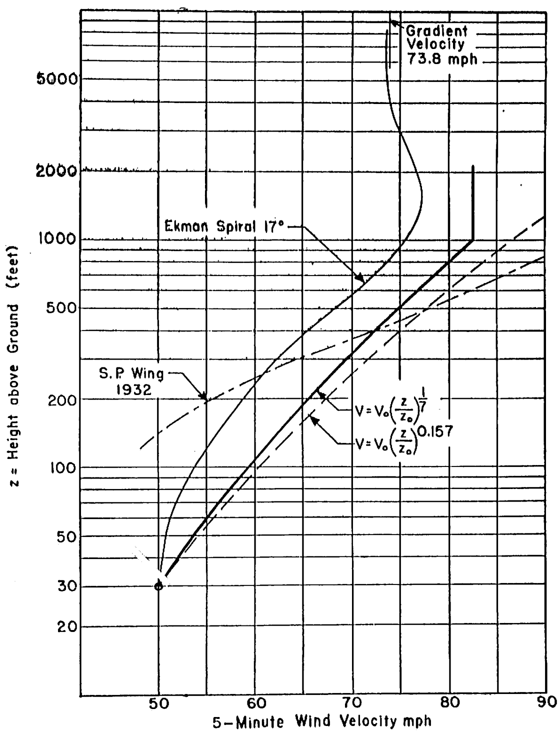

Fig. 2 - Graphical Comparison of Four Different Wind Profile Curves [3]

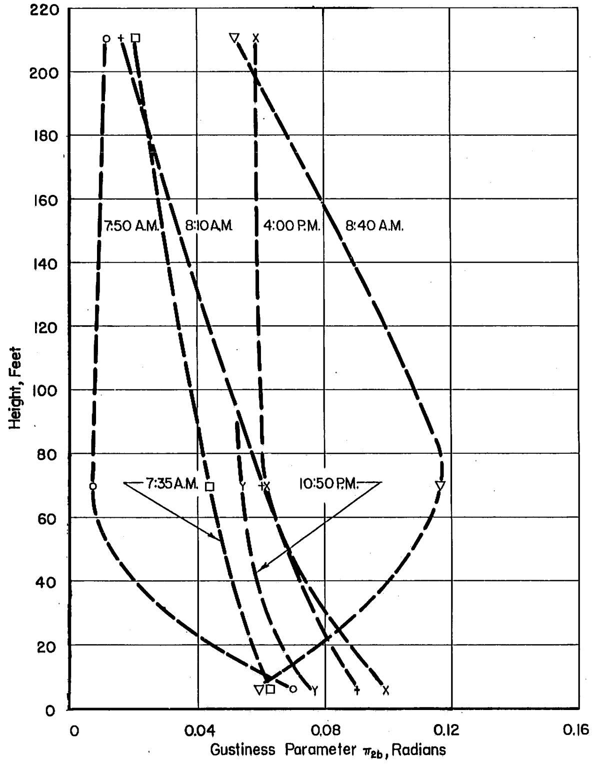

Fig. 3 - Variation of Gustiness Parameter with Height as a Function of the Thermal Effects of the Daily Solar Cycle [6]

Data taken from a tower on the California desert.

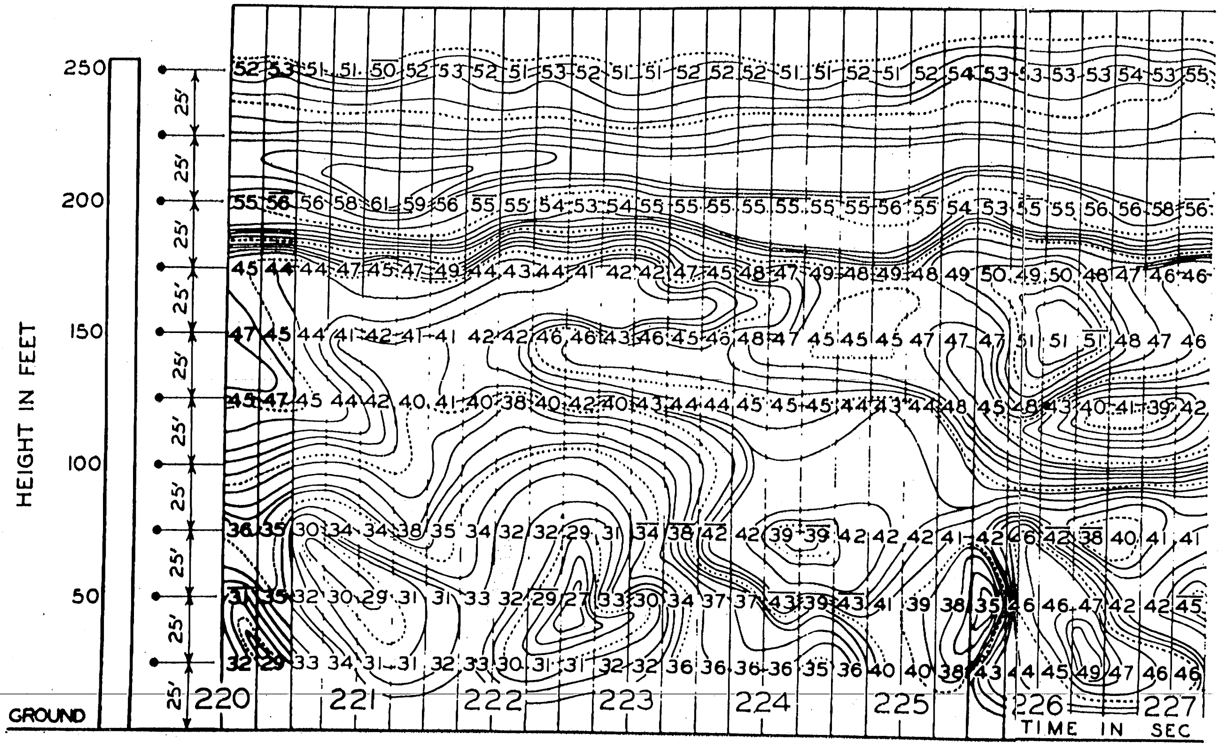

Fig. 4 - Structure of a Storm Wind Passing a Tower Equipped with Pressure Plate Anemometers [3]
Isovel numbers are in miles per hour.

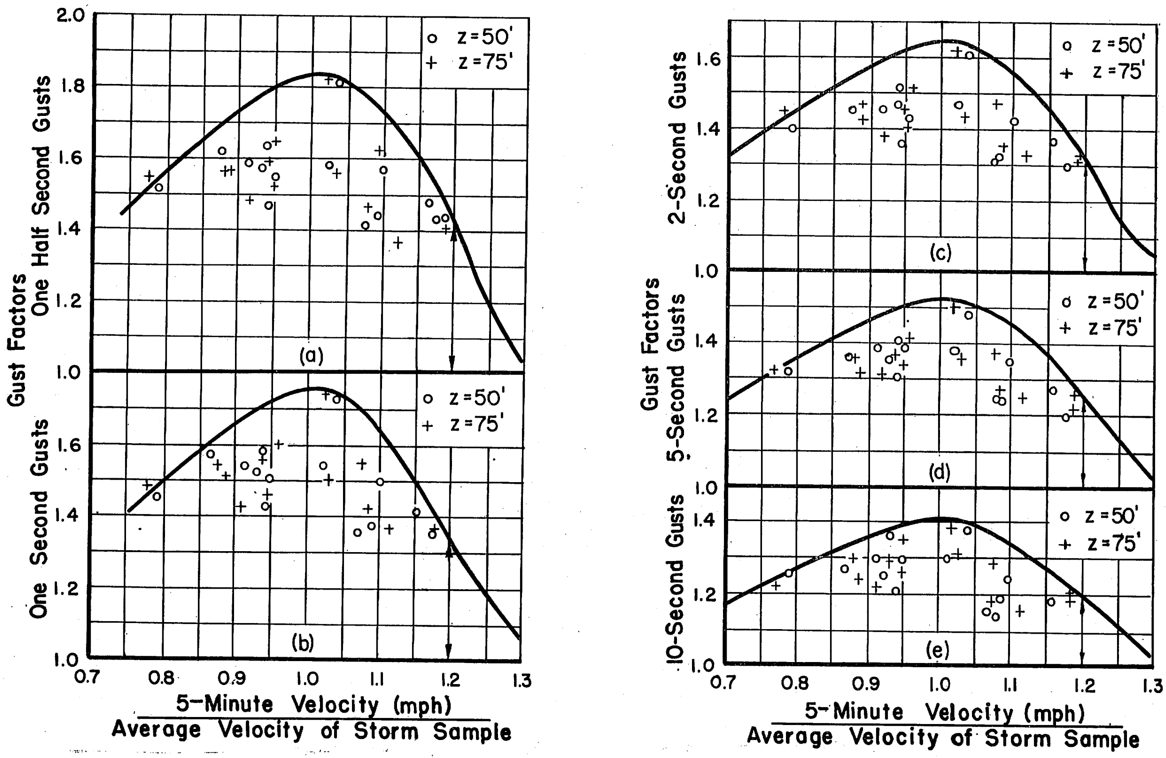

Fig. 5 - Variation of Gust Factors with Gust Duration and Various Time Samplings for a Storm Wind [3]
Curve is a statistical maximum envelope.

II. DYNAMIC PRESSURE ANEMOMETERS

A. General Considerations

The pressure or force exerted by the wind has been used as a basis for wind velocity measurement since the earliest attempts to develop anemometers. The forms of such instruments have developed in wide variety and certain of these today, as in the past, serve to give us most of the factual wind knowledge that we have. In general, these instruments may be assumed to fall into two basic classes; namely, those which measure, in effect, the unit dynamic pressure of the wind, and those which measure the total dynamic force on a directly exposed area. Devices of the first class are rather limited in form and are perhaps best represented by the Pitot tube. Devices of the second class are numerous in form, but must be considered to have two basic subdivisions: notably, those with essentially stationary pressure areas, such as the pressure plate or pendulum devices; and those with moving or rotating pressure areas, such as the rotating vane or cup devices.

All of the above types are dependent on the fundamental relation between stagnation pressure and velocity which results from employing the familiar Bernoulli equation

$$p = \rho\frac{V^2}{2}$$

where p is pressure in pounds per square foot, ρ is the density in slugs per cubic foot equal to weight per cubic foot/g, and V is the velocity in feet per second.

This basic expression for unit pressure may be extended to include finite pressure areas by employing the conventional lift (L) or drag (D) relations to yield a force value in pounds

$$L = C_L A\rho\frac{V^2}{2} \qquad \text{or} \qquad D = C_D A\rho\frac{V^2}{2}$$

where A is the projected frontal area of the body in square feet, and C_L or C_D is the calibrated measure of the form characteristics of the body.

Although the above equations approximate the functional relation between the wind velocity and some pressure or force value, a wide variety of secondary variables influences the relation and usually necessitates physical calibration before instrument application. Important among these are the natural factors affecting the magnitude of the air density ρ which is directly proportional to the atmospheric pressure and inversely proportional to the absolute temperature. While the remainder of this section will be devoted to a discussion of the capabilities and shortcomings of various dynamic pressure anemometers, it should be pointed out here that dynamic pressure devices are inherently ill-suited to the limitations of the problem under discussion despite their tremendous past contribution to wind observations in general. The basic reason for this conclusion stems from the fact that man's desire for knowledge of the wind is generally associated with velocity values of sufficient magnitude to produce workable dynamic pressure or force values when applied to the three foregoing basic equations. In contrast to the general problem, the velocities of concern herein are of a very small value, and in the second-power relations of the equations result in pressure values so small that they are readily obscured by or confused with concurrent extraneous natural forces. While existing instruments are available to measure pressure values of the magnitude under consideration accurately (for example for $V = 10$ fps and $\rho = 0.0024$: $p = 0.0024 \times 10^2/2 = 0.12$ psf $= 0.00083$ psi $= 0.023$ in. of water $= 0.0017$ in. of mercury), these are, in general, precision, nonrugged laboratory devices which are not readily adaptable to field use. Despite the inherent difficulties attending use of low-velocity dynamic pressure anemometers, a few possibilities do exist for such development. These possibilities, together with a wealth of test literature on the higher velocity types, make it desirable to review the potentialities of this group of instruments.

The following order of review will be employed:

Pressure Tube Anemometers

1. The Pitot Tube
2. The Dines Anemometer
3. The Multiple Pressure Tube Anemometer

Force Devices

1. Stationary Devices
    a. The Pendulum, Alnor, and Bridled Cup Anemometers
    b. The Deflecting Filament
    c. The Pressure Plate
    d. The Drag Sphere
2. Rotational Devices
    a. The Rotational Cup
    b. The Vane or Windmill
    c. The Propeller

B. Pressure Tube Anemometers (Pitot, Dines, Multiple Tubes, etc.)

A wind of moderate velocity blowing into the end of a square-cut tube which has been blocked against through-flow, creates a dynamic positive pressure which is quite accurately related to the wind velocity by the previously given equation $p = C_1 \rho V^2/2$. This dynamic pressure exists over and above the normally present static pressure p_o in the undisturbed flow so that a total pressure of $P_T = p_o + C_2 \rho V^2/2$ exists in the tube.

If the tube is approximately aligned with the wind direction, the value of C_2 will be very nearly unity. If the angle between the wind and the tube axis ψ is progressively increased, the value of C_2 will decline from unity and will pass through zero at some angular value around 50°, then become increasingly negative. The exact shape of the curve relating C_2 and ψ will vary considerably and be dependent on the relative compressibility of the air as measured by the Mach number, the relative viscosity of the air as measured by the Reynolds number, the shape and roughness of the tube, and the relative turbulence of the air stream. The nature of this variation is shown in Figs. 6, 7, and 8.

In Fig. 6, the measured data include not only a square-cut (90°) tube end, but also tube ends cut with other common angles. From the latter it is significant that the dynamic pressure value is definitely affected by the shape of the body surrounding the opening except for the position where the plane of the pressure opening is turned square with the wind. This dimensional sensitivity includes not only the body values in the vicinity of the opening, but also the value of such dimensions as h and d of the related support structure.

In Fig. 7 the pressure hole is in the wall of a cylindrical tube, and data are plotted for the C_2, ψ relation for a variety of Mach numbers. It is significant that for $\psi = 0$, the value of C_2 will increasingly exceed unity as the Mach number grows. Fortunately, this excess is negligible (a small fraction of 1 per cent) for speeds less than 100 fps (data not shown).

In Fig. 8, the pressure hole is in the surface of a sphere and the data are plotted for the C_2, ψ relation for two values of the Reynolds number. The data demonstrate that the positive dynamic pressures at low values of ψ are unaffected by the viscous properties of the air, but an increasing sensitivity occurs with the larger ψ values. The latter flow "separation" effect is an unstable influence and is dependent also on the inherent turbulence of the stream and the body roughness. Other tests [3] on cylinders and spheres have also shown that the viscous effects will become influential even for the low ψ values if the Reynolds number based on the cylinder or sphere diameter has a value less than about 100. These effects may tend to increase C_2 as much as four or five times for extremely small Reynolds number values but, in general, have negligible influence for practical velocities and sizes of tubes.

With the foregoing pressure tube generalities in mind, we may proceed to examine the various tube forms which have been developed.

1. The Pitot Tube

The Pitot tube, which is the oldest and commonest of these devices, consists of a simple bent tube with one end facing the wind and the other connected to an external pressure meter which can serve to interpret accurately the total pressure p_T represented by the foregoing equations. When manually rotated or equipped with bearings and weather vane steering to keep it within $\pm 5^\circ$ of the true direction of a nonturbulent wind, the Pitot tube constitutes a very simple physical device; it is, furthermore, an anemometer of such fundamental soundness of principle that calibration is quite unnecessary for a wide variety of physical conditions, since C_2 will be unity. This value will not hold, however, for turbulent winds since these, in effect, are constituted by continually and rapidly changing values for both V and ψ. The mechanism of this concurrent action is rather complex and results in a pressure indication somewhat higher than that which should exist for the mean velocity of an equivalent steady wind. This excess may amount to as much as 2 per cent for highly turbulent flows, but is usually much smaller.

Since the Pitot tube normally measures the total pressure head, any determination of the velocity must include a measurement and subtraction of the coexisting static pressure p_o. It is this latter measurement which usually involves the principal errors in a pressure tube velocity measurement because it is difficult to insert an instrument into a flow to measure this value without creating dynamic pressures which tend to obscure it.

This problem has been quite thoroughly studied with the end result of producing the Pitot-static tube, which is a physical arrangement in which a single housing tube carries two pressure taps in close proximity. The Prandtl type of Pitot-static tube [4], shown in Fig. 9, is quite typical of this form of instrument and consists of a total head opening at the end of the tube and a manifolded ring of pressure holes around the cylindrical part of the tube. The latter holes have been positioned and formed to measure static pressure as nearly as possible. The differential pressure between the single opening and the manifolded holes leads to a composite $(C_2)_c$ value of virtually unity for the arrangement. It is quite insensitive to direction for $\psi = \pm 15^\circ$.

The Pitot-static tube, like the total head tube, shows sensitivity to turbulent flows by registering extraneous pressures from both sets of holes. The net result is that the $(C_2)_c$ value may be as much as 4 per cent higher for turbulent flows to compensate for the higher secondary pressure values.

The obvious merits of the Pitot tube have made it one of the most useful tools in fluid velocity investigations, particularly where the velocity is sufficiently high to produce measurable pressures. This has been especially true in the field of aeronautical research with its associated high velocities, but has led to virtually no direct use in the field of meteorology with its much lower velocities. Its principal disadvantages as related to the current study are two-fold. The first of these is concerned with the difficulty of attempting to make accurate field measurements of the very small pressure values generated, particularly if the values fluctuate rapidly. The second is concerned with keeping the tube in approximate alignment with the wind when the wind direction varies widely and rapidly. This alignment is usually achieved using the wind's own force on steering-wind-vane surfaces. This force is small for low winds and requires a large vane area, low angular inertia, and low friction bearings if good alignment response is to be achieved.

In an effort to overcome the first of these disadvantages, considerable research has been directed toward increasing the basic pressure difference or, in effect, achieving a higher $(C_2)_c$ value. A survey of these potentialities indicates that little can be done to increase the total pressure p_T, but the trends evidenced in Figs. 6, 7, and 8, indicate that selected placement of the usual low-pressure tap can do a great deal to produce a pressure modification which takes advantage of the available negative dynamic pressures and thus produces an elevated $(C_2)_c$ value. A quite common way of utilizing this principle consists of mounting the low-pressure tap in a position equivalent to $\psi = 90^\circ$ or $\psi = 180^\circ$ in the support strut. The resulting $(C_2)_c$ values are in the neighborhood of 1.6 for 90°, and 1.1 to 1.6 for 180°. The favorable increases may be magnified even further if the low-pressure tap is placed in a venturi-like housing as shown in Fig. 10. The $(C_2)_c$ value in such a case reaches three to five with suitable proportioning. A further increase to eight or nine can be accomplished if a second venturi is fitted within the first, so that the exit of the inner nozzle lies at the throat of the outer nozzle.

Unfortunately, these very favorable pressure magnitudes are produced by body forms which are subject to unstable flow separation effects and a sensitivity to variation in the Reynolds number or the ψ-angle. They are, accordingly, unstable in the $(C_2)_c$ value unless carefully calibrated and corrected for ambient conditions. A much more stable form of this venturi type has been developed [2] by replacing the downstream conical diffuser with an abrupt expansion. The resulting form has a Reynolds number stability, but the $(C_2)_c$ value has dropped to about 1.6.

The net conclusions of this survey would indicate that the $(C_2)_c$ value or output pressure may be increased above unity, but probably not above 1.5 to 2.0 without incurring possible sources of error.

2. The Dines Anemometer

The Dines pressure tube is a special version of the Pitot tube modified to adapt it to permanent meteorological stations. It utilizes the total positive pressure created by a tube facing the wind and enhances the measurement of the low-pressure value by placing the pressure tap in a negative dynamic region. The Dines instrument, which was developed nearly 60 years ago, is commonly employed by the British Meteorological Office and is shown in Fig. 11.

In the figure, A is the pressure opening, which is free to rotate about support shaft M on ball bearing C under the steering action of a large wind vane. The positive dynamic pressure is transmitted to the pressure meter through pipe F. The negative pressure is created and tapped off in region G by 96 small holes arranged around the periphery of a stationary tube in four staggered rows. Despite the fact that many of the 96 holes will be under positive pressure, the bulk of them (see Fig. 7) will be in a negative region and will yield a negative average which is transmitted to the pressure meter through pipe J. The remainder of the assembly provides support, housing, and seals for the pressure lines.

The value of $(C_2)_{c_2}$ for the Dines instrument is 1.49 and yields the equation $\Delta p = 0.00034\ V^2$ in which Δp is inches of water and V is feet per second for standard air conditions.

The Dines sensory head is in practice usually connected to a sensitive liquid manometer for precision laboratory work, a recording liquid float manometer for permanent weather stations, or a sensitive metallic diaphragm manometer for portable field use.

Despite a substantial pressure multiplication in the Dines instrument, it still possesses, for the current study, the same inherent disadvantages as the Pitot tube; that is, the pressure value is still very small and mechanical rotation is required. The standard weather station unit is not considered effective below about 6 fps.

3. The Multiple Pressure Tube Anemometer

The second disadvantage of the Pitot devices, the problem of mechanical rotation, has also been subjected to considerable investigation in the past. The two products of this investigation are stationary forms of tubes with very little sensitivity to wind angle for use in measuring the wind velocity, and forms which possess marked sensitivity to wind angle for measuring the wind direction. The velocity-measuring types have usually employed body forms which attempt to flatten and widen the zero slope regions of a pressure curve such as Fig. 8, while the direction-measuring types utilize the pressure values from the steeply sloped, nearly linear portion of such a curve.

A spherical body form [6] incorporating both of these systems is shown in Fig. 12. In this body, the paired H-B or D-G pressure taps serve to measure the directional wind alignment in their respective planes while the venturi-housed tap yields the positive velocity pressure in a manner similar to that of the simpler Kiel tube, commonly employed in aerodynamic testing. The average of the 164 holes in the sphere afterbody yields the enhanced negative dynamic pressure. The net result of the pressure-tap combination is a stationary instrument capable of accurately measuring both the wind direction and velocity within an angular range of about $\psi = \pm 45^\circ$, or a quadrant of the full wind circle. While this design accomplishment gives a considerably advanced aerodynamic research tool, it still falls far short of providing the 360° of coverage necessary to a meteorological field instrument. The possibility does exist, however, of combining the equivalent of four such units with a pressure transmission system which will select the single unit which is the best measure of the wind action.

A recent attempt to develop a stationary type with a full 360° of coverage is described by Goudy and Colvin [7] and resulted in the general assembly shown in Fig. 13. In this unit, the sensory element exposed to the wind is the small horizontal disk shown at the top of the figure. This disk has four small pressure holes disposed at 90° around the thin outer edge. The holes are 180° apart, and are paired and connected to transmit the differential pressures to two diaphragm pressure units. The mechanical motion of the diaphragms is converted to electrical signals with eventual dial readings as shown. The original paper is devoted principally to a discussion of the theory of the pressure values. It offers no experimental evidence other than to state that the device worked with a practical accuracy above 10 mph, but was adversely affected at low speed. The adverse effects with changing speed appear to be some inherent sensitivity of the body form to wind turbulence or viscosity. The disk geometry also seems to provide some sensitivity to the existence of vertical components in the wind, a condition which is variably present in most winds, particularly if they are turbulent. The time response of the instrument would be judged as slow in view of the substantial size of the diaphragm units required to produce the necessary actuating force at low velocities. While this instrument has a very desirable objective, the available proof of success does not seem to warrant further exploitation in the interest of the current study.

4. Pressure Meters

It has been previously indicated that one of the prime disadvantages of all low-velocity pressure tube devices is the difficulty encountered in accurately measuring the tiny pressures which are generated. A review of the nature of such pressure-measuring devices is therefore in order in the interest of clarifying this limitation.

The most fundamental and common means of measuring low pressures is by application of the unknown pressure as a dynamic balancing force against the static gravitational load represented by a liquid column where the balance force of such a column can be accurately evaluated by measuring its height and density. While the density of such a column is readily measured with accuracy, the determination of the column height presents difficulties when the physical length is of very small magnitude. Numerous micrometer mechanisms and optical systems (for example, see [8]) have been developed into micromanometers and in some cases have achieved extremely small measurements. However, from their very nature these devices are not suited to the measurement of rapidly changing pressure values, nor is it practical to operate and maintain their sensitive elements under rough handling conditions in the field.

The liquid float manometer used in the recorder of the standard Dines pressure tube anemometer is an ingenious modification of the liquid column manometer. It achieves a force substantial for recording purposes by use of a large float which in turn requires an application of a considerable liquid mass. Where the wind is of fair velocity and a steady nature, this float recorder is very effective; but under rapidly varying or gust conditions, the fluid friction and mass inertia of the liquid columns cause a material lag in the float response and result in erroneous records. The error in this case increases with the frequency of the wind's gustiness. Sherlock and Stout [9] made comparative measures of anemometer response times and concluded that the Dines recorder required 10 sec or more for a full response.

Aside from the liquid-column type of pressure gage, the commonest elements employed for low pressures are elastic deformation devices, notably metallic diaphragms and metallic bellows. These elements are commonly employed in altimeters and velocity meters for aircraft, and in the nonliquid or aneroid barometer. With a suitable diameter and thinness, the diaphragm type can be made to produce mechanical motion under very low pressure differentials. The allowable motion and load range is, however, very small if the motion is to be confined to the linear elastic range, and permanent set or damage may readily occur with only moderate overloads. Corrugation of the diaphragm will considerably multiply the motion range and decrease the resistance. The motion range may be further increased by adding successive stages or laminations, as shown in Fig. 14. However, the latter approach is quite limited, as the laminated stack evidences a lateral instability and a sensitivity to external vibrations. As a result of these limits, the best values achieved with the ultra-sensitive, direct reading, master standard aneroid manometer of one of the better American makers attain an accuracy of 1.0 millibar or about 0.029 in. of mercury. While this value is seemingly very small, it is actually about 17 times the positive dynamic pressure produced by a wind of only 10 fps. In addition, the meter is relatively fragile, and if subjected to a large range of pressures and rapid fluctuations it would probably show considerable drift with time because of hysteresis effects in the internal structure of the metal. Values as low as 0.10 millibar or 0.0029 in. of mercury can be achieved, but they are complicated by excessive temperature and hysteresis effects and the need for frequent calibrations.

Efforts have been made to relieve the diaphragm of the frictional loading of the direct-reading gearing and pointer and thus improve the accuracy and sensitivity of diaphragm devices. One such unit, described by Diebler and Cordero [10], consisted of a corrugated thin diaphragm with two wire coils positioned at the center and on one side of the disk. Any deflection of the disk due to pressurizing produced a mutual inductance change in the coils with a resulting secondary voltage which was a function of the deflection. The voltage was amplified in an electronic circuit and read on a d-c microammeter. The electronic system detected motions of less than 0.00005 in. and was suited to a full-scale range of 0.0005 in. for the most sensitive values. The mutual inductance signal was much smaller than that which might be achieved with a capacitance system, but secondary problems having to do with disk alignment and remote transmission problems through cables favored the former system. The mutual inductance system was also preferred to magnetic core types of devices, which exerted a reactive force on the diaphragm and thus tended to obscure the pressure signal; or to resistance-strain-gage devices, which showed a considerable time shift with secondary hysteresis effects.

With a 2.87-in. diameter, 0.001-in. thick, brass disk, the pressure sensitivity of the assembly was 0.000004 in. of mercury or one part in 500 for a full-scale range of 0.002 in. of mercury. This amounted to a motion of 0.00002 in. per micron of mercury pressure (1 micron = 0.00004 in.). The range of the full scale could be readily adjusted with the amplifier to a maximum of 0.004 in. of mercury (0.0545 in. of water) and a minimum of one-tenth of this.

The unit was essentially a laboratory instrument without full compensation for field temperature conditions and other adverse ambient effects. It does, however, appear to approximate the pressure range coverage for the winds of interest in this study, notably the range of 1 to 30 fps. [This corresponds to a pressure range of $(30/1)^2$ or 900, and pressure values from 0.00034 in. of water to 0.305 in. of water for a Dines type of tube with a $(C_2)_c$ value of 1.5.]

A somewhat analogous design of pressure device is described by Day [11] in which the diaphragm served as part of the pressure envelope of an electronic tube. The metallic disk in this case was sealed to the tube glass, and the interior was evacuated in the usual manner. Motion of the diaphragm under applied external pressure mechanically varied the interelectrode spacing, which was very sensitive to motion. The diaphragm proved sensitive to temperature but was effectively compensated by Thermistors in the circuit. Some hysteresis effects were evident. The high initial load imposed on the diaphragm by the evacuation is believed to reduce the sensitivity of the unit materially although no limiting data were offered.

The use of crystals and other materials with inherent pressure-electric properties was not investigated. While these materials are capable of differentially measuring very rapid pressure fluctuations, they are not generally considered stable enough for accurate absolute measurement of small pressures.

5. Summary

A review of the foregoing material on pressure tube anemometers seems to indicate that certain potentialities do exist for development of this type of meter for the current problem, but numerous stumbling blocks must still be cleared.

C. Force Devices

1. Stationary Devices

a. The Pendulum, Alnor, and Bridled Cup Anemometers

The pendulum anemometer consists of a plate directly exposed to the pressure of the wind. It is so mounted that it rotates to face the wind while remaining free to swing about a horizontal axis above the center of gravity but in the plane of the plate. The plate swings upward to permit its weight to balance the wind force. An attached arc is calibrated in units of wind velocity. The device is undesirable as an accurate velocity instrument because of its unstable flutter in turbulent winds, limited velocity range, nonlinear scale, and confusing sensitivity to the vertical wind component. While the instrument is simple and inexpensive, current interest is slight and chiefly academic. Described by R. Hook in 1667, it is notable as the oldest of mechanical anemometers.

A modified portable version of this device is manufactured today by the Illinois Testing Laboratories of Chicago, Illinois. This instrument, known as the "Alnor Velometer" (not to be confused with the "Alnor Thermo Anemometer" described elsewhere), consists of a small box containing a curved duct which is largely obstructed by a pivot-mounted, lightweight, flat plate with a restoring force supplied by a hairspring. The swing of the spring-loaded flat plate, which is due to a stream of air entering the box through an orifice, has been calibrated on a graduated arc. With proper selection of orifice size the instrument is reputed to read velocities from 20 to 24,000 fpm with an accuracy of 3 per cent of full scale. The instrument, which has been developed for use in industrial air-ventilating studies, is not considered adaptable to the present problem.

The bridled cup anemometer is essentially the same as the pendulum and Alnor units in that a force is developed by the dynamic wind on an exposed area. The force displaces the area in an amount proportional to the wind speed. In this case, the exposed area is a wheel with a large number of wind cups attached to its periphery. The wheel is attached to a vertical shaft so that the unbalanced wind force on the cups causes an angular displacement against restoring springs. The calibrated relation between wind speed and displacement is remotely read through a Selsyn electrical transmission and has been observed as unsuitable for velocities below about 10 fps.

The wheeled cup is independent of the horizontal direction of wind exposure, but is a relatively complex, inefficient, and bulky means of achieving an effective force value. The mass inertia of the wheel is large, and response to velocity fluctuations oftener than about 5 times per min has been observed as erroneous. The device is believed to be obsolete in American manufacture and is considered poorly adapted to the needs of the current problem.

b. The Filament Flowmeter

A very sensitive velocity meter apparently has been achieved by optically observing the deflection of a cantilevered, very fine, quartz fiber filament placed in the flow stream. A unit referred to in [12] obtained satisfactory velocity measurements to the order of 1 cm per sec by such means, but only by controlling temperature values to stabilize the viscous and temperature-sensitive flow conditions.

Lee and Silverman [13], as well as Specht and Brubach [14], have made studies with a very fine wire stretched across the flow stream in a tube. The deflection of the wire was optically magnified and photographically recorded as a measure of the air velocity. With proper control the instrument may be made sensitive to very low wind values.

While the above methods appear to offer intriguing possibilities for extreme low-velocity measurements, their sensitivity to secondary natural forces caused by ambient conditions is believed to offer serious difficulties in applying the principles to a remotely located, rugged, field instrument.

c. The Normal Pressure Plate Anemometer (Sherlock and Stout)

This device is fundamentally similar to the pendulum, Alnor, and bridled cup anemometers in that the displacement of a spring-loaded pressure plate serves as a calibrated index of the wind velocity. It differs from the others principally in that the exposed area (and force) is large and remains normal to the wind, and the area displacement is small and is directly and sensitively converted to an electric signal. Sherlock and Stout [9] developed and employed a number of these units in recording the structure of storm winds. Their final design is shown in Fig. 15 and consists of the 8- by 9-in. pressure plate A which is kept normal to the horizontal wind by the weather vane C causing rotation about the ball bearing and slip rings at the top of the supporting mast. The pressure plate is backed by a streamlined housing B which protects the sensory electrical elements. The aluminum pressure plate is attached at its lower edge to the support frame through a flexure hinge which eliminates play but provides only minor resistance to small angular displacements. The plate pressure is conveyed through a push rod to a stiff restoring spring D. Armature E, which is attached to spring D, varies the electrical impedance of the coil F as the air gap or proximity of E varies with the wind pressure. The electrical value is applied to an a-c bridge circuit so that the resulting out-of-balance current is an index of the velocity. Recordings of the velocity were made with a photo paper oscillograph.

This instrument was designed for the purpose of measuring storm gusts with velocities between 30 and 75 mph and proved to have a response time of about 1/8 sec and a natural frequency of 115 cps. The maximum plate movement was about 0.005 inches. A wind tunnel calibration for the instrument is shown in Fig. 16 and typical recordings are shown in Fig. 17. A large number of these recordings has been analyzed and integrated to give plottings of the type shown in Fig. 4. They constitute what are probably the finest storm wind records that have ever been made.

It is unfortunate that the basic design of this excellent instrument was intended only for higher velocity winds and is inadequate to cope with the small forces represented by the slower winds. It is apparent from the curve of Fig. 16 and the previously cited drag force equation that the working forces available at lower velocities are extremely small and would necessitate radical design changes if adequate accuracy and response were to be expected. Sherlock and Stout gave a number of valuable suggestions for design improvements of this nature and it is possible that these, together with modern lightweight materials, might produce a practical design for lower velocities. The drag sphere, which is separately described later, is in essence a low-velocity unit designed along lines similar to this.

d. The Drag Sphere

As previously pointed out, the use of the dynamic pressure generated by a wind to measure its velocity is attended with considerable difficulty in the low-velocity range because of the very small forces that are available for measurement. An examination of the drag force equation $D = C_D A \rho(V^2/2)$, does, however, indicate that for a given wind the force D can be raised to any desired value by merely increasing the magnitude of the controllable variable A which is the exposed area. This should, however, be done in such a manner that only the effective dynamic force is multiplied and obscuring secondary forces are minimized.

A practical instrument design would, therefore, attempt to make the area A only sufficiently large to produce a workable force D. It would also be desirable to dispose this area in a form insensitive to wind direction. Thus, rotation of the sensory head might be eliminated and the head made stationary. Disposition of the area as a sphere would appear to answer the latter requirement.

The next phase of such a design calls for the selection of a force-displacement unit which can be readily attached to the sphere as a convenient measure of the force which is, in turn, a function of the air speed. In a design analysis proceeding along these lines at the St. Anthony Falls Hydraulic Laboratory, a design was evolved that consisted of a drag sphere unit mounted on top of a vertical flexure rod which was anchored at its base. If the cantilevered rod is circular in section, the magnitude of its flexural displacement will be a measure of the speed of a horizontal wind and the displacement will be in the direction of the wind.

During the course of this design study the general search of the literature disclosed that similar rationalizing had led to workable designs of spherical drag units by Vershinski [15], who employed a very similar device for measuring turbulence pulsations in flowing water; and by Knapp [16], who used a related form for detecting the direction and magnitude of water currents near the bottom of a harbor.

Vershinski employed a square flexure rod and attached resistance-strain gages to the rod faces near the anchored end. Opposing pairs of strain gages were fed into an a-c electrical bridge. These were followed by an amplifier, phase-sensitive detector, filter, and deflector system of a cathode-ray tube. Deformation of the flexure rod was evidenced by the movement of the ray on the screen of the tube. With two sets of resistances arranged at 90° on the flexure rod and fed to the two mutually perpendicular deflector systems of the oscillographic tube, the direction and magnitude of motion of the ray displacement on the screen proved to be in accord with the direction and magnitude of a hydrodynamic force applied to the sphere in a plane normal to the rod. While no figures were given, the instrument apparently had a response time sufficient to record short water wave patterns.

Knapp employed a sphere attached to the lower end of a vertical rod which was attached to a plate at its top. This plate was, in turn, restrained by three strain gage cells whose combined electrical output was proportional to the horizontal hydrodynamic load applied to the sphere independent of the direction of this applied force. A 360° wire-wound potentiometer was concentric with the rod so that a rigid disk attached to the rod and fitted with a special peripheral ring contact would make an electrical point contact on the potentiometer for a very slight rod displacement. Because the point of contact was a function of the direction of the hydrodynamic force, the potentiometer output was a function and measure of the force direction. The general arrangement of this mechanism is shown in the diagrammatic sketch of Fig. 18.

In the St. Anthony Falls sphere design, which is shown schematically in Fig. 19, the drag area consisted of a 6-in. diameter sphere A spun from 0.025-in. aluminum and affixed through a plate B to the top of a vertical steel flexure rod C of 3/16-in. diameter. This rod was, in turn, rigidly attached to a steel base plate D. A rigid housing tube E protected the flexure rod and provided interior support to the electrical strain-measuring devices F. Thrust pin G conveyed the flexural displacement of rod C to measuring unit F. The two F-G assemblies were positioned within the sphere at 90° with respect to rod C. Flexural displacements of rod C were resolved into two strain components at the two measuring devices F and both the magnitude and direction of the applied force could be interpreted from the electrical output of the strain units.

In the pilot experimental unit constructed at St. Anthony Falls, the strain units F consisted of standard linear variable differential transformers as made by Schaevitz Engineering of Camden, New Jersey. These tiny transformers provided a very accurate and sensitive way of electrically measuring a mechanical motion by sensing the displacement of a core in the magnetic field of a transformer. The units had a motion range of ±0.04 in. and were designed to operate at 3 to 10 volts for frequencies between 400 and 20,000 cps. The average accuracy was given as 0.0004 in. with a sensitivity of (0.002 volt/0.001 in.) per volt input. The transformers were preferred to resistance-strain gages because of their relatively better ruggedness, flexibility of application, stability, and insensitivity to many ambient variables.

The 6-in. sphere diameter was selected to produce flows with a Reynolds number lying in the flattened region between 10^3 and 2×10^5 for velocities between 1 and 50 fps, as shown in Fig. 20. This range is somewhat variable in drag characteristics but gives a Reynolds value beyond the low-temperature-sensitive values and short of the critical separation range. The flexure rod dimensions of 3/16 in. and 12 in. were selected to produce drag-force displacements matching the range of the transformer units.

Pilot studies of this unit in a wind tunnel with steady velocities produced the calibration curve shown in Fig. 21. The curve was obtained with the wind aligned with one of the transformer elements. The pilot tests indicated that some expansion of the low-velocity range would be desirable, together with some form of vibration damping. This unit is considered a potentially very workable magnitude and direction anemometer combined.

2. Rotational Devices

a. The Rotational Cup Anemometer

The cup anemometer consists of a number of cups affixed to the ends of light horizontal radial arms which are attached in turn to a hub which rotates on a vertical shaft. The cup is formed to offer a greater drag coefficient or force (see p. 13) when the vertical open face of the cup is presented to the wind. In a complete cup wheel exposed to a wind this force system produces a torque which initiates rotation and accelerates the wheel to some terminal rate of revolution representing a balance of dynamic fluid forces and mechanical friction for the given wind condition. This rate will be some function of the wind speed, but it is independent of the horizontal direction of the wind. The nature of the wind flow pattern around the moving cups is too complex for analysis without resort to physical tests. If the wheel is exposed to a gusty wind, the relation between dynamic wind forces and rotor inertia is such that the wheel will tend to register more revolutions than it should for the average of the variable velocity.

Robinson, who developed the first form of this instrument in 1846, considered that the relation between wind speed and rotary speed was established by a quantity known as the cup factor, which is defined by the ratio of the wind speed to centerline cup speed. Robinson erroneously assumed that this ratio had a fixed value of 3 regardless of the cup diameter and arm length. It was later shown that this value varied between 2 and 3 for different designs and was not constant for a given design but varied slightly with velocity. A low cup factor would give a desirably high number of cup revolutions in a slow wind, but a high cup factor would tend to reduce the wear on the mechanical parts.

A complete cup anemometer may be considered to consist of (1) the driving cups, (2) the supporting rotor for the cups, (3) the anti-friction bearing system which supports the rotor, and (4) the revolution-counting mechanism which indicates or records the rate of revolution.

The number of cups on the rotor was originally selected as four by Robinson and this number was adopted by the U. S. Weather Bureau in its early instruments. This design persisted until the 1920's when Patterson [18] made studies and tests on cup wheels with from two to six cups. He established that three cups gave a greater torque per unit weight and were less variable with shifts in the incident wind angle. These investigations led to the adoption of the three-cup unit by the American, Canadian, and British weather services in the mid 1920's.

The original smooth-edged hemispherical cups used by Robinson were shown by Marvin [19] and Dryden [20] in 1934 to be much more sensitive to variations in the turbulence level of the wind than cups with a beaded or rolled stiffening edge. As a result of these studies most cups today are provided with a beaded edge.

The shape of the cups (which were originally hemispherical) was shown by Sheppard [21] to yield a more linear relation between rotor speed and wind speed if the cup shape was changed to a conical form. This change in shape also materially reduced the over-registration in gusty winds. The conical cup is general today.

The size of the cup is largely dependent on the amount of energy required to overcome the rotor-bearing friction and actuate the counter mechanism. This size should, however, be no larger than necessary because inefficient form of the cups offers a considerable drag force on the structure which supports the anemometer. Modern units with mechanical counters, mechanical contactors, or electrical generators usually employ cups of about 5-in. diameter in order to get adequate power. These units must also be built more heavily and thus suffer considerable inertia effects with a high starting speed and slow response. On the other hand, instruments built for sensitive research studies have their counting friction minimized and use small-sized, lightweight cups. Most of the modern instruments of this type follow a design which was predicted by Spilhaus [22] on the basis of dimensional analysis in 1934, and established through analysis and test by Sheppard [21] in 1940. These units employ three beaded conical cups of about 2-1/8-in. diameter on a cup circle of about 2-3/4-in. radius and are fabricated to give minimum mass per unit area. They are not generally intended to operate in winds above 90 fps.

The cups have been made of a variety of materials, with the older units generally employing noncorrosive copper or its alloys. This material has the disadvantage of contributing to inertia effects through its substantial weight and of contributing to errors if it permanently distorts under the stresses induced by high centrifugal forces occurring with high wind speeds. Since it is generally recognized that the sensitivity of a cup anemometer is proportional to the ratio of active surface to weight of the sensitive element, lightweight alloys are used with the sensitive research type of low-speed instrument. Monel metal has been employed with a unit rated up to 200 mph. One unit has employed plastic cups as a substitute for copper with a marked reduction in inertia and over-registration in gusty winds. The plastic also suffered only temporary deformation in high winds.

Cup anemometers have sometimes exhibited a ringing sound [23] when running at certain critical speeds, with attendant peculiarities of the calibration curve. This vibration condition has been attributed to internal fabricating stresses due to welding, etc., and may be excited by the complete reversal of stress that occurs with each revolution of the rotor. Heat treating and aging of the rotor were found to improve these critical values.

The supporting rotor for the cups is in a form that will provide adequate cup support, low and stable wind resistance, and a practical mode of fabrication. The length of the arms supporting the cups was investigated by Spilhaus and Sheppard with the result that most instruments today have a cup wheel diameter (center-to-center of cups) which is about 2.5 to 4 times the cup diameter. The smaller ratios appear more constant and desirable in their performance.

The size of the cup wheel is also of considerable significance with regard to the size of turbulence eddy to which the anemometer will respond. Fergusson [24] in tests of cup anemometers in varying winds concluded that the number of rotations necessary for an instrument to acquire a new velocity is fairly constant for all wind velocities and instrument sizes, but varies with the mass inertia. For small instruments approximately 3.5 rotations were required to acquire the new velocity. Since the cup factor for these wheels was around 2.5 to 3 it would appear that a new wind value would have to persist for a travel length of some 20 to 30 wheel diameters before the wheel would acquire the new velocity. Kampe de Feriet [25] was of the opinion that a value of 5 to 10 fitted the conditions of his test. On this basis the time response of a cup anemometer to variable winds would appear rather slow.

The relation between the cup diameter and arm length has some influence on the tendency of a cup anemometer to over-register in a gusty wind, but Scrase and Sheppard [26] were of the opinion that this factor was of secondary importance as compared to the relative mass inertia of the wheel.

The bearings which support the cup rotor are intended to minimize the frictional drag of rotation in a manner consistent with the speed range, handling, and servicing problems of the installation; and the resulting instrument sensitivity and calibration stability are largely dependent on this friction minimum. In general the bearings consist of a thrust bearing and either one or two radial bearings to maintain alignment of the rotor spindle. The radial and thrust function may be combined in a single bearing in some cases.

The simplest, most rugged, and cheapest bearings are usually metallic sleeve bearings for radial loads, and hardened cone and cup forms for the thrust bearing. While these forms are quite practical, they have considerable inherent friction and result in a considerable variation in static and running friction with high starting speeds and influence on the calibration linearity. The materials of such bearings must be carefully selected. Ives [23] describes tests of units with bronze sleeve bearings which were fitted to steel shafts at 60° F. These were found to be excessively loose at 120° F and to seize at 20° F. Use of steel sleeves stabilized the fit but gave slightly greater friction. The material must also be examined with regard to its sensitivity to corrosion by rain and salty coastal air or damage by abrasive dusts. Attempts are made to provide bearing seals, but these cannot be 100 per cent effective without contributing frictional drag. A source of heat in the bearing housing has been found to arrest corrosion and stabilize friction in some installations.

Sheppard [21] tested a small sensitive anemometer with ball bearings and found it to yield a lower torque (6.01×10^{-6} in.-lb) than an older form of jewel bearing (1.81×10^{-5} in.-lb). They also gave a more nearly equal static and dynamic friction and were less critical of alignment than older bearings. Modern American instruments by Beckman and Whitley, Bendix-Friez, and The Instrument Corporation use ball bearings.

Latimer [27] describes a unit made by Lane-Wells employing a jewelled thrust bearing with bronze radial sleeve and a starting velocity of 30 to 40 fpm. Calibration of this unit showed a turning rate of about 14 rpm per fps. C. F. Casella and Company [28] describe a unit with a sapphire and hardened steel bearing with very low torque (1.06×10^{-6} in.-lb) and extremely small difference between starting and running friction. These features permit an even rotation to as low as 0.25 fps of wind speed.

The nature and use of lubricants in the bearings, together with the problems of cleaning, are other important considerations in the anemometer bearing design.

A revolution-counting or rate-signaling device is an essential part of any cup anemometer, and a wide variety of mechanisms has been developed to serve this function. In general these mechanisms have served as either instantaneous indicators or chart recorders and involve either mechanical counting devices or a mechanical-electrical conversion to permit remote transmission and use of electrical indicator or recording instruments.

The older and simpler devices usually consisted of a purely mechanical counter driven by the cup rotor. This system had the disadvantage of involving considerable mechanical friction and a consequent erratic performance at low speeds together with high starting speed. Remote transmission of the signal to a convenient position was not readily possible. Sheppard [21] greatly increased the sensitivity by incorporating a spring-driven watch works whose escapement was actuated but not driven by the cup rotors with the result that the rotor experienced only a very small drag. This unit responded to velocities of less than 1 fps but had only a limited operating cycle because of the spring-driven motor mechanism.

Many standard units have employed rotors with attached electric generators which produce an output voltage which actuates a direct-reading voltmeter serving as the speed indicator. These units are simple and effective in reading mean values, but the added rotor inertia damps the response to gust variations and increases the starting wind speed.

Latimer [27] describes a device employing a rotor with two knives which pass through two mercury-filled pots to complete an electrical switching circuit. This unit possessed simplicity, low frictional resistance to motion, and low voltage and current. It had no vacuum tubes or amplifiers. He also describes another device employing a magnet attached to the rotor and tripping an external switching circuit. A slight magnetic drag is involved in this operation.

Corwin [29] attached a disc to the rotor. The disc contained punched holes whose passage near two fixed electrical coils created a pulse serving as the signal. The system involved no drag on the rotor but required an amplifying electronic circuit. A unit of this type has been made by Gurley and worked to a minimum of about 1 mph.

A signal system with minimum frictional drag is represented by devices in which the rotor interrupts a beam of light directed at a photoelectric cell. Deacon [30] describes such a unit as employed in British research, and West [31] describes a commercial unit made by Beckman and Whitley in this country.

Ives [32] describes an electrical circuit which integrates the output of several meters to produce an average velocity for an area of coverage. The circuit employs a condenser discharge unit.

Cup anemometers are generally intended to be attached to a rigid type of spar or mast mounting, but in special cases they have been attached to kites in a free suspension system. Observations of the unit under such conditions indicated that the anemometer axis inclined from 0° to 20°. Fergusson [24], in an attempt to determine the influence of such inclination, made suitable tests and concluded that angles up to 30° could be sustained without significant effect unless the anemometer was very small or heavy.

The literature does not expand on the influence of the ambient variables of temperature, density, and viscosity upon the performance of the cup anemometer. However, since it is a dynamic pressure instrument it must respond to the previously mentioned equation

$$p = \rho \frac{V^2}{2}$$

in which the air density ρ is directly proportional to the atmospheric pressure and inversely proportional to the absolute temperature. The error will be insignificant for nominal changes of pressure and temperature from the calibration conditions, but for larger changes correction may be desirable.

The direct influence of viscosity and its dependence on temperature is not apparent, but it is not deemed too important if the beaded conical cup is employed to minimize the Reynolds number influence on flow separation conditions.

There is no evidence of a physical evaluation of the effect of rain on the registry of a cup anemometer, but Marvin [33] does conjecture on the probability of its influence. His conclusion is that the rain tends to cause a slight opposition to the normal rotation caused by the wind.

The literature indicates that the following individuals or firms may be contacted as a source of supply for quality cup anemometer units of modern design:

Beckman and Whitley, Inc.
985 San Carlos Avenue
San Carlos, California

C. F. Casella and Company, Ltd.
Regent House, Fitzroy Square
London, W. I., England

Friez Instrument Corporation
1400 Taylor Avenue
Baltimore, Maryland

Dr. Stewart Grinnell
Stanford University
Palo Alto, California

W. and L. E. Gurley
Troy, New York

The Instrument Corporation
4 North Central Avenue
Baltimore, Maryland

Lane-Wells Company
Los Angeles, California

Negretti and Zambra
122 Regent Street
London, W. I., England

In summary it may be said that the cup anemometer is a device capable of being built to measure wind speeds from about 1 to 50 fps with small error. Such a unit would be of practical use in field operations but would require considerable care in handling and protection from severe weather exposure.

It is capable of producing a variety of electrical signals for remote transmission and subsequent use. The instrument has a long development history, and established procurement sources are available. The instrument should preferably be rigidly mounted, but there is evidence that performance on a nonrigid or balloon mounting might be tolerable. The instrument has no ability to measure direction. Its time response is probably a matter of several seconds at low wind velocities.

b. The Vane, Windmill, and Propeller Anemometers

This type of anemometer is essentially a windmill consisting of blade areas arranged at the end of radial arms which are in turn attached at their inner ends to a hub which is free to rotate about a bearing spindle. In most cases the plane of the rotor is positioned perpendicular to the wind and the axis or spindle is horizontal and in line with the wind. The blades are positioned in such a way that the aerodynamic force of the wind causes the blades to rotate about the spindle and accelerate until a terminal or equilibrium speed is achieved which is just sufficient to overcome the friction. This terminal rotary speed is generally a linear function of the wind velocity. The inherent force - speed relations of this arrangement are such that the wheel rotates at a relatively high speed and the instrument is well suited to producing measurable readings at low wind velocities.

The so-called vane anemometer is one form of this type of device. It is a portable small-sized unit in which the vane rotor is usually shrouded with a cylindrical casing and is manually aligned to face the wind. The axis of the rotor is gear-connected to an attached dial indicator which shows the number of revolutions. If the revolution count is correlated with a stop watch measurement, the velocity of the wind may be inferred from a suitable calibration curve.

This instrument is intended for low-speed measurements in ventilating studies and is not housed or adapted for meteorological studies in the free air. For this reason it will be by-passed here in favor of its counterparts which are better adapted to field studies of the natural wind. However, it may be worth noting that Ower [34] gives a quite complete discussion of this instrument and that it is a standard production of a number of manufacturers.

The windmill type of device as used for field meteorological studies has been in use since the developments of Woltman in 1790 and Richard in 1887.

Richard's "cinemometre" consisted of six spoke arms with sails affixed to provide a screw action. Its pitch yielded one revolution for one meter of advancing wind. The device was provided with a steering vane and vertical bearing spindle which permitted self-orientation in the wind. It was very sensitive and responsive and has long served as a comparative standard for other wind research instruments although it is not sufficiently rugged to permit permanent all-weather installation.

The Dines "Helicoid" was a somewhat similar sensitive windmill. It carried only two rotor blades which were pitched to one revolution for each half meter of wind advance.

These devices were followed by an even more sensitive development by Fergusson [24] which variously employed two to six sails or blades made of balsa wood.

The following generalizations have been established by both theory and test for the windmill type of device:

1. The relation between wind speed and angular velocity is essentially linear if the friction is low. The angular velocity is relatively high as compared to cup wheels.

2. Friction exercises a significant effect only at low speeds.

3. For moderate to high speeds a good windmill will follow the mean velocity to within 1 or 2 per cent. The fastest winds for which this is true are fixed only by the ability of the blade structure to resist deformation.

4. The windmill blades run with the wind with only a very light steady aerodynamic load unless the mill is driving an indicator demanding considerable energy. As a result of this light loading, the blade structure may be relatively flimsy compared to the cup anemometer members which are subjected to high loads of a continuously reversible nature. The principal windmill blade stress is the result of the centrifugal forces accompanying the high rotary speed.

5. The windmill, unlike the cup anemometer, must be oriented in the wind with a vane or other device and thus requires additional bearings and a commutator to transmit the rotor count. These additional complexities are partially compensated for by the fact that the orienting mechanism provides an inherent direction indicator.

6. To provide a low starting speed and a sensitive response to gusty winds, the driving torque should be large relative to the friction. This in turn requires large blade areas disposed at a considerable radius arm with small weight and inertia.

7. Ambient variations of the air density through temperature or humidity changes have a negligible influence on the performance except when the velocity is very low.

8. The response of the meter to variations of wind direction is dependent on the inertia characteristics of the orienting vane system. If the inertia is high the rotor will tend to under-register with increasing yaw angles. Yaw angles less than 15° have relatively little effect.

9. Pulsations of the velocity tend to produce over-registrations of the rotor. These are rather small for nominal variations of velocity but increase rapidly with the amplitude of the variation.

10. Natural winds usually combine variations of direction and velocity so that the under- and over-registrations balance out fairly well for meters of low inertia.

11. Inclination of a windmill axis up to 10° with the horizontal produces an inappreciable change in the registration. Only slight effects are evident at the 20° angles that have been observed for kite-suspended instruments.

12. The inherent sensitivity of the mill-type design to aerodynamic forces also increases the sensitivity to extraneous forces caused by dirt, poor lubrication, precipitation, etc.

13. Response to changes in velocity were observed to require about 1 sec for Richard's cinemometre and about 1/6 sec for Fergusson's balsa mill.

The Bendix-Friez "Aerovane" unit shown in Fig. 22 [35, 36] is a recent modern commercial development combining the previous findings on windmill anemometers into a 3-bladed propeller-type device capable of being used at permanent meteorological stations to provide both full velocity and directional coverage.

The molded plastic propeller rotates either a self-synchronous motor-generator or a d-c magneto voltage generator, depending on the end signal desired. The generator unit is contained in a streamlined housing which serves also as the support for the lightweight, aerodynamically stable, responsive, directional vane. The vertical spindle also contains a self-synchronous motor for transmission of the direction signal. Both signals may be readily transmitted up to 1000 ft. The transmitter unit weighs about 10 lb.

This unit has been tested to show a starting speed varying from 1.8 to 3.0 fps and has been observed to measure natural winds to 140 fps and wind tunnel values to 300 fps. It is provided with moisture and dirt seals and has shown evidence of ability to withstand severe weather exposure. It is equipped with long-life silicone lubricant and sealed ball bearings.

The design appears to be a good balance of the separate inherent tendencies to over- and under-register for various abnormal conditions. The time response (63 per cent of equilibrium) was measured as requiring the passage of about 20 ft of wind. The mass per unit area of blade was fairly high but the concentration of weight near the hub led to a nominal moment of inertia.

In summary it appears that the windmill anemometer is capable of being designed as a quite sensitive and responsive wind meter. This sensitivity is, however, achieved at the expense of ruggedness, and those research units which demonstrate the desired properties have not as yet been developed into practical field units. The Aerovane, the only practical commercially available unit, is well designed and proven but has sacrificed the low-velocity zone of interest to achieve ruggedness. The design is inherently adaptable to the problem at hand but would require an extensive development program. The system is especially advantageous in that directional signals accompany the velocity magnitude. There also appears to be some possibility of making a workable unit for balloon suspensions.

D. References

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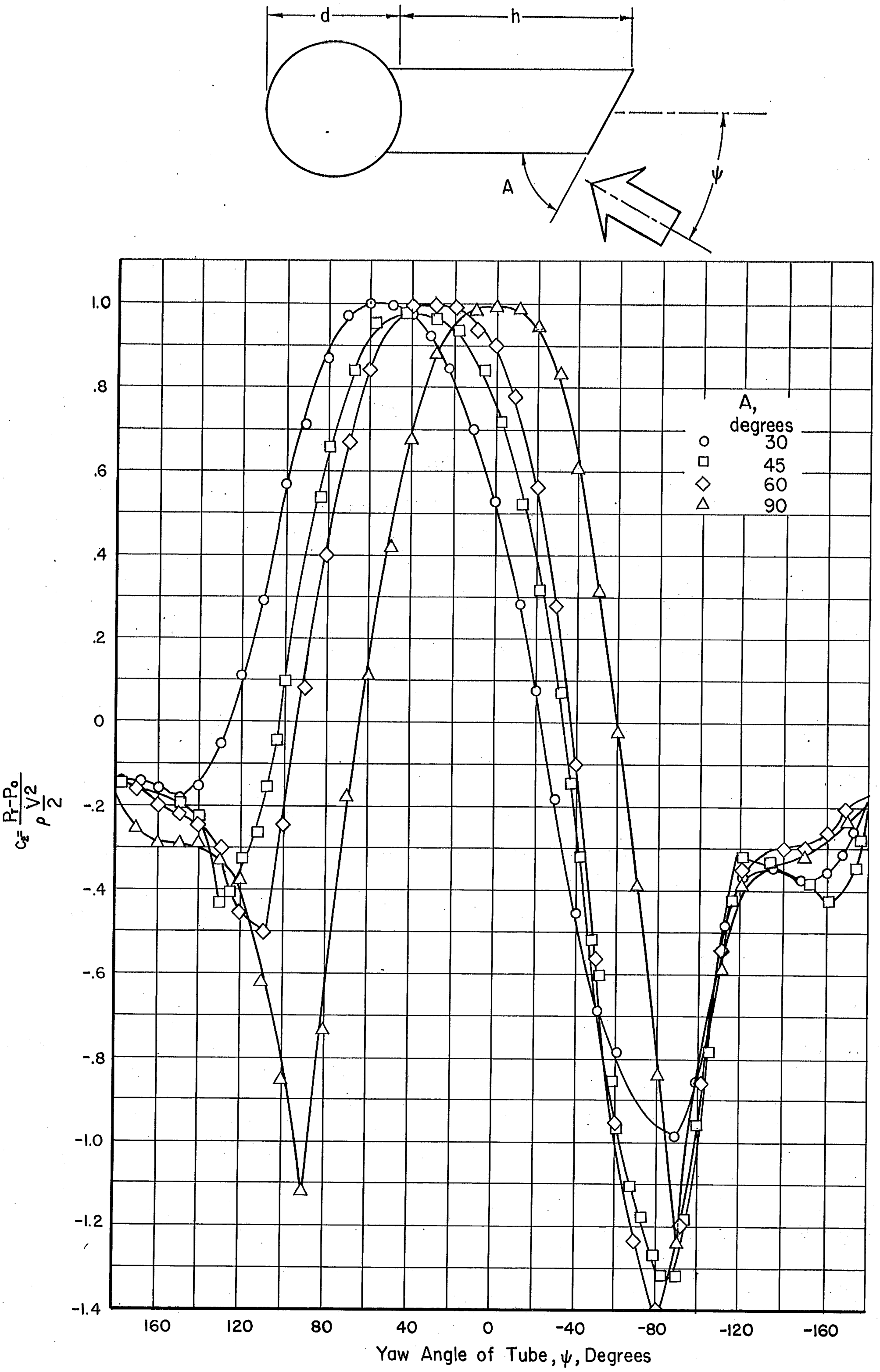

Fig. 6 - Variation of Pressure Tube Values with Angular Alignment of Wind for Four Different Tube Tip Shapes [1]

Air velocity 295 fps.

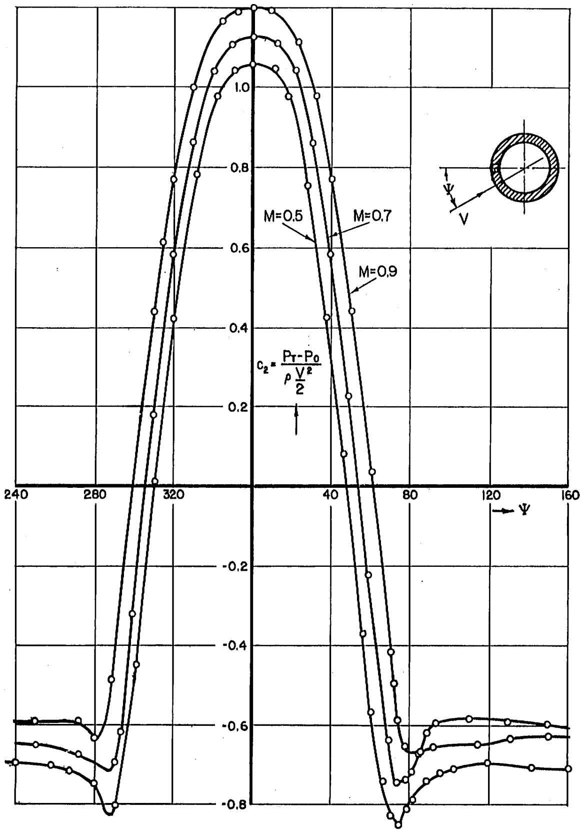

Fig. 7 - Variation of Cylinder Pressure Tube Values with Angular Wind Alignment for Three Values of the Mach Number [2]

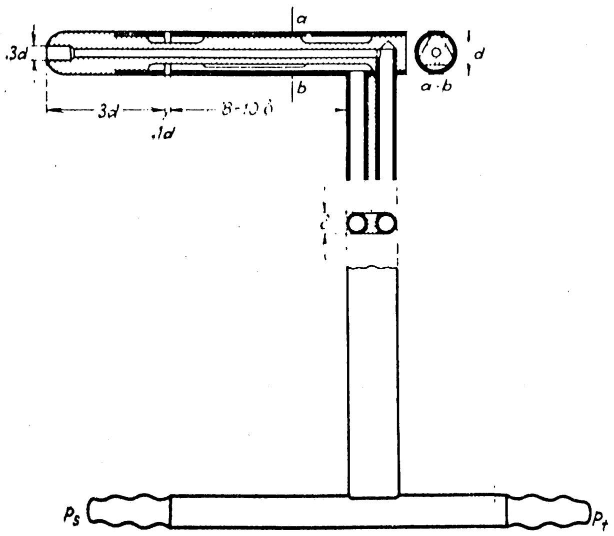

Fig. 9 - Prandtl-type Pitot-Static Tube [4]

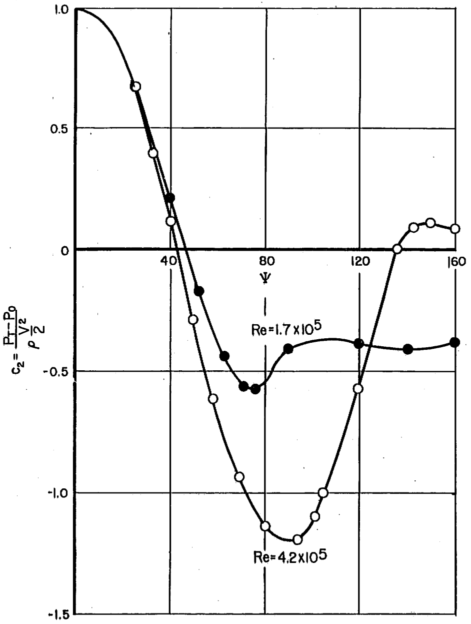

Fig. 8 - Variation of Sphere Pressure Values with Angular Wind Alignment for Two Values of the Reynolds Number [2]

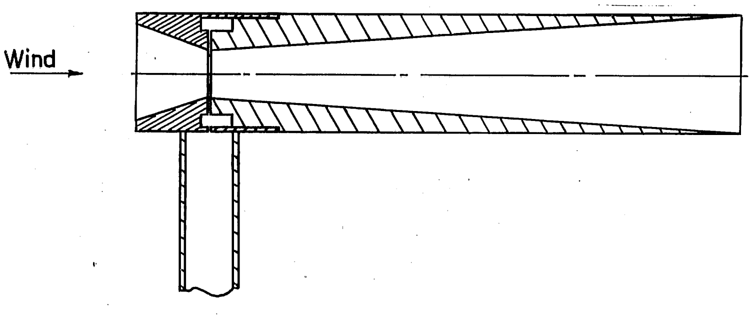

Fig. 10 - Venturi Housing Used to Create a Depressed Static Pressure Value [2]

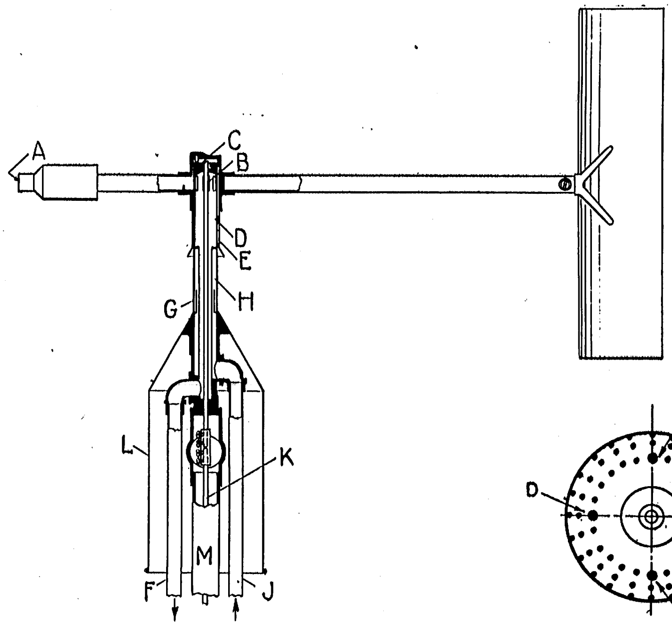

Fig. 11 – The Dines Pressure Tube Anemometer [5]

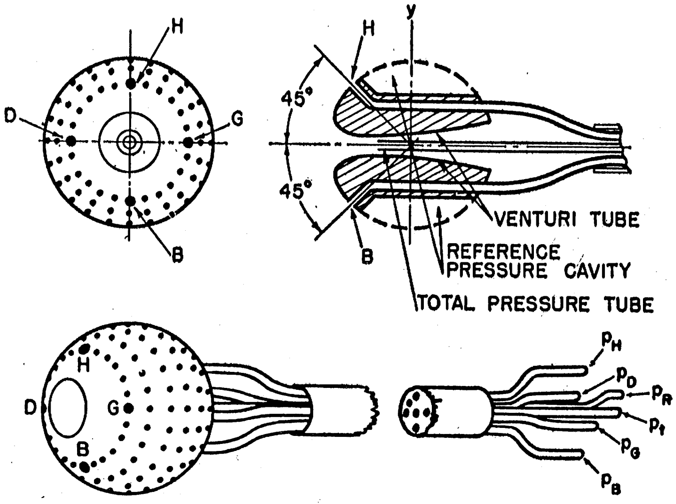

Fig. 12 – Spherical Headed Pressure Tube for Measuring Wind Velocity and Direction without Instrument Rotation [6]

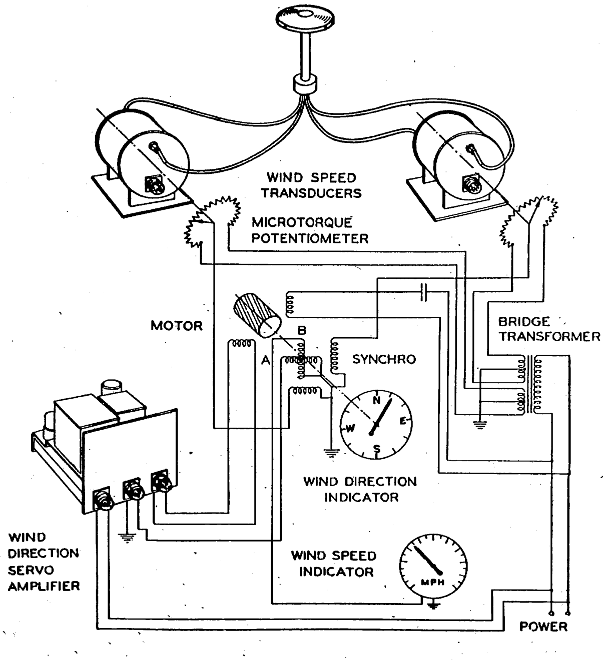

Fig. 13 – Schematic Diagram of the Multiple Pressure Tube Anemometer [7]

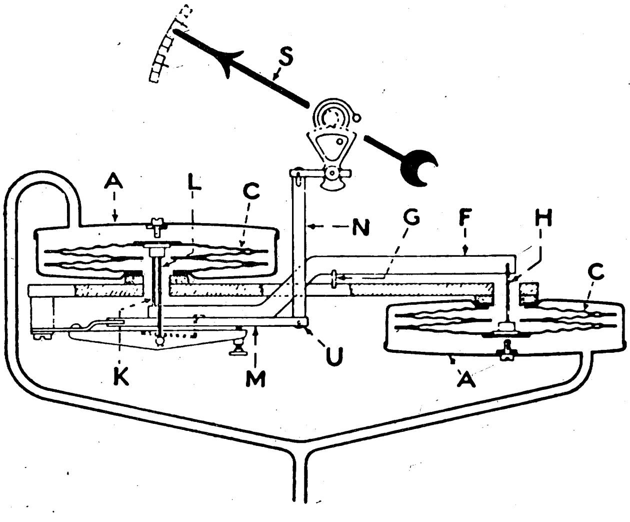

Fig. 14 – Elastic Diaphragm Pressure Meter of a Type Employed with Portable Pressure Tube Anemometers [5]

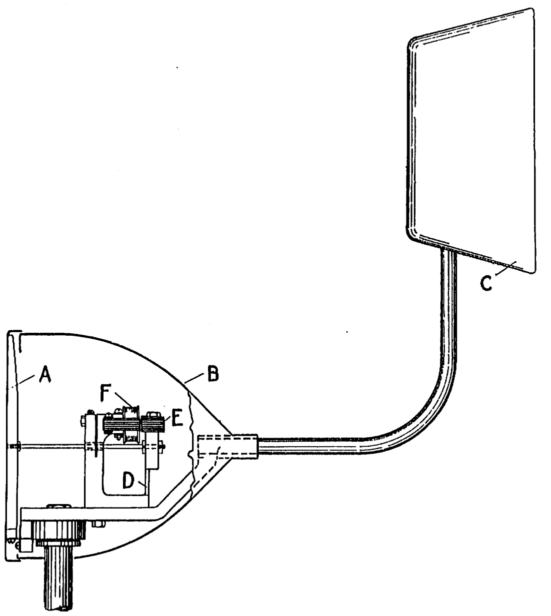

Fig. 15 - The Normal Pressure Plate Anemometer of Sherlock and Stout [5]

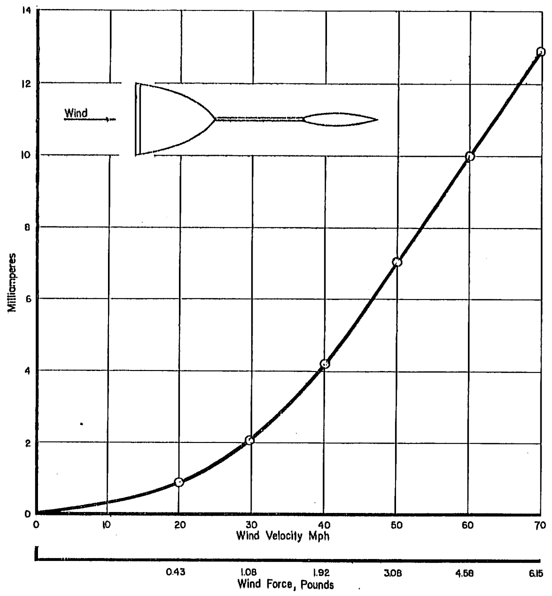

Fig. 16 - Wind Tunnel Calibration Curve for the Normal Pressure Plate Anemometer [9]

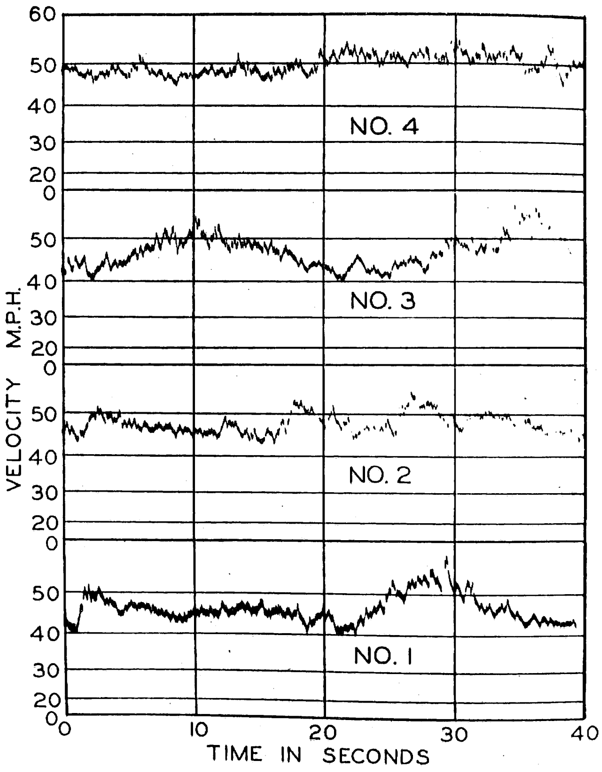

Fig. 17-Records of a Natural Wind as Taken with the Normal Pressure Plate Anemometer [9]

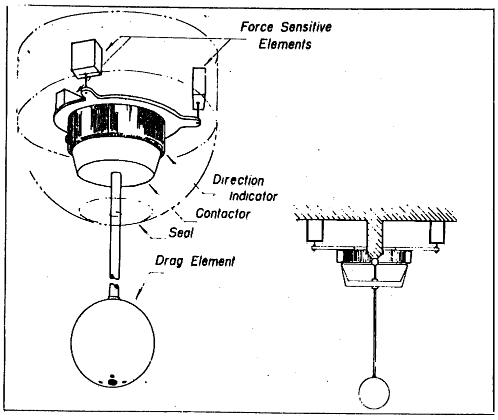

Fig. 18-Diagrammatic Sketch of Drag Sphere Current Meter by Knapp [16]

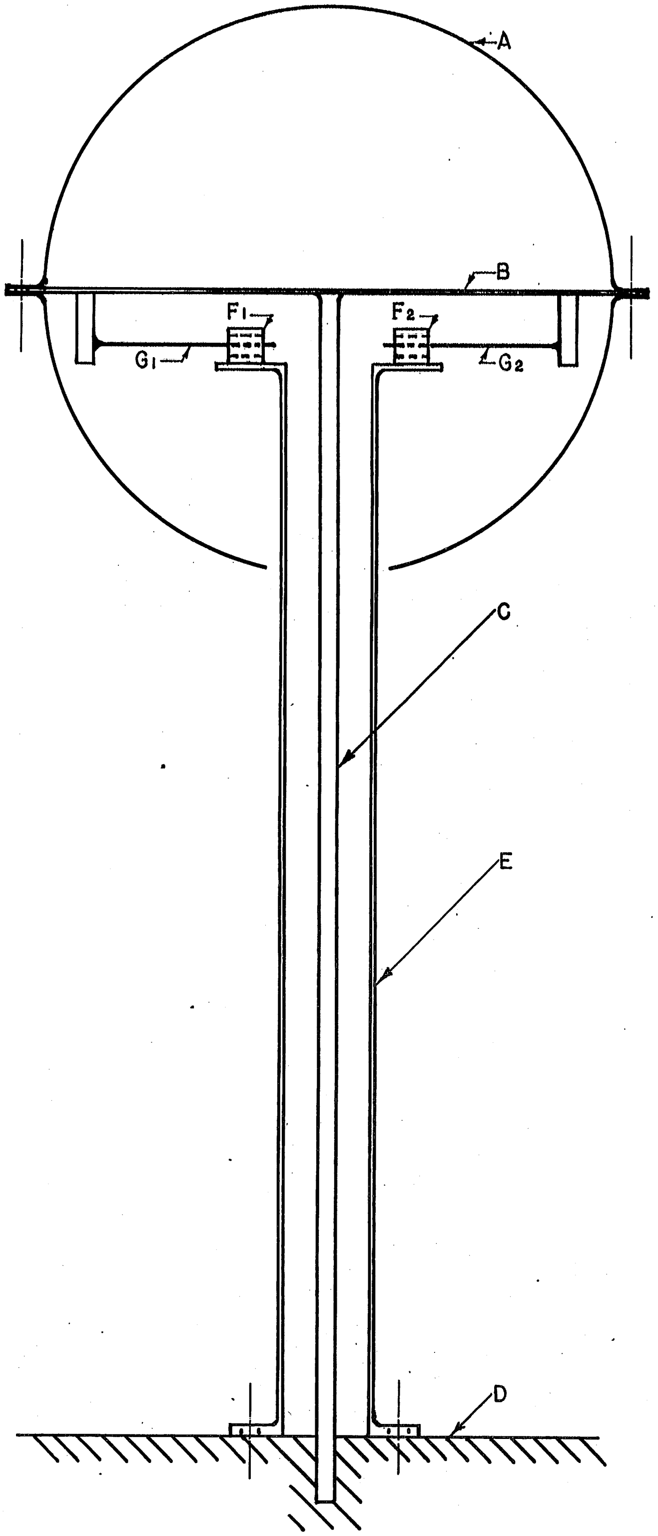

Fig. 19 - Diagrammatic Sketch of the St. Anthony Falls Drag Sphere Anemometer
(G_1-F_1 is at 90° to G_2-F_2)

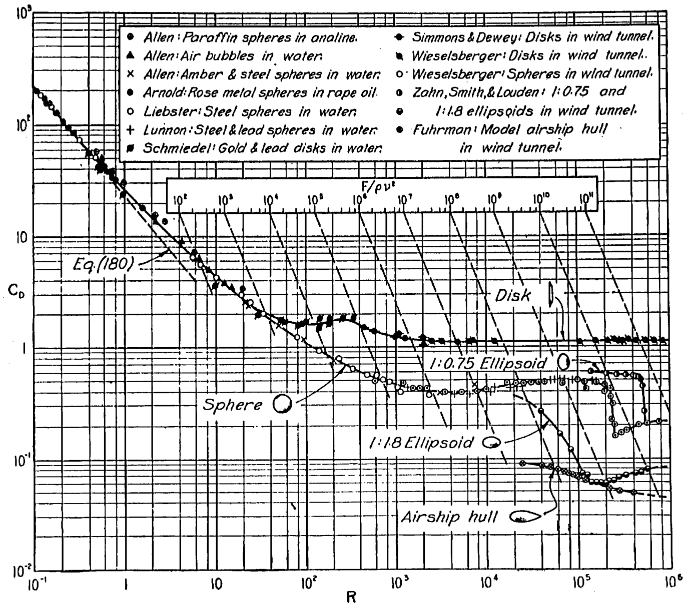

Fig. 20 - Coefficients of Drag as a Function of the Reynolds Number for Bodies of Revolution [17]

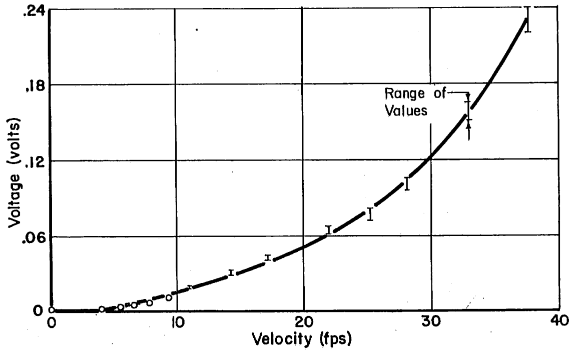

Fig. 21 - Velocity Calibration for the St. Anthony Falls Drag Sphere

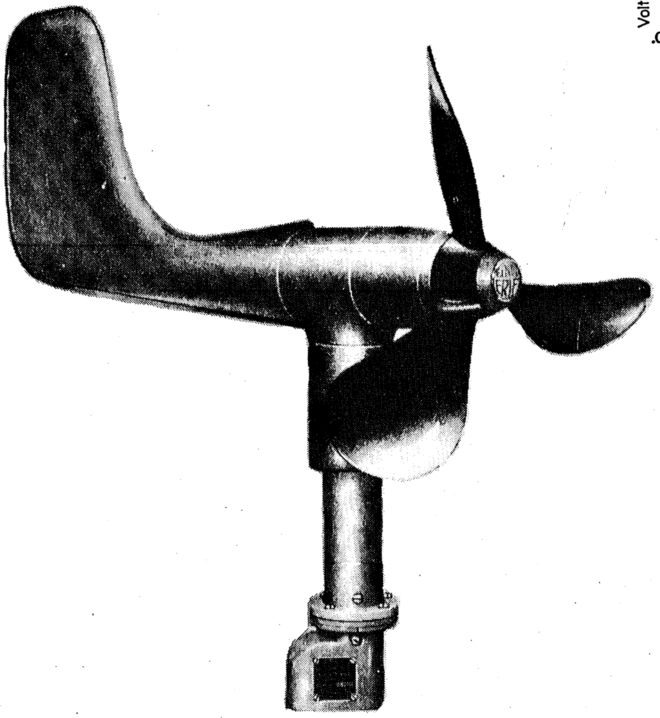

Fig. 22 - The Bendix-Friez Aerovane Anemometer
(taken from Bendix-Friez Bulletin 9)

III. THERMAL ANEMOMETERS

A. General Considerations

Wind velocity measurement as a function of the rate at which heat is removed from a heated body placed in the wind is a form of anemometry with a considerable history. However, only in recent years have there been significant practical developments.

While the cooling effect of a wind is not fundamentally more powerful than certain of its pressure and force effects, utilization of this effect has a distinct practical advantage. It can employ the long history and intensive development found in the field of thermal measurements. This advantage is most notable in the methods which convert thermal values to electrical values by means which are physically reliable yet simple, and thus permit the use of the extremely sensitive and accurate electrical reading instruments which are today so well developed. The basic lack of moving mechanical elements in the sensory probe, the inherent ease of transmission of electrical signals for remote indication or recording, and the established accuracy of electrical reading devices lead to an anemometer type which will undoubtedly find an expanding field of general application. This is particularly true for problems such as the present one since the inherent sensitivity of these devices to low-speed winds is rather unique.

If thermal anemometers are to be discussed in an increasing order of estimated usefulness in this application, it is deemed proper first to discuss briefly the Kata thermometer and the electrically heated glass thermometer, even though these devices are considered inapplicable in this case.

These reviews will be followed by discussions of the potentially more useful thermal devices represented by the vortex thermometer air speed indicator, the hot-wire anemometer, the "Anemotherm," the Thermistor anemometer, and the heated thermocouple anemometer.

B. The Kata Thermometer

The Kata thermometer is a glass tube thermometer with a relatively large bulb and only two graduations on its stem, these being normally at values corresponding to 35° and 38° C.

The instrument is used for measuring wind velocities by heating it to a temperature somewhat over 40° C and then exposing it to the test air stream and observing the stop watch time for the liquid column to fall from 38° to 35°.

The wind speed is determined by solving the equation

$$B^2 V = \left[\frac{F}{(36.5 - t)\ T - A}\right]^2$$

where B, F, and A are instrumental constants of calibration, T the time in seconds, t the air temperature, and V the velocity.

The instrument is capable of measuring low wind speeds but only in a noncontinuous manner and in terms of a mean wind speed for a relatively substantial time period. It is in no way adaptable to the measuring problem under consideration.

C. The Electrically Heated Glass Thermometer

This anemometer, which has been described by Yaglou [1], consists of a glass tube thermometer whose bulb has been surrounded with a fine wire heating coil. A voltage applied to the heating coil by an external source is held constant while the heater thermometer is exposed to the test air stream. The measured excess of temperature of the heated thermometer over the temperature read on an unheated companion thermometer is a calibrated index of the air velocity.

The temperature of the wire usually varies from about 10° to 30° F above air temperature depending on the air velocity and the applied voltage. Regulation of the voltage permits selection of velocity ranges varying from 10 to 6000 fpm.

The wind speed may be determined by use of an equation very similar to that employed for the Kata thermometer and the hot-wire anemometer. It is:

$$\frac{\text{Net milliwatts of heat input}}{\text{Temp of heated thermometer} - \text{Air Temp}} = K_o + K_1\sqrt{\text{velocity in ft per min}}$$

The constants K_o and K_1 are calibration constants of the instrument and with suitable plotting of test values yield a practically linear relation.

The usual natural range of ambient temperatures, humidities, barometric pressures, and radiation exposure do not produce significant errors in instrument use. The instrument is insensitive to wind direction for a wide range of angular orientations and is reasonably insensitive to the convective air currents induced by its own heating action except at low velocities. Under practical conditions, errors of less than 5 per cent may be expected with use of this instrument.

Because of the appreciable thermal mass of the sensory elements, the responsiveness of the instrument is slow under low-velocity conditions and an equilibrium time as long as 10 min has been observed. The responsiveness at higher velocities is, of course, much better. The stability of the instrument is good since the thermometer elements are very stable and deterioration of the resistance wire of the heating coil could not be detected after 4 years of use. The instrument is commercially produced by Willson Products, Inc. of Reading, Pennsylvania, for industrial use as an anemometer. No record of its use in meteorological studies has been noted.

The existing form of this instrument is not considered adaptable to the measuring problem under consideration, although modifications along the lines represented by the Anemotherm, which is described later, may offer possibilities.

D. The Vortex Thermometer Air Speed Indicator

If a cylindrical tube such as that shown in Fig. 23 is placed normal to an air stream with an upstream opening near one end disposed to admit the air in a tangential manner and a downstream opening at the opposite end arranged to exhaust the air, a natural spiral vortex flow of air will exist within the tube. The strength of this spiral vortex will depend considerably on the shape of the intake and its favorable positioning in a high dynamic pressure region, and the shape of the exhaust opening and its placement in a low dynamic pressure region. While the flow pattern in the tube is rather complex, it will apparently approximate a high-speed free vortex which possesses the usual vortex property of high pressure near the outside and low pressure near the center, with the differential pressure a function of the square of the air stream velocity. Because the air is a compressible gas, it will show evidence of an elevated temperature in the region of the intake where it has been subjected to aerodynamic compression and will evidence a depression in temperature as it passes from this high-pressure peripheral region of the vortex to the lower pressure of the core. While the drop in temperature is not extreme, it is significant and can serve as an index of the velocity of the stream which produced the vortex.

Vonnegut [2], who describes tests of the tube shown in Fig. 23, found the thermal differences to be as shown in Fig. 24 where the upper curve indicates the extent of the heating in the compression region, and the lower curve the extent of the cooling in the low-pressure region. The principal purpose of these tests was to design a thermometer housing which would permit true air temperature readings to be made in an airplane without the obscuring thermal action of dynamic compressibility effects. This was achieved by proper adjustment of the vortex chamber as shown in the middle curves of Fig. 24.

The interest in using the thermal difference as a measure of the air speed was secondary in these studies, but a simple meter was built using two Thermistor temperature-measuring units in the vortex housing, one of these being mounted near the periphery and the other at the center. The temperature difference between the Thermistors was measured by a microammeter in a simple bridge circuit. Limited aircraft tests of this speed indicator were promising when compared with the conventional aircraft speed indicator, but they were not pursued.

Because the only published physical tests of this instrument were made at aircraft speeds, there is no evidence to indicate the critical difficulties which might occur in the low-velocity region. It is conceivable that a considerable development program might be necessary to assess or cure the problems which are probably associated with application to low velocities under varied field conditions.

The instrument requires physical orientation with respect to the wind direction and is therefore to be dismissed as a stationary wind velocity-sensing device. It does not seem to possess properties which make it inherently adaptable as a direction-sensing device.

Unlike the thermal-electrical velocity relations of the hot-wire, Thermistor, and thermocouple anemometers in which the velocity may vary as the square or fourth power of the sensory value, the vortex thermometer is more in keeping with the dynamic pressure devices in which the velocity varies as the square root of the sensory value. It is conceivable that eventual instrument developments might combine these sensory elements and their differing characteristics in various combinations for best emphasis or range treatment of the desired velocities.

E. The Hot-wire Anemometer

1. General

This instrument, which is the most widely known of the thermal anemometers, depends for its operation upon the electrical measurement of the rate at which thermal energy is being dissipated from the surface of an electrically heated short cylindrical wire exposed to a moving air stream. It has been quite thoroughly investigated both experimentally and analytically since its conception in about 1912, with the bulk of the analysis leaning heavily on the early but still valid theory of King [3]. The experimental efforts have concentrated on the unique very high-speed response of the instrument. Because of this feature, it has become the preeminent tool for measurement of fluctuating fluid velocities and turbulence structure. Unfortunately, the very features which give the instrument its sensitivity and remarkable response detract from its stability and ruggedness to the extent that it is an instrument of temperamental delicacy capable of producing results only in expert hands in a laboratory environment. For the latter reasons it is not considered a potential solution to the problem at hand, but because of its long history of development and basic relation to all other thermal anemometers it is worthy of some discussion in this report.

King's analysis established that the rate of heat loss depended very considerably on the orientation of the wire with respect to the air stream direction and he evolved equations for the two most significant positions. These positions are with the wire axis parallel to the flow, and with the axis normal thereto. While the parallel position offers a greater sensitivity and some geometric benefits in high-speed measurements, it is not generally as sensitive as the normal placement and is, therefore, seldom used in practice.

Since all electrical detection of thermal change is essentially a measurement of electrical resistance, hot-wire instruments must basically have this objective. However, in practice two methods are employed; namely, the method of constant temperature or resistance and the method of constant current. (A third but lesser used method of constant voltage is sometimes employed.) Which of the two former methods to employ depends on the nature of the wire selection and operating conditions of a given problem since the resulting sensitivity depends on the combination of conditions. End readings of velocity are taken from a suitably calibrated ammeter, voltmeter, or potentiometer whose choice depends on the nature of the circuit and the desired precision.

King's basic equation for the normal wire position has been experimentally confirmed and is

$$H = i^2R = (a + b\sqrt{V})(T - T_a)$$

where H is the heat loss per unit length of wire,
i is the electric heating current,
R is the resistance of the wire,
a is a constant of calibration depending largely on the characteristic radiative and convective loss in still air,
b is a constant of calibration depending mainly on the wire diameter and the physical properties of the air,
V is the air stream velocity,
T is the wire temperature, and
T_a is the ambient air temperature.

This basic equation is materially simplified for the constant temperature mode of operation since this will also result in a constant resistance and a constant value for the temperature differential $T - T_a$. The equation then becomes

$$i^2 = K_1 + K_2\sqrt{V}$$

The equation may be further reduced in practice if a given fluid is employed and the resistance at zero velocity (i_o) is physically measured. That is,

$$i^2 = i_o^2 + K\sqrt{V}$$

From the last equation it is apparent that the fourth-root relation between the current and velocity provides a very high degree of sensitivity at low air speeds. A graphic demonstration of this is shown in the measured values of Fig. 25. The figure also serves to demonstrate that use of a higher wire temperature yields a steeper curve or greater velocity sensitivity over the entire range but most notably at the lower velocities. Constant K of the last equation involves dependence on many factors including (according to King) the quantity $\sqrt{2\pi k s \rho d}$ where k is the thermal conductivity of air, s is the specific heat of air at constant volume, ρ is the air density, and d is the wire diameter.

Because of lack of precise knowledge of the value of k near the wire and the value of d, it is not possible to evaluate the fourth-root equation by absolute means. Reliance must be placed on physical calibrations such as are shown in Fig. 25. Fortunately, measurement of i_o and K under controlled conditions permits a ready calibration.

Since King's basic equations indicate that the relation between velocity and current is a function of k, s, and ρ, all of which are properties of the air and which are subject to some variation in nature, it is appropriate to examine the probable influence of natural changes. The principal natural changes which can occur are in temperature, barometric pressure, and humidity. It may be concluded from the discussions of Ower [4] and Schubauer [5] that:

1. Air temperature influences both the temperature differential acting at the wire and also the density of the air. The former effect and its compensation will be discussed later. Ower's analysis indicates that the latter effect is defined by the fact that "if V is the velocity corresponding, according to the calibration curve for density ρ_o, to a current i, the same current will correspond, when the density is ρ_1, to an air speed $V\rho_o/\rho_1$." Since the densities ρ_o and ρ_1 are calculable from observations of temperature, the correction may be easily made and should be made if large temperature ranges are in prospect. Ower states that natural ranges of temperature will have no significant effect on k and s.

2. Barometric pressure may be established to have the same type of influence that temperature has on the density and may be corrected for in the same manner by appropriate use of the gas laws. There is no physical evidence that natural ranges of pressure have any influence on k and s.

3. Humidity influences on the density ρ are established by Ower as having less than a 1 per cent effect for a wide natural range. However,

the tests of Schubauer indicate that the effect on k is quite marked. Results show an increase of about 2 per cent in heat loss per degree of rise in wire temperature for a 25 to 70 per cent change in relative humidity at around 77° F. A change in heat loss of 2 per cent is equivalent in turn to an air speed change of about 6 per cent. It is Schubauer's contention that a considerable part of the erratic performance of hot-wires is traceable to neglect of this factor. The value of s is not known to be significantly affected by humidity.

There is no evidence of the effect of rain or snow impinging on a hot-wire, but it may be presumed that such action will be disturbing and possibly damaging.

Where it is especially desirable to reduce the varying sensitivity of Fig. 25 to a more linear relationship, Weske [6] showed that the hot-wire anemometer may be connected to a suitable nonlinear electronic amplifier with output results as shown in Fig. 26.

In its usual form the sensory element of the meter consists of a fine wire stretched across the ends of two supporting prongs through which an electric current is passed. Because the resistance is most conveniently measured by a Wheatstone bridge whose accuracy increases with the magnitude of the resistance, it is desirable that the wire be as small in diameter and as long as possible. The wire length usually varies from about 1/8 to 1/2 inch. The shorter wires more nearly approximate a point measurement of velocity, but their measurement and analysis are complicated by the relatively large thermal end effects contributed by the mounting prongs. The longer wires offer a greater sensitivity, but at the expense of fragility.

The wire diameter is usually between 0.0005 and 0.006 inches. The smaller wire diameters require a smaller electric current to maintain a selected wire temperature and minimize flow disturbance, but they are more sensitive to physical damage and the influence of physical contaminants such as dust. They are also more subject to calibration drift through aging and may be melted by rather small accidental current overloads. The larger wire diameters are more robust but draw considerable current (a 0.0025-in. wire drew $i_o = 0.5$ amp, and $i = 1.0$ amp for a wire temperature of 1800° F and a velocity of 16 fps). They also have a greater sensitivity because of their greater area, but they have a retarded response because of their greater thermal mass.

The ideal wire material should have high tensile strength, low thermal expansion, high coefficient of resistivity, high resistivity, and high chemical and electrical stability. No one metal seems to possess all of the best values for these properties; platinum is probably the most satisfactory at low velocities or temperatures, while the high tensile properties of tungsten make it the most desirable for high velocities or temperatures.

The wire temperatures which have found use in practice range from about 360° to 1800° F, although an upper limit of 900° F is recommended. The higher the wire temperature maintained, the more sensitive is the meter over the whole range (see Fig. 25), and the values of resistance and current are larger and more accurately measurable. The higher temperature, however, requires a substantial power supply, entails danger of melting the wire, and induces secondary effects due to weakening and deflection of the wire.

The equation values of i_o and K relate to a specific excess temperature of the wire over that of the surrounding air. For this reason the use of a high wire temperature will permit a moderate range of ambient air temperatures without excessive shifts of the constants of calibration. More moderate wire temperatures may be employed but require corrections for ambient temperatures or an automatically compensated electrical circuit.

High temperatures must be avoided in low-velocity studies since the convective air currents set up by the presence of the heated wire locally obscure and distort a low-velocity test air stream. A minimum velocity value of about 1/4 fps is established by this limitation for a wire of 0.001-in. diameter unless it has been accounted for by instrument calibration. The upper limits of speed are apparently of no significance in this study since Weske [6] achieved values in the supersonic range.

The hot-wire anemometer is well known for its instability with time. This is usually sufficient to require recalibration of the instrument every few days if accuracy of the results is to be expected. The exact cause of this change is not known but is due, to a considerable extent, to dust and to chemical and mechanical changes in the exterior of the wire and its junctions with the support prongs. These effects usually increase with temperature increases.

An attempt to increase the ruggedness of the wire and to stabilize its calibration by providing an external shield is described by Simmons [7].

This effort resulted in some improvement of these two factors but complicated the arrangement and materially reduced the speed of response.

The most notable characteristic of the hot-wire anemometer is the extreme rapidity of its time of response to velocity fluctuations. While ordinary procedures of operation will readily permit response to fluctuations varying from steady to 1/100 sec, Weske [8] achieved response to 8000 cps by utilizing the inherent properties of the constant temperature method. More recent studies indicate that values to 40,000 cycles can be achieved. The advantage of the constant temperature method is that only very tiny temperature changes of the very tiny thermal mass of the wire are involved.

Among the more favorable properties of the hot-wire anemometer is its inherent sensitivity to wind direction. This property was recognized by King [3] in his earliest work, for, as indicated previously, he evolved two distinct equations or performance depending on whether the wire axis was along or normal to the air stream. In other words, the convective heat loss and electric output of the wire is a function of the angular orientation of the wire axis with respect to the wind direction. Tests of a single wire and a simple bridge circuit indicated that the rate of change of heat loss with angle of wind incidence is large between angles of 30° and 60° and good sensitivity is attainable. Weske [6], working with a wire whose circuit had been adjusted to a linear sensitivity, as previously discussed and as shown in Fig. 26, found the directional sensitivity of such a wire to be as shown in Fig. 27. The plotting of Fig. 27 is for a nickel wire of 0.0005-in. diameter and 7/32-in. length and for a speed range between 100 and 300 fps. It is noteworthy that data plotting in terms of the ratio (current at α° incidence)/(current at 90° incidence) makes a fairly good fit with the arbitrary curve $\sin \alpha$. In these data, 90° incidence represents the wire normal to the flow.

It is apparent from Weske's data that a single stationary hot-wire possesses fairly sensitive action over the angular range from 0° to 70° or 80° but is rather insensitive in the vicinity of 90°. The single wire is also incapable of indicating the phase position; that is, to which of the four quadrants of 360° of direction it is responding in a two-dimensional flow.

Ferrari [9] describes studies in which two heated wires are used in two-dimensional wind studies. In these studies the two identical wires are placed parallel very close together and are perpendicular to the plane containing the two-dimensional wind. The wires are in adjacent arms of a Wheatstone bridge and when the plane of the two wires is oriented normal to the wind direction the cooling is symmetrical and the bridge is balanced. If the plane of the wires is rotated so that one wire tends to shield the other, asymmetry of cooling results; and the bridge unbalance is proportional to the angular rotation. Direction is found by determining the position and phase of maximum unbalance. Operation of a system of this kind disclosed that platinum-iridium wires 0.52 in. long, 0.0059 inches in diameter, and 0.0205 in. apart, when operated on a constant-current circuit at a wind speed of 33 fps produced a difference of resistance in the two wires with a value of 0.0143 ohms per degree of angular change. This value changed slightly with air speed. The data do not disclose the angular range over which good sensitivity prevails. It is possible that sensitivity is adequate over a wide angular range and will permit such an instrument to be employed as a nonrotated directional meter. However, without auxiliary features it is difficult to see how the symmetry of a single pair of wires could sense or discriminate for more than 180° of arc. Goldstein [10] states that the accuracy is of the order of ±1/4°.

Magnan [11] briefly describes a directional system employed in meteorological research which also used two parallel hot-wires. This was somewhat analogous to the system described by Ferrari. It differs in that the wires were not close to each other, but were placed instead a slight distance from and parallel to a relatively larger cylinder. The two wires were separated by about a 60° angle of arc around the periphery of the large cylinder to take advantage of differential velocity values which occur around the periphery. Placement of this assembly in a wind produced balanced cooling of the wires when symmetrically placed and an unbalance growing with the asymmetry. The unbalance was electrically measured by making the two hot-wires serve as two arms of a Wheatstone bridge, complete with two fixed resistances, a center zeroed ammeter or galvanometer, and a battery supplying a constant voltage. This simple circuit with a suitable choice of components produced a meter current proportionate to the angle of asymmetry with the wind. Fortunately, Magnan's calibration experience showed that the assembly measured only velocity differences, and the angular indications were practically independent of the absolute velocity value for tests up to 140 fps.

Magnan's data do not elaborate on the details of construction or operating limits of this device. They do, however, indicate that the assembly was set up with a photographic recording oscillograph plus a differentiating circuit which measured the rate of change of the wind angle as well as the angle itself. Analysis of such a recording showed that with the instrument mounted 5 m above the ground in a wind of 33 to 39.5 fps velocity, the responsiveness was such that angular changes of velocities of as much as 200° per sec were recorded. This record also showed that the angular value swung from about ±30°; the rapidity of swing in one case varied through two cycles of about ±100° per sec in a period of 1/3 sec.

The instrument presumably required manual orientation into the general wind and is assumed limited to angles of about 45° either side of the null direction because of separation effects involved in the aerodynamics of flow around the cylinder.

Ferrari [9] also discusses a system in which the two wires are arranged as a "V" with a vertex angle of about 10°. These wires when pointed symmetrically into the wind by manual rotation are very sensitive to any tendency toward asymmetry of position or differences of cooling. Two platinum wires 0.00106 inches in diameter and 3.08 in. long arranged in this manner proved to have a difference of resistance which changed at a rate of 0.2 ohms per degree and permitted angular determinations to a fraction of one degree with virtual independence of the wind speed. Additional data on this form of device are also offered by Simmons and Bailey [12]. The sensitivity to a third dimension may be gained, where necessary, by adding a third wire to form a pointed pyramid.

Willis [13] indicates that the "V" arrangement described by Ferrari may also be arranged as an "X" with somewhat comparable results.

There is no evidence in the literature that any attempt has been made to develop a wind direction meter of the hot-wire type which can operate without rotation and achieve sensitivity and discrimination for a full 360° of two-dimensional wind direction. However, the foregoing extracts from the literature indicate strong basic directional characteristics which might possibly be developed to the desired extent. Such development is discussed further on page 71 with regard to rod-type Thermistors.

Remote indication of the velocity values of a hot-wire via an electric transmission system are premissible. The sensitivity to the influence of resistances in the lead wires varies with the basic circuits employed but is not considered to negate the use of the device, although care in handling is essential to good results.

The hot-wire anemometer has in the past been a specially constructed experimental device. The only known American source of this equipment is the Flow Corporation, 56 Kirkland Street, Cambridge, Massachusetts. A few sources are also available in Europe.

2. Summary

This device, which measures electrical resistance as the convective cooling action of a wind on an electrically heated small cylindrical wire, is possessed of an exceedingly rapid response to wind fluctuations and very definite directional properties. However, the physical delicacy and lack of ruggedness of the hot-wire does not recommend its use for practical field operations nor does its continual calibration drift with age and dust accumulation make it desirable for permanent installation.

F. The Heated Resistance Thermometer

1. General

This type of anemometer depends for its sensory action on the electric resistance thermometer, which is a relatively common device with an extensive history of development in certain precision thermal measuring applications. The resistance thermometer is a temperature-measuring device which utilizes the fact that the electrical resistance of a calibrated metallic conductor increases as its temperature increases (a positive temperature coefficient of resistivity).

While the resistance thermometer is incapable of directly detecting the presence of motion in an air mass to which it may be exposed, addition of an intimately associated heater unit can indirectly provide the thermometer with such sensitivity. This process is accomplished by supplying the heater with a measured quantity of heat which in turn can elevate the attached resistance thermometer to some terminal temperature which is a function of the rate of convective cooling effected by the movement of the air mass. Published evidence of the analysis and test of such a device has not been found, but it is probable that such tests would establish that the equation for velocity would be approximated by that given on page 54 for the hot-wire anemometer.

An assembly of this type of device would consist of the resistance element proper, the resistance evaluation circuit, the heater, and the heater supply circuit. The resistance element should be selected to possess the best compromise between a large temperature coefficient of resistance, practical production reproducibility, and stability of resistance with use and exposure. In thermometer practice platinum wire is used for best quality instruments, or nickel wire where costs preclude the use of platinum. With proper handling the platinum units may yield temperature measurements with accuracies of the order of 1 part in 10,000.

The metals more commonly employed for this use have a positive temperature coefficient of resistivity of about 0.22 per cent per degree at 68° F. Because this unit value is relatively small, larger and more conveniently measurable values of instrument resistance may be obtained by employing either a substantial temperature differential through the heating unit or a considerable length of the resistance wire. Since use of large temperature values initiates secondary convective air currents which are detrimental to accuracy of low-velocity measurements, it is probably more practical to achieve the desired value by increasing the length of wire with a coiled loop. This is in contrast to the short wire lengths and very high temperature differentials usually employed with the hot-wire anemometer.

The resistance evaluation circuit in the case of thermometers usually consists of either a deflection or balanced type of Wheatstone-bridge circuit, the choice depending on the speed of response desired and whether reading or recording galvanometers are to be employed.

Since no published material is available on preferred construction of the heater unit and circuit, it is presumed that comparable heaters employed with the heated glass thermometer-anemometer as described by Yaglou [1] or the heated thermocouple anemometer described by Nottage [14] may serve as a guide. Yaglou in working with velocities of about 50 fps used a fine manganin heating coil with an input of approximately 2 milliwatts at 2 to 6 volts. Nottage employed a constantan coil with a resistance of 0.31 ohms and maximum currents as high as 1.7 amps.

Because the operation of the resistance thermometer is based on small changes of resistance, it is apparent that electrical transmission of the velocity value from the sensory probe to some remote location will require care in treating the transmission leads if accuracy is expected. Compensation for lead line errors may be quite effectively handled by using three-wire lead lines arranged to balance the bridge circuit. In this regard Rhodes [15] states:

> It should be appreciated that the resistance thermometer is inherently an instrument of high precision but that in practice it is also highly temperamental and difficult to maintain as compared with the thermo-electric (thermocouple) pyrometer. The main cause for trouble lies in the difficulty of establishing and maintaining good electrical contact at all points. Every contact must be soldered with the greatest care, and no damage or partial break in the lead lines must be permitted. The instrument is so sensitive to changes in contact resistance that contacts that appear perfect will actually be a source of error.

Although the published literature fails to disclose discussions of developmental treatments of this type of anemometer, a commercial instrument of this type known as the Anemotherm has been available in recent years. It is offered by the Anemostat Corporation of America, New York, New York. The company manufactures a line of flow control devices for use in heating and ventilating systems, and offers the Anemotherm as a tool for their proper installation and adjustment. Although the Anemotherm was developed for specialized industrial use, it was deemed advisable to examine this device for characteristics especially pertinent to meteorological studies. A number of observations of a standard unit were made at the St. Anthony Falls Hydraulic Laboratory, together with the photographs shown in Figs. 28 and 29. Figure 28 shows the control and indicator face of the small box which houses the operating batteries and auxiliary components. The velocity indicator, which has two selectable ranges (presumably achieved by employing two alternate heating currents through the selector switch control), is shown on the lower two scales. It is notable that the total range is from 10 to 6000 ft per min with prime sensitivity occurring in the low-velocity range. On the upper scales the indicator also shows alternate temperature and differential static pressure readings which are achieved by internal circuit switching and manipulation of a special housing on the sensory probe.

Figure 29 shows an enlarged view of the cable-connected sensory probe. This probe consists of an inner bundle of parallel and insulated metal rods which serve as the coil-support form for a spirally wrapped wire unit which in itself consists of a loose winding of a spiral nature. The strands of this winding consist in turn of a central core wire (the heater element) spirally wound with a considerable length of a tight wrap wire (the resistance bridge element). Both the heater wire and the bridge wire appeared to be of the order of No. 40 gage (0.003 in.) with a light enamel insulation coating.

The more tightly wound coil elements constituting the left-hand one-third of the coil shown in Fig. 29 are those which the circuit employs for velocity measurements, while the right-hand two-thirds is the alternate temperature-measuring element (also used for ambient temperature compensation for the velocity coils).

Manipulation of the instrument in a test air current disclosed the following:

1. The sensitivity of the indicator appeared to be consistent with the graduation employed on the reading scale.

2. Re-zeroing of the dial to compensate for progressive battery decay or other drift sources was readily accomplished with the adjustment knobs supplied.

3. The geometric makeup of the probe was such that nondirectional velocity sensitivity was substantially achieved if the probe was oriented in accord with the instructions supplied (angle of probe should be within 45° to 90° of direction of air flow).

4. The instrument had a poor time response to rapid changes in velocity produced by passing it rapidly into and out of the air stream. This response appeared to be of the order of 5 to 10 sec for a wide variety of selected velocities. The trade literature relating to the instrument indicated that damping had been provided to prevent oscillation and permit easy reading with the fluctuating or turbulent flow which might be encountered in industrial applications. Examination of the instrument led to the conclusion that such damping must be contributed inherently by the geometric arrangement of the elements of the probe, as shown in Fig. 29, and partially by the enamel insulation. It may be noted that the coil

form elements are of relatively large dimension and thus must contribute considerably to the thermal mass inertia as well as provide considerable blockage to free ventilation of the sensitive wiring. The closely spaced coil windings also contribute to such blockage.

5. The instrument demonstrated a mild sensitivity to solar radiation.

6. The Wheatstone-bridge circuit employed in this unit is of the deflection type.

2. Summary

On the basis of the general information available on resistance thermometers and the examination of one specialized anemometer form of the device as represented by the Anemotherm, it appears probable that an instrument based on this principle might be developed to answer some of the needs of this application. At the present time it appears that the simplicity, sensitivity, and accuracy desired could be readily achieved; but considerable work would be necessary to obtain a probe form which would retain the sensitivity, decrease the time response, and yet provide adequate ruggedness to sustain severe weather exposure conditions. It is possible that no happy compromise of the latter requirements can be achieved.

The very desirable ability of the device to operate with a nonrigid probe mounting is overbalanced by its inability to sense direction. It is conceivable that with suitable development the sensory wires of the probe might be geometrically arranged to yield directional characteristics in a manner similar to the directional concepts discussed separately herein relative to the hot-wire anemometer.

Because the instrument operation is based on measurement of small resistance changes, remote transmission of signals will require refined circuit treatment if accuracy is to be maintained.

G. The Thermistor Anemometer

1. General

The Thermistor (thermally sensitive resistor) is a relatively new proprietary type of electrical circuit component possessing unique thermal-electrical properties. Unlike the more common thermal-electric elements which are conductors made of pure or alloyed metals, the Thermistor is made of a class of materials known as semiconductors; that is, a material whose conductivity lies between that of an insulator and a conductor. This material is utilized in thermal or velocity-measuring problems in a manner very similar to that employed for metallic resistances, as previously described in the discussion of resistance thermometers. However, the two differ considerably because of the inherent differences of conductors and semiconductors. The principal inherent differences are illustrated graphically in Fig. 30 and are as follows:

1. The specific resistance of the Thermistor is very high compared with that of metallic resistance wire.

2. The rate of resistance change with temperature change is much higher (as much as 500 times) for the Thermistor materials than with platinum and other temperature-sensitive materials, thus an extremely sensitive thermal material is provided for instrument usage.

3. Unlike metals which have a positive temperature coefficient of resistance, the Thermistor has a negative value. That is, the resistance decreases as the temperature increases.

The existence and some of the properties of the metallic oxides, nitrides, carbides, and sulphides which constitute the semiconductors of which Thermistors can be made have been known for over a century. However, it was not until the early 1930's that the Bell Telephone Laboratories began the intensive development activities that made these units available in a limited way in the research programs of World War II and on a broader commercial basis a few years thereafter. The chief block to an earlier utilization of their peculiar properties lay principally in the inability to produce units with stable chemical and electrical characteristics and specified qualities. These problems of production have, however, been overcome and the units are available today in a wide variety of shapes, sizes, and characteristics which are known for their small size, thermal sensitivity, stability, and physical ruggedness.

The Thermistor as a unit is made of a selected semiconductor (largely an alloy of nickel oxide and manganese oxide) which has been fired to produce a hard, ceramic-like material. This in turn has connection wires attached to it and is attached to or enclosed in a suitable separate or inherent housing unit. These housings usually assume the form of a disc, rod, bead, or flake, the geometry depending principally on mounting convenience and the desired heat dissipation characteristics attending certain mass-area dispositions of the material. The units are available as standard production items by the Western Electric Company and a number of other licensees under the Bell System patents.

In the Thermistor anemometers which have thus far been discussed in publications, the bead form of Thermistor has been used exclusively, apparently because this shape can be formed in very small size with an approximately non-directional, spherical shape. The resistance-temperature characteristics of a bead Thermistor built for this type of work are shown in Fig. 31.

In common with most other thermal-electrical anemometers, functional operation of the device is dependent on heating the sensory element above the ambient air temperature and then electrically noting the convective rate of cooling effected by passage of the wind stream.

Fortunately, the Thermistor relation between resistance and applied current is such that a direct or self-heating action readily takes place with results as typified in Fig. 32. The shape of these curves is desirable in that a near linearity exists in the right-hand or heated portion of the curve and the influence of ambient air temperatures in the natural range is relatively small.

Some standard Thermistors are provided with an attached or indirect heater which can be operated from a circuit separate from that of the Thermistor proper. This type of construction permits some flexibility in circuit design and is similar to the separate heating elements employed with the Anemotherm and some of the thermocouple units described elsewhere. The construction is not to be recommended since adequate performance together with simplicity of fabrication can be achieved by direct inherent heating of the Thermistor. Direct heating also minimizes the material mass and consequent thermal lag in the sensory unit.

In the United States, Hales [16] and Sanford [17] investigated rather extensively the anemometer properties of the most desirable standard bead Thermistor available at the time (Western Electric Company Type D-176980).

Penman and Long [18] conducted parallel experiments in England on a bead Thermistor of British manufacture. The properties of the Western Electric unit are shown in Figs. 31 and 32. They are as follows:

1. The solid bead was approximately spherical and 0.013 inches in diameter. It was mounted on two paired wire leads which were 0.001 inches in diameter and 0.125 in. long.

2. The cold resistance, which was measured at a power small enough to prevent heating, was 75,000 ohms at 77° F (25° C).

3. The temperature coefficient was approximately -2.4 per cent per degree at 77° F and -1.56 per cent per degree at 212° F (100° C).

4. The maximum continuous current (still air) which could be applied to this unit without damaging it was 5 milliamperes a-c or d-c. A current of about 3 milliamperes was actually used in most of the tests since this was low enough to achieve velocity sensitivity but high enough to avoid excessive ambient temperature effects.

5. The maximum current which could be applied without causing heating was about 0.02 milliamperes.

6. The thermal time constant (still air) was approximately 0.5 sec. The thermal time constant is defined from the mathematical properties of the assumed exponential cooling curve as the time required for a Thermistor to change 63 per cent of the difference between its initial temperature value and that of its new surroundings when no electric power is being dissipated.

7. The dissipation constant (still air) was approximately 0.067 milliwatts per degree Fahrenheit. The dissipation constant is defined as the proportionality between power dissipation and the consequent temperature increase.

Examination of the relations indicated in Fig. 32 led Sanford [17] to investigate and determine the most fruitful manner in which to manipulate the sensory element electrically. His investigations developed along the following three lines of measurement:

1. Operation with a constant current together with measurement of the Thermistor resistance by means of a simple Wheatstone bridge on which the potential was varied to maintain the constant current.

2. Operation with a constant resistance together with measurement of the Thermistor voltage. This mode of operation required suitable control of the bridge input current.

3. Operation with a constant bridge supply voltage and measurement of the bridge output voltage.

On the basis of comparative measurements and analytical computations for these three basic systems, Sanford concluded that the constant resistance type of operation offered the greatest promise for anemometer applications.

The general characteristics of Thermistors, notably the bead type, as applied to anemometer problems may be described as follows:

a. Velocity Sensitivity

It is apparent from Figs. 31 and 33 that the greatest velocity sensitivity lies in the low-temperature region and that increase in either velocity or ambient temperature will tend to dull this sensitivity. For a rather wide range of test conditions the bead Thermistor under constant-current operation produced minimum to maximum resistance change of about 1 to 10 with an average value of about 51 ohms per fps. Under constant-resistance operation the voltage range minimum to maximum was about 1 to 5 with an average value of about 0.075 volts per fps. From the standpoint of general stability, operation by the latter method seems more desirable. An indication of the practical values achieved by Hales is evidenced by the typical calibration graph shown in Fig. 34. As in the case of other heated anemometers, care must be taken to minimize the heat input to avoid secondary induced convective air currents around the sensory elements. The inherent ability of the bead Thermistor to produce high sensitivity with low power input is very favorable in this respect.

b. Ambient Temperature Sensitivity

As evidenced in Fig. 31, the Thermistor is temperature-sensitive, the degree of sensitivity depending on the range or mode of operation. Hales felt that operations in the region of the right-hand end of Fig. 32 did not justify temperature corrections unless high accuracy or a very wide temperature range was called for. Sanford's observations led to the conclusion that the error was of the order of 0.41 per cent per degree Fahrenheit for the constant-current method and 0.27 for the constant-resistance method, and probably should be corrected for. This correction is especially important in the velocity range below 5 mph (7.3 fps) where the sensitivity is the greatest, as evidenced in Fig. 33. The lower error of the constant-resistance method could be further corrected for ambient temperature shifts by use of a second Thermistor in the circuit which would be exposed to the air stream under unheated conditions. This suggestion by Sanford appears practical since comparable and satisfactory corrections were achieved in the Hastings heated thermopile anemometer and in the Anemotherm which are discussed elsewhere in this report. Becker, Green, and Pearson [19] indicate that ambient temperature compensation with Thermistors is common practice.

c. Time Lag Errors

The thermal time lag of response of a Thermistor element is the complex function of its thermal mass together with its dissipation characteristics and environs. The bead type of element has been employed in past anemometer investigations largely because of its tiny thermal mass and corresponding speed of response. While disc, rod, and flake forms (particularly the latter) would present a greater area per unit mass and consequently faster response for a given mass, they apparently have not been built in the tiny yet rugged size offered by the bead form. The 0.5-sec lag previously mentioned for the bead was a "still air" measured value which is the maximum value that might be expected. This value decreases very rapidly with initial air movement and then more slowly as the velocity increases. Sanford calculated that the moving air value could drop to about 25 per cent of the original "still air" value in a constant-current type of operation. In the constant-resistance operation, the time lag is even more favorable since in this operation the resistance and the Thermistor temperature remain nearly constant and the time lag theoretically approaches zero. Sanford's tests of this mode of operation, made by manually thrusting the bead anemometer into a wind stream, indicated that the defined time constant was 0.040 sec and substantially 100 per cent change was achieved in 0.085 sec. These values include an estimated 0.050 sec of transient time of insertion. The values remained quite constant over a wide range of test velocities. On this basis it would appear that the thermal lag of this bead is quite small.

d. Directionality

The tiny bead type of Thermistor used by Hales and Sanford is produced by torch-melting a small mass of semiconductor paste placed astraddle two parallel lead wires. The bead is not mold-formed and assumes its final shape only under the influence of gravity and surface tension forces as it cools to a solid state. The result is a bead whose shape approximates (though possibly with considerable deviation) a sphere. When such a nonsymmetrical shape is employed as a surface of thermal dissipation, it is quite apparent that it will possess distinctly directional properties in an air stream. Sanford found this variation with orientation to be as much as 20 per cent. Because of this variation, Hales found it necessary in his field investigations to provide for weather vane orientation of the Thermistor unit as shown in Fig. 35.

The accounts of Thermistor anemometry have not included indications of interest in developing their directional characteristics. The physical similarity of the rod Thermistor and the hot-wire anemometer suggests, however, that the former device might well possess the marked directional characteristics of the latter while retaining the more rugged characteristics of the former.

In an attempt to determine the very general nature of these possible directional characteristics, pilot studies were conducted at the St. Anthony Falls Laboratory for three separate arrangements of the sensory Thermistor elements suggested by previous work with the hot-wire anemometer. These arrangements and the resulting findings are briefly described below.

1. A Western Electric Company rod Thermistor Type 13A (diameter 0.055 in., length 0.5 in.) was revolved in a plane parallel to a wind stream. The galvanometer readings from the constant-current bridge circuit are shown in Fig. 36(a) for readings taken at increments of 22-1/2° around the circle. The line drawn is an approximate mean of values whose range of scatter is indicated in the plotting.

2. Two rod Thermistors Type 13A were placed parallel and in close proximity. These were maintained perpendicular to the wind stream as they were rotated. The resulting directional pattern is shown in Fig. 36(b). The range of scatter for these values was very large.

3. A Bendix-Friez rod Thermistor Type 517613-1 (diameter 0.018 in., length 1.5 in.) was mounted with its axis parallel to that of a long, smooth, 1-in. diameter cylinder 1/8 in. from the outer surface of the cylinder. The cylinder axis was placed normal to the wind stream and the cylinder was rotated about its axis. The resulting velocity response for various positions of rotation are shown in Fig. 36(c).

While the above simple findings indicate shortcomings in either the aerodynamic flow stability or the circuit, there is a definite and promising indication of a basic directional sensitivity that might prove worthy of further development.

e. Radiation Sensitivity

Sanford computed the probable magnitude of errors contributed by radiant heating effects and with assumptions of the worst possible conditions found that an error of about 10 per cent might be expected. However, under ordinary conditions the effect would be quite small and corrections unnecessary, since mounting conditions would normally permit shielding in a manner which would achieve reasonable protection and stability. Staley [20] attempted to coat the Thermistors with various materials to reduce radiation uncertainties. His success was short-lived, however, because all of the effective types suffered quite rapid deterioration with the weather and were not recommended for extended exposure.

f. Aging and Drift

Sanford's [17] investigation of the anemometric properties of Thermistors apparently presumed that the Thermistor element is a chemically and electrically stable material. This presumption is evidenced by Hales' [16] inability to detect any changes in a 4-month period of exposure. Staley [20], however, using rod Thermistors manufactured by Paul A. Sanborn, found that not only was circuit compensation necessary for adjusting initial differences in individual Thermistors, but care must be taken to recalibrate for time drift if precision results are to be expected. Comparative tests of a number of these units established that the amount of drift with time was small and rather random in magnitude. The drift was apparently due to internal changes since test units exposed to the weather acted must the same as unweathered units. These tests covered a period of 18 months.

Becker, Green, and Pearson [19] indicate that this drift or aging may be minimized by proper selection and handling of the materials of manufacture, by enclosing the Thermistor in an impervious layer of glass or other material, and by pre-aging the unit in an oven for several days or weeks at a temperature somewhat above its use temperature. The effect of pre-aging is demonstrated in Fig. 37, which indicates that the drift is less than 0.3 per cent per year after the initial week. The drift is even less than this for the glass-coated beads used by Hales and Sanford. The very moderate range of temperatures to which a Thermistor is subjected in anemometer problems is also favorable to their time stability.

g. Production Reproducibility

While the aging drift of properly manufactured Thermistors appears to be practically insignificant, the initial differences between individual Thermistors is fairly substantial and must be compensated for by proper circuit arrangements if alternate Thermistors are to possess a common calibration in multiple switching installations. Anderson [21] has established a preferred method of circuit compensation which reduces this difference to an insignificant amount. A small reduction in sensitivity accompanies this compensation.

h. Signal Transmission

The resistances encountered in the transmission lines of remote indicating systems are relatively small in comparison with the high inherent resistance of a Thermistor unit. For this reason remote signal transmission may be accomplished with insignificant errors where Thermistors constitute the sensory element.

i. Ruggedness

The very small physical dimensions of the Thermistor units employable in anemometer studies is attended by a considerable delicacy and susceptibility to damage in physical handling. This is a property common to all of the sensitive thermal anemometers but was not mentioned by Hales or Sanford as a limiting factor in practical use of Thermistor devices. However, in the pilot studies conducted at the St. Anthony Falls Hydraulic Laboratory some destructive damage was encountered in reasonably careful handling of both the bead (Western Electric D-176980) and rod (Bendix-Friez 517613-1) forms. Damage by physical field handling can be guarded against by suitable arrangement of the mounting and shielding accessories if only two-dimensional or horizontal winds are to be studied. However, damage by impinging or clinging dust, rain, or ice under storm wind conditions might be of a serious nature. Hales' use of the bead element in tropical micrometeorological studies and Sanford's laboratory studies are not deemed satisfying evidence of adequate ruggedness.

j. Secondary Ambient Effects

In addition to the temperature, radiation, dirt, icing, and rain effects previously discussed, it is conceivable that atmospheric humidity and density changes might cause measurable errors. No specific investigation of these conditions is apparent in the literature, but the basic similarity of operation of the heated Thermistor, the heated thermocouple, and the hot-wire anemometer makes the findings with regard to the latter instrument reasonably applicable to the former. On the basis of these findings, as separately discussed under the hot-wire anemometer, it may be concluded that reasonable natural changes of temperature and barometric pressure will not cause significant changes in density. Large changes in humidity caused significant shifts in hot-wire calibrations but are believed to be less significant to the Thermistor because its elevation of temperature is relatively much less.

k. Mounting Limitations

Since this device involves no utilization of wind or gravitational force, a rigidity of mounting and orientation is not essential to a reasonable measurement of the wind velocity. In addition, since the sensory signals are readily transmitted by cable it would appear that mounting by suspension from a moored balloon is quite practical and has, in fact, been accomplished in the studies described by Hales as shown in Fig. 35.

l. Development

Thermistor units are manufactured by the Western Electric Company and its licensees. Among these licensees are the Instrument Division, Victory Engineering Corporation, Springfield Road, Union, New Jersey; and Friez Instrument Division, Bendix Aviation Corporation, 1432 Taylor Avenue, Baltimore, Maryland. Correspondence contact with both of these latter organizations has established a willingness to cooperate in development programs leading to use of Thermistors in anemometers.

2. Summary

This device, which measures an electric voltage (or resistance) as the result of the convective cooling action of a wind on a self-heated proprietary resistance element known as a Thermistor, is believed to offer a practical and satisfactory means of measuring ordnance values of low-velocity winds near the earth's surface. In the bead form in which it has been extensively tested, it was found, comparatively, to be highly sensitive, rapidly responsive, stable, simple, compact, reasonably rugged, and inexpensive. The sensory head contains no moving parts and is adaptable to a variety of physical mountings. It can even be trailed to a considerable height in multiple units from a moored balloon for studies of wind pattern.

The basic resistance of the sensory element is high; the output can thus be readily transmitted for remote indication without serious errors of transmission. Electronic accessories are essential to the operation. The device is a modern development with a limited history of use in special research work. No commercial anemometer development activity is known.

Development to date has centered around measurement of velocity magnitude only. There have been no evident attempts to develop a nonrotated type of direction-sensing assembly although the potentialities of such a system appear fairly good.

H. The Heated Thermocouple Anemometer

1. General

This instrument, which is a relative newcomer to the field of anemometry, is based on principles which go back to the discovery of thermoelectric effects by Seebeck in 1821. While the use of the thermocouple in anemometry was only lightly probed prior to 1940, an extensive background development of the thermocouple in the field of thermal measurements has been pursued for a much longer time. The principles and materials for the more recent anemometer studies, therefore, draw heavily on the findings in the field of thermal measurements.

The basic operation of the thermocouple depends on the fact that when two selected dissimilar metallic wires are fused at their ends and the fused junction subjected to heat, an electromotive force will be generated and a current will tend to flow across the junction. Metals are selected with inherent characteristics which produce a maximum practical emf for a given temperature condition. A secondary emf and temperature relation also exists where the junctions of the two special thermocouple wires connect with lead wires going to the remainder of the electric circuit. Since a dissimilarity of metals also occurs at these unheated or so-called "cold junctions," a small secondary emf is generated at these two points. The externally measurable emf, which is an index of temperature, is then really measuring the difference in temperature between the "hot" and "cold" junctions, and the total emf is then a function of the magnitude of the temperature differential and the characteristics of the metals forming the junctions.

The material of the thermocouple proper is selected for the following characteristics:

(a) Resistance to external oxidation or corrosion which may produce drift in the calibration.

(b) Freedom from internal impurities which may cause parasitic currents and progressive shift in the calibration.

(c) Near constancy of resistance as a function of temperature.

(d) Near linearity of voltage as a function of temperature differential.

(e) The ability to be physically fabricated into a practical probe.

(f) The ability to withstand structurally the imposed loads (aerodynamic and adverse weather loads).

(g) Ability to be reproduced in quantity with essentially constant characteristics (important in reading multiple or alternate probes in a metering network).

A wide variety of pure metals and alloys has been used in combinations to produce thermocouples for various purposes. It appears, however, that the most satisfactory results are usually achieved with employment of the noble metals, most notably platinum and its alloys.

Since the total emf generated is only a small absolute value, accurate measurement of the differential temperature requires accurate measurement of a very small voltage. To further magnify this voltage for increased accuracy of measurement, it is customary to arrange a number of thermocouples in series and thus multiply the effect. Such a device with a large number of "hot" and "cold" junctions is known as a thermopile. The above-described assembly has been modified in a number of ways to improve the convenience, cost, or accuracy of its use in the field of temperature measurement.

The special modifications which permit this device to be used for air velocity measurements consist basically of heating the hot junctions of the thermocouple or pile with a measured supply of heat from an external source. Exposure of the heated thermocouple to the air stream whose velocity is to be measured will result in convective cooling of the heated junction and a consequent drop in the emf impressed across the junctions of the pile. This relation results in an emf which is inversely proportional to the air velocity. The emf may be read as velocity on a suitably calibrated voltmeter. In effect then, this instrument is similar to a hot-wire anemometer combined with a thermopile to produce an instrument which retains the sensitivity but not the delicacy of the hot-wire device.

It has been established analytically and experimentally [22] that the following equation, based on the same convective cooling principles as the hot-wire anemometer, approximates the velocity-voltage relation which exists for a heated thermocouple anemometer.

$$V = (C/E - k)^2 / 4\pi k s \rho d$$

where V is the velocity of the air stream,
E is the voltage generated by the thermopile,
C is a constant depending on units,
k is the thermal conductivity of air,
s is the specific heat of air at constant volume,
ρ is the air density, and
d is the diameter of the wire.

In the earlier forms of this instrument [14, 23, 24, 25, 26, 27], the metered heat supply for the hot junction was in the indirect form of a selected electric current fed into a resistance heating coil which surrounded or contacted the hot junction of the thermocouple or pile.

In a later form [22, 28], heating is accomplished by superimposing a suitable alternating current directly across the thermopile itself while simultaneously maintaining a d-c measurement of the developed thermocouple emf. This later form appears to offer considerable physical simplification of the sensory probe unit, and by reduction of the probe mass and consequent thermal lag materially improves the time response of the instrument to fluctuating velocity conditions.

The general nature of the calibration curve obtained with a heated thermocouple anemometer is demonstrated in Fig. 38, which is taken from [28]. Note that it is the nature of the curve to produce rapid rates of change or high sensitivity in the low-velocity range. This unique property of characteristic thermal anemometer curves is especially desirable where low velocities are of interest.

While Fig. 38 represents a calibration for a selected magnitude of electric heating current, the range of velocity coverage may readily be shifted substantially to the right or left by merely changing the magnitude of the selected heating current. A family of more or less parallel curves may be obtained by such selection. The curves may also be adjusted in position by changing the relative proximity of the hot and cold junctions, since the greatest emf will be maintained when the cold junction is sufficiently remote to be beyond the thermal influence of the hot junction. However, practical, compact packaging of the probe elements for many applications may dictate that less than the optimum proximity be employed. In such cases, adequate emf generation may depend on additional thermocouples in the pile. Additional couples and emf boost may also be essential in very low-velocity instruments because only moderate heating currents can be employed lest the heating action itself induce secondary convective air currents which tend to confuse or obscure the air current which is being measured. With suitable adjustment of these control variables, this type of instrument has been used for velocity measurements varying between 0.083 fps and 600 fps.

In one modern commercial form of this device [22], the thermopile consists of alternate sections of dissimilar noble metal wires butt-welded together to form a continuous wire. The cold junctions of the couple are attached to copper mounting studs which by reason of their relatively larger mass, area, and thermal conductivity serve to bring the cold junctions approximately to the ambient temperature of the air stream to which the copper studs are exposed, even though the hot junctions (of small mass) are in rather close proximity to the cooling studs. A nondirectional probe head of this type, made by the Hastings Instrument Company of Hampton, Virginia, is shown in Fig. 39. The measured diameter of the thermocouple wires in this unit was 0.0035 inches.

An additional adjustment has been employed in this instrument to alter the fact that a normal heated thermocouple arrangement delivers a voltage output which is maximum for zero air velocity and decreases with increasing velocity. This effect can be reversed and some improvement accomplished in adjusting the accuracy and range coverage by including in the circuit a second series of thermocouples which are of opposite polarity. These thermocouples are physically shielded from exposure to the air stream. With this arrangement, the indicator may be adjusted to read zero voltage at zero air velocity and the full-scale voltage reading may be adjusted to the selected velocity range.

This instrument has also been provided with a third thermopile to insure corrective rapid instrument response to sudden temperature changes in the observed air stream. Slow temperature changes will have an approximately equal effect on the hot and cold junctions of the original two thermopiles, and the instrument reading will show no significant influence by changes in ambient temperature or radiation conditions. However, if the temperature changes are rapid, compensation is necessary because the thermal capacity and thermal inertia of the small hot junctions differ materially from those of the large stud-mounted cold junctions. Consequently, sudden temperature changes give a meter indication similar to a sudden velocity change. The third thermopile is selected to provide a corrective polarity opposed to that of the hot junction thermopiles and is exposed to the air stream. This unit is disposed in series in the d-c-measuring circuit and can be made fully corrective for all practical temperatures and accuracies.

The circuit diagram for this type of unit is shown in Fig. 40. In it, the a-c transformer supplies heating current and provides a center tap which permits installation of the d-c voltmeter in a line which has small a-c potential. The practical range, sensitivity, and readability of this type of instrument when employed with standard self-balancing potentiometer indicators and recorders is demonstrated by the representative instrument scales shown in Fig. 41.

Since the electrical output of a thermocouple is in the form of a voltage, remote indication or transmission of the signal for a considerable distance without distortion is readily possible and has some advantage over anemometers which produce a weak current as the basic signal. Shielding of the transmission from induced currents may be necessary in exceptional installation conditions but is not normally required.

The instruments employed for measuring the signal voltage require careful selection or circuit adjustment to give emphasis to the most desired velocity range. It is apparent from the form of the basic equation and the shape of the curve of Fig. 38 that the greatest sensitivity occurs in the low-velocity end of the range covered. Therefore, problems requiring a large range of coverage may necessitate provisions to step-regulate the heater current to achieve best reading emphasis for a particular velocity condition. Regulation of this type may be manual or automatic depending on the problem requirements.

Power supply to the heater element of the instrument appears to be most satisfactory in the form of alternating current; and 110-volt, 60-cycle equipment has been developed. Where the voltage source varies significantly a voltage regulator is recommended as a basic part of the equipment.

The amount of power required to heat the thermocouple for an effective emf output is a variable depending on the particular characteristics of the thermopile and its exposure. The Hastings nondirectional unit was found to require approximately 100 milliwatts of 110-volt a-c power.

Since the physical arrangement of this type of meter has been designed to provide sensitivity to the velocity properties of the air stream, it may be well to examine the possible influence of variations in the other more common properties of the stream, notably the temperature, barometric pressure, and vapor content or humidity. Temperature effects and their corrections have already been discussed in their direct function, but since temperature may also adversely influence the k, ρ, and s values (thermal conductivity, density, and specific heat) of the previously given characteristic equation, it should also be re-examined.

A review of the previously given characteristic equation for the performance of this instrument indicates that k, ρ, and s are the only quantities which will be affected by probable variations in the more common properties of the air stream. The question of whether the ambient changes are sufficient to affect the instrument accuracy significantly has been discussed by Ower [4]*, Hastings [28], and Schubauer [5] and is here separately

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*Ower, pp. 243-245 and 284-286.

discussed in the treatment of similar considerations for the hot-wire anemometer. The conclusions are that large changes in ambient conditions must be corrected for if high accuracy of results is to be expected. However, the effects of nominal ambient changes are usually considered negligible.

The housing unit for the thermopile probe unit may be built in a variety of shapes to suit the nature of the particular velocity problem. In the Hastings nondirectional sensory unit shown in Fig. 39, housing pieces have been arranged above and below the thermopile to minimize the influence of contact by rain and snow or radiation effects from solar or other sources. This unit may also be provided with special heaters to combat severe icing conditions although moderate icing may be controlled by the inherent heating action.

A somewhat cleaner and more rugged housing arrangement was achieved [23] by incasing the thermocouple and heater elements within a small metal sphere. While the nondirectional characteristics of this design were good, the metallic mass of the housing introduced quite large thermal lag and slow velocity response.

The sensory element has also been condensed to fit within the tip of a housing shaped like a Pitot impact tube. In this form it has been used like a Pitot for determination of velocity distribution details. Since thermocouple dimensions are small, such units have, on occasion, been built with small overall tube dimensions. Unfortunately, these units acquire their directional properties only in response to proper mechanical rotation of the sensory head in the correct orientation.

A commercially available unit of this type developed principally for use in air conditioning studies is known as the "Alnor Thermo-Anemometer." This unit, which is built by the Illinois Testing Laboratories of Chicago, Illinois, is a compactly packaged, portable, battery-operated unit. It is shown in Fig. 42.

The velocity indicator has two selectable ranges which are 0-300 and 70-2000 fpm. The single sensory thermocouple is formed by crossing and fusing two dissimilar wires and physically arranging them in a structural pyramid within a 1/4-in. diameter probe tube as shown in Fig. 43. An examination and a few tests of a typical unit of this instrument at the St. Anthony Falls Laboratory disclosed the following features and characteristics.

1. There was no evidence of compensation provisions for temperature effects. The thermocouple was observed to operate at an elevated temperature which should materially reduce the ambient temperature sensitivity.

2. The simple circuit arrangement utilized low voltage and appreciable current, and required adjustment for the lead cable employed. The basic circuit would not permit remote transmission without additional compensation or provisions.

3. Measurement of the time constant (63 per cent defined thermal time constant) of the sensory head alone gave a value of about 0.55 sec at a velocity of 0.42 fps with values progressively declining to about 0.12 sec at 8.3 fps.

4. Starting with the axis of the hole in the sensory head (see Fig. 43) aligned with the wind, the probe rod could be rotated about its axis about ±25° without producing a significant change in the velocity reading.

There is no evidence of development of an all-electric, stationary, nonmechanical direction-sensing device based on the thermocouple, although development of a thermocouple-equipped assembly similar to the Thermistor directional unit utilized in Fig. 36(c) may offer some promise. Such a unit would have multiple thermocouples disposed about a stationary vertical cylinder with differential readings indicating the direction.

The dimensions (1.8-in. diameter) of a nondirectional head of the type shown in Fig. 39 are relatively small in terms of meteorological dimensions and may be considered to give a point velocity. While meteorological experience with this device is limited, one of these units has been in continuous use for several years in a mounting on top of a building and is stated [22] to have consistently delivered velocity data without failure or zero shift. It is conceivable that accumulated dirt deposits on the thermopiles may cause a calibration shift with time, but simulated tests [22] of this possibility indicated that less than a 5 per cent drift may be expected and may be compensated for by a simple adjustment of the heating current to the probe to produce a rezeroing of the indicator under zero wind conditions.

The Hastings literature does not contain factual data as to the time of response of the heated thermocouple unit to velocity fluctuations, but an examination of the general literature on thermocouples proved quite helpful.

The work of Carbon, Kutsch, and Hawkins [29] utilizing a platinum couple and a limited set of variables resulted in the response data shown in Fig. 44. This curve indicates that a wire of 0.003-in. diameter (the measured diameter of the Hastings unit) might be expected to yield a response time of about 0.1 sec for a wind of 30 fps. The response time was established to be a function of Reynolds number and not the velocity alone.

The work of Scadron and Warshawsky [30], which employed a substantial range of conditions of analysis and test, established that the thermocouple material, configuration, and size, together with the gas pressure, Mach number, and Reynolds number, influence the time constant. While the nature of the Hastings material is unknown and the configuration and Mach number of interest are a departure from the character of the other units tested, the data indicated that by an extrapolated rough estimate the time constant of the Hastings instrument should be about 0.1 to 0.2 sec for a wind of 30 fps.

As a subsequent check on these estimates, the responsiveness of the Hastings instrument was actually tested in an approximate manner at the St. Anthony Falls Hydraulic Laboratory by a very rapid change of wind exposure from zero to about 20 fps. An analysis of the response records indicated that the measured response time was approximately 0.09 sec.

Since all of the above three time values are for the 63 per cent defined thermal time constant previously described for the Thermistor unit, they must be multiplied two or three times to approximate a practical response time. On this basis the response time for a thermocouple anemometer of the Hastings type would be of the order of 1/4 to 1/3 sec. It is believed that additional circuit compensation might reduce this to about 1/10 sec.

Mounting of a thermocouple anemometer for natural wind measurements may be done in the same manner as that employed for conventional weather instruments; that is, on a mast positioned at a desired point. If multiple mountings on a vertical support are required they may be made on a rigid or guyed mast or tower with horizontal offset spars supporting the individual probes or, conceivably, with a vertical cable pendent from a spar at the top of the mast or tower. The geometrical make-up of the probe unit shown in Fig. 39 would permit incorporation of the probes directly in the cable line with the cable made up to provide the requisite multiple electric leads as well as the tensile support. While the rigidity of support provided by a structural tower is highly desirable, it is believed that satisfactory measurements could also be achieved in temporary field installations by substituting a moored balloon for the tower. Studies extending to a considerable height might be accomplished by such an approach.

Commercial sources of development experience with this type of anemometer are believed to be found only in the Hastings Instrument Company of Hampton, Virginia. Correspondence with the company indicates that they have already had extensive experience with developments of this device for specialized application by the military services and their contractors, and they are prepared to expedite other special developments.

It is also possible that the Illinois Testing Laboratories can build a thermocouple type of unit that is better adapted to field meteorological studies than their Alnor Thermo-Anemometer.

2. Summary

This device, which measures an electric voltage as the result of the convective cooling action of a wind on a heated thermocouple, is believed practical and satisfactory for measuring low-velocity winds near the earth's surface. It is sufficiently rugged to sustain the abuse of normal natural winds and weather, yet it retains enough sensitivity and responsiveness for adequate accuracy. The sensory head contains no moving part and is adaptable to a variety of physical mountings. It can even be trailed to a considerable height in multiple units from a moored balloon for studies of a wind pattern. The basic output of the device is a voltage with full-scale values of the order of 10 millivolts. The output may readily be transmitted for remote indication and no amplifying elements are necessary

The device is a modern development with only a limited history of commercial exploitation in meteorological anemometry, but it is based on old and proven thermoelectric principles and materials.

The sensory head is at this time limited to measurement of velocity magnitude only, and separate means must be provided for determination of wind direction.

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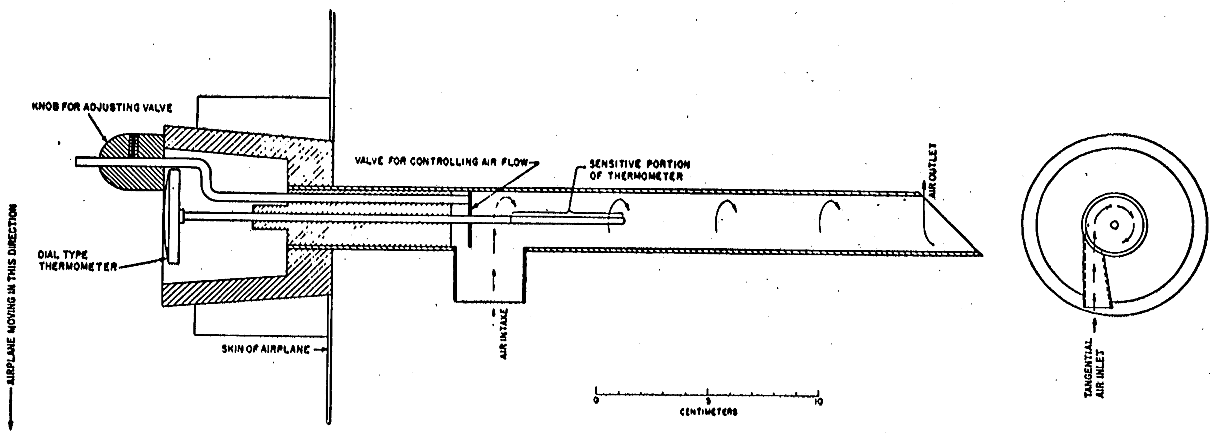


Fig. 23 - Physical Arrangement of Vortex Thermometer Air Speed Indicator [2]

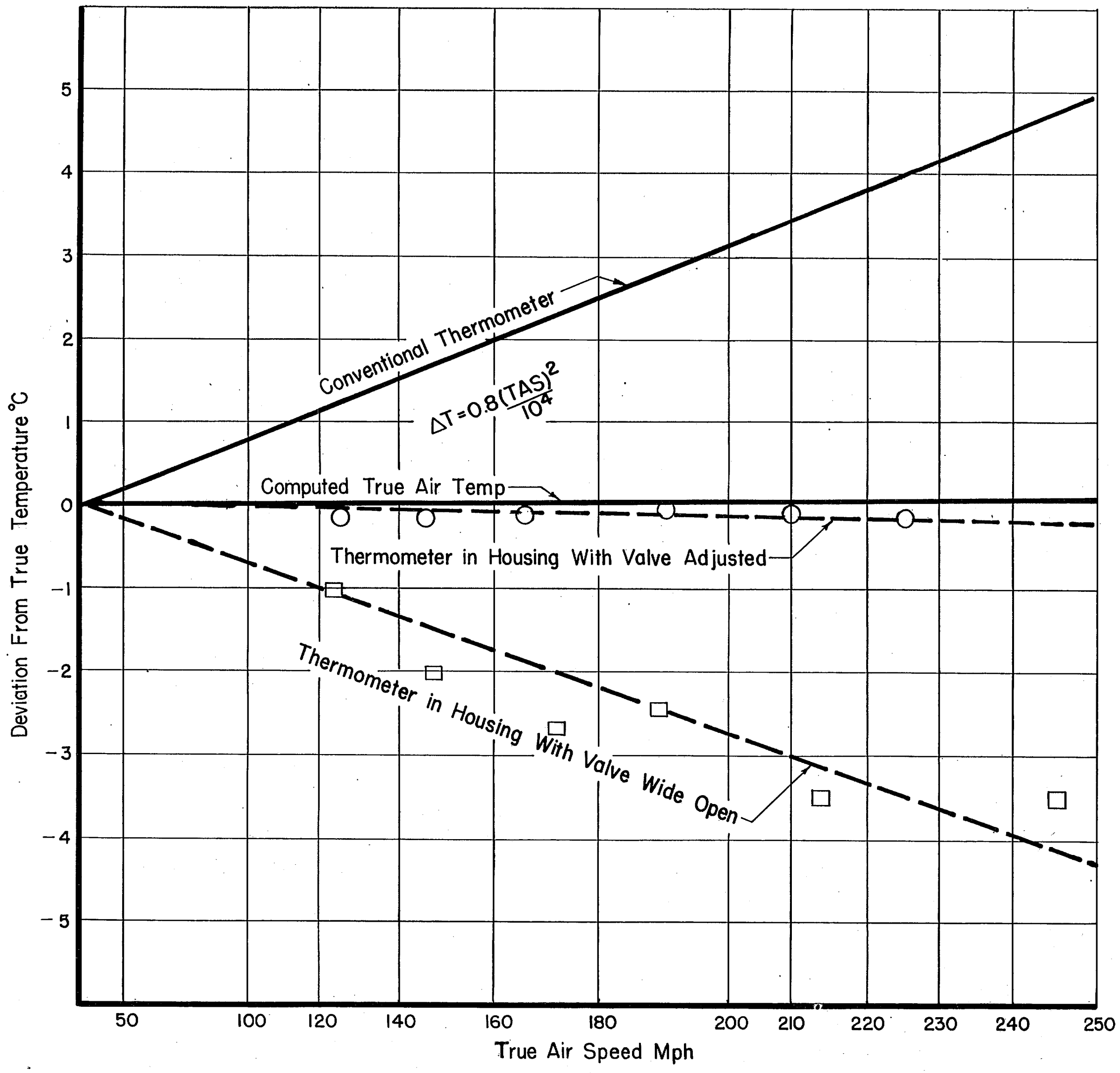


Fig. 24 - Variation of Temperature with Velocity in the Vortex Thermometer Air Speed Indicator of Fig. 23 [2]

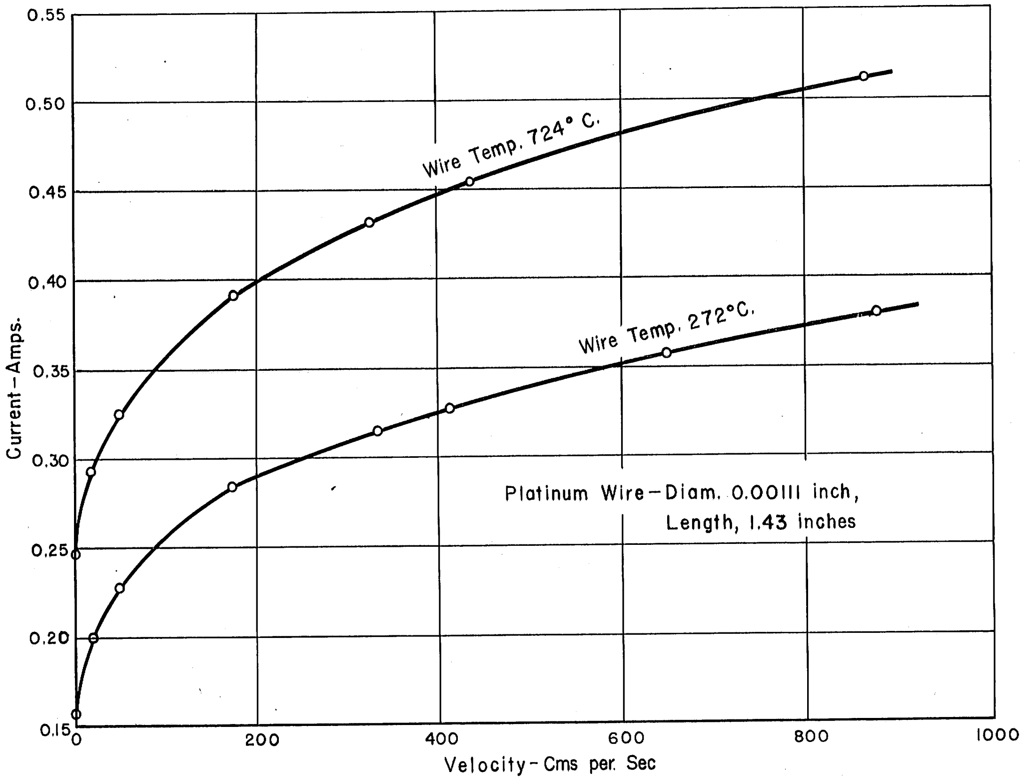


Fig. 25 - Typical Characteristic Curves for a Hot-wire Anemometer Positioned Normal to the Air Stream and Operated under Constant Temperature Conditions [4]

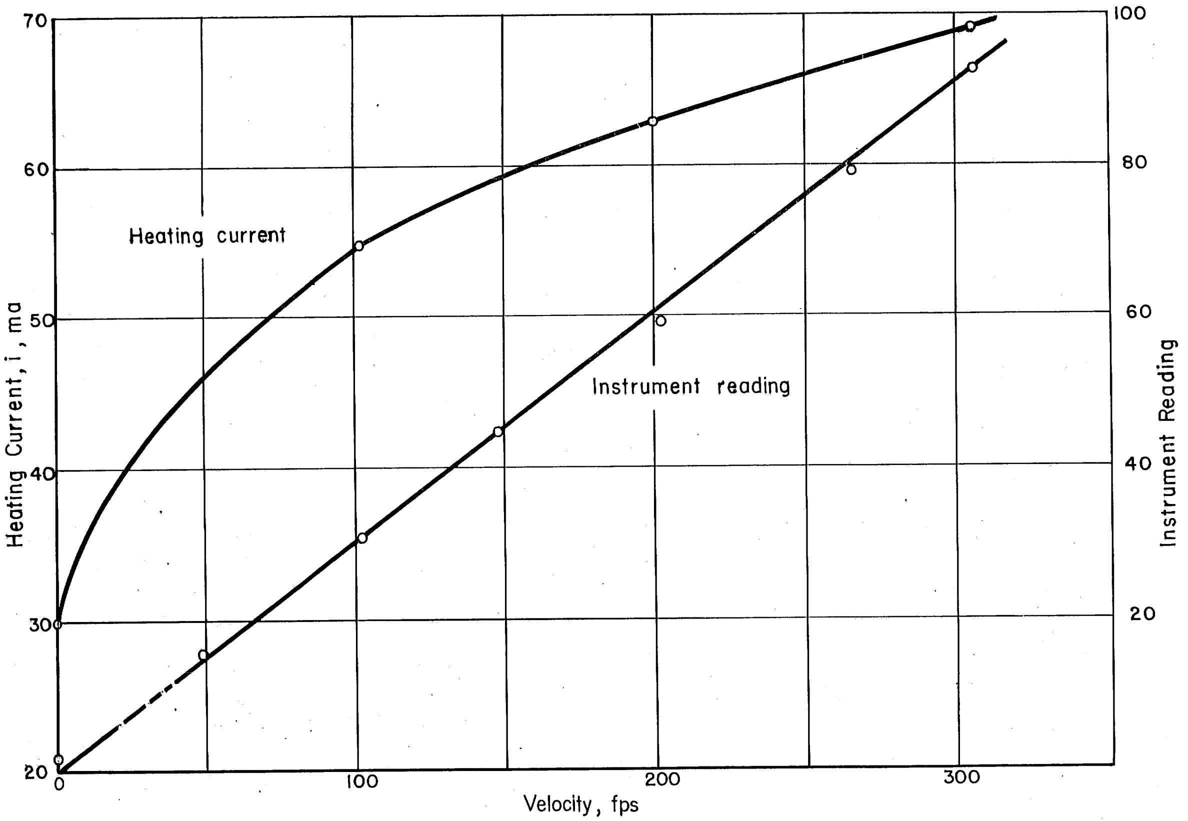


Fig. 26 - Adjustment of Normal Fourth-Power Curve to a Linear Form for a Wire 0.0005 Inch in Diameter and 7/32 Inch Long [6]

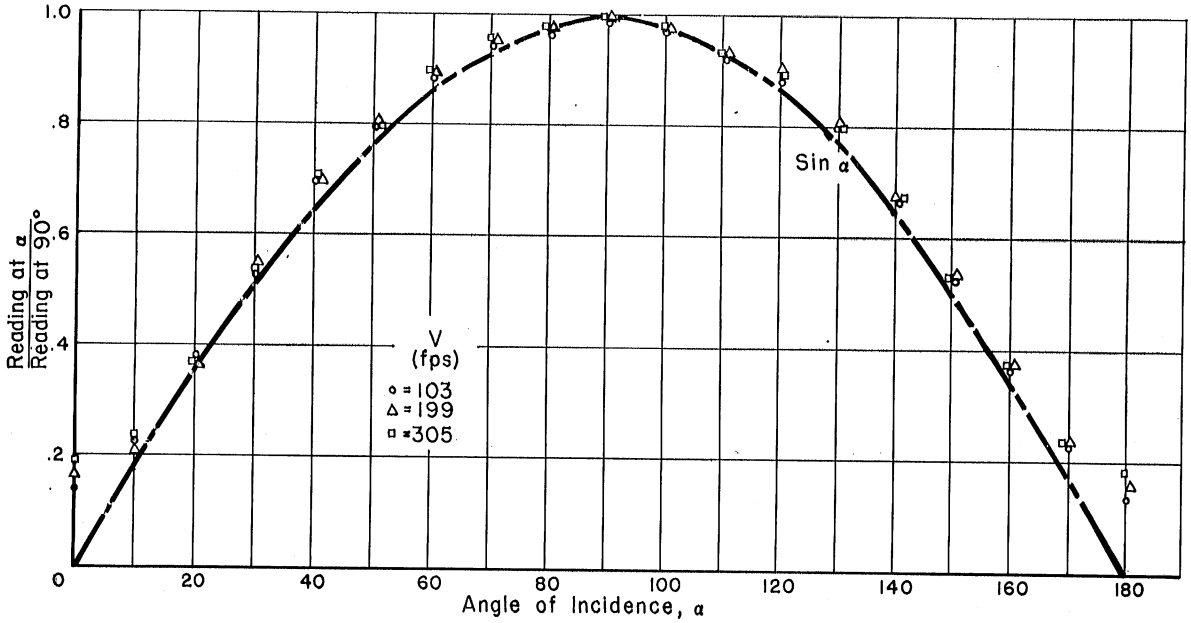


Fig. 27 - Directional Characteristics of a Hot-wire Anemometer [6]
(nickel wire of 0.0005-in diameter, 7/32-in. length; circuit adjusted to linearity; α = 90° with wire normal to flow)

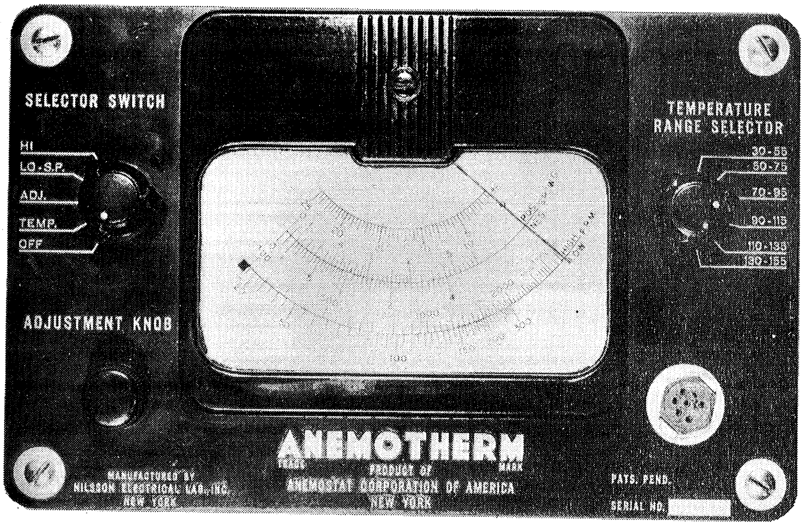


Fig. 28 - Control and Indicator Face of the Anemotherm Unit

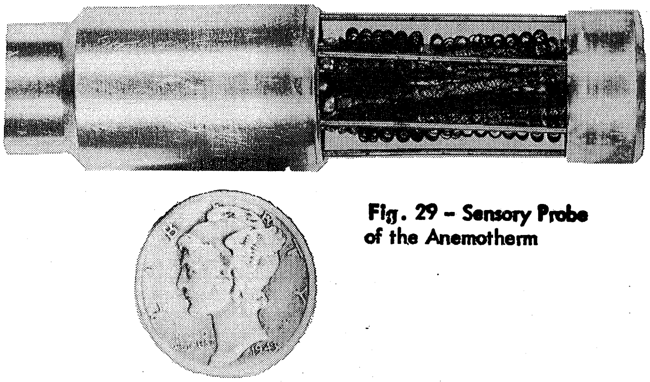


Fig. 29 - Sensory Probe of the Anemotherm

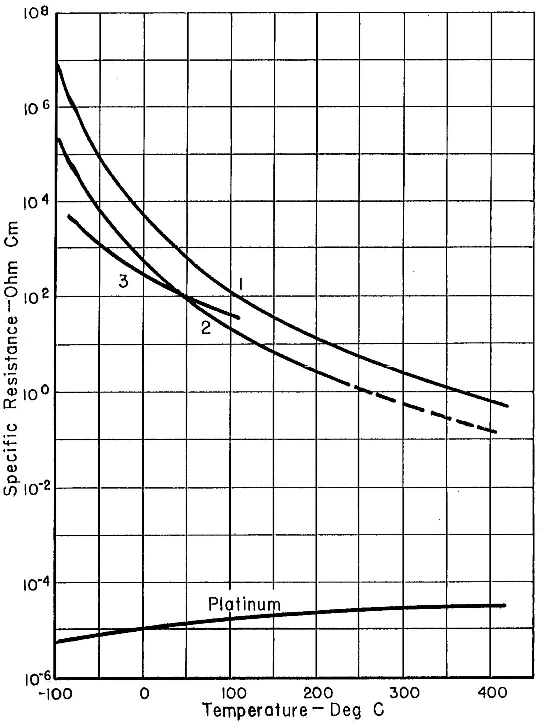


Fig. 30 – Specific Resistance vs Temperature for Three Thermistor Materials Compared with Platinum [19]

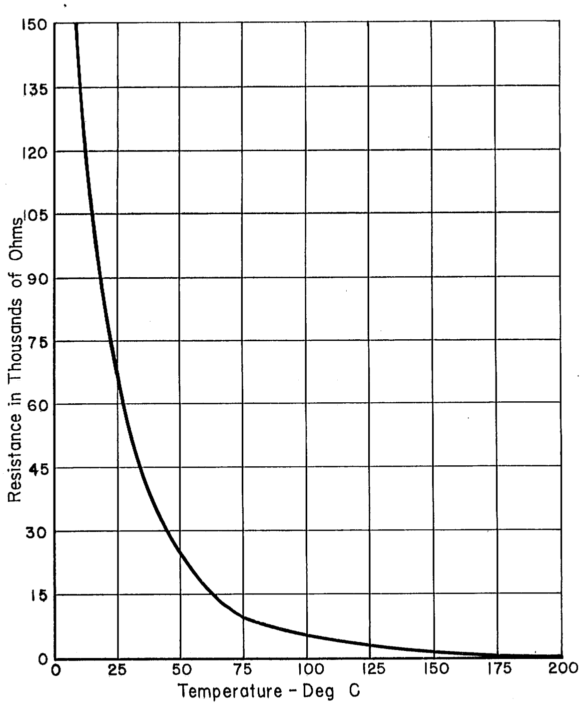


Fig. 31 – Resistance of a Bead Thermistor vs Temperature [16]

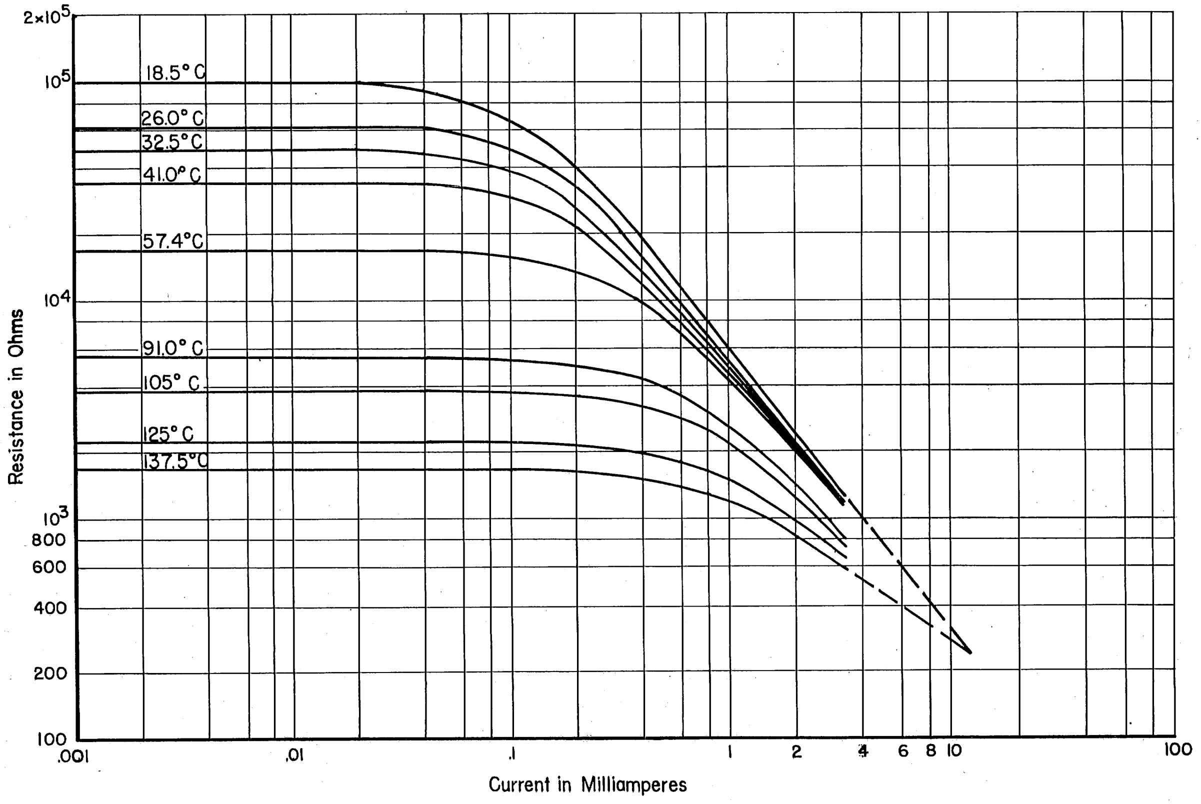


Fig. 32 – Resistance of a Bead Thermistor vs Current for Various Ambient Temperatures [16]

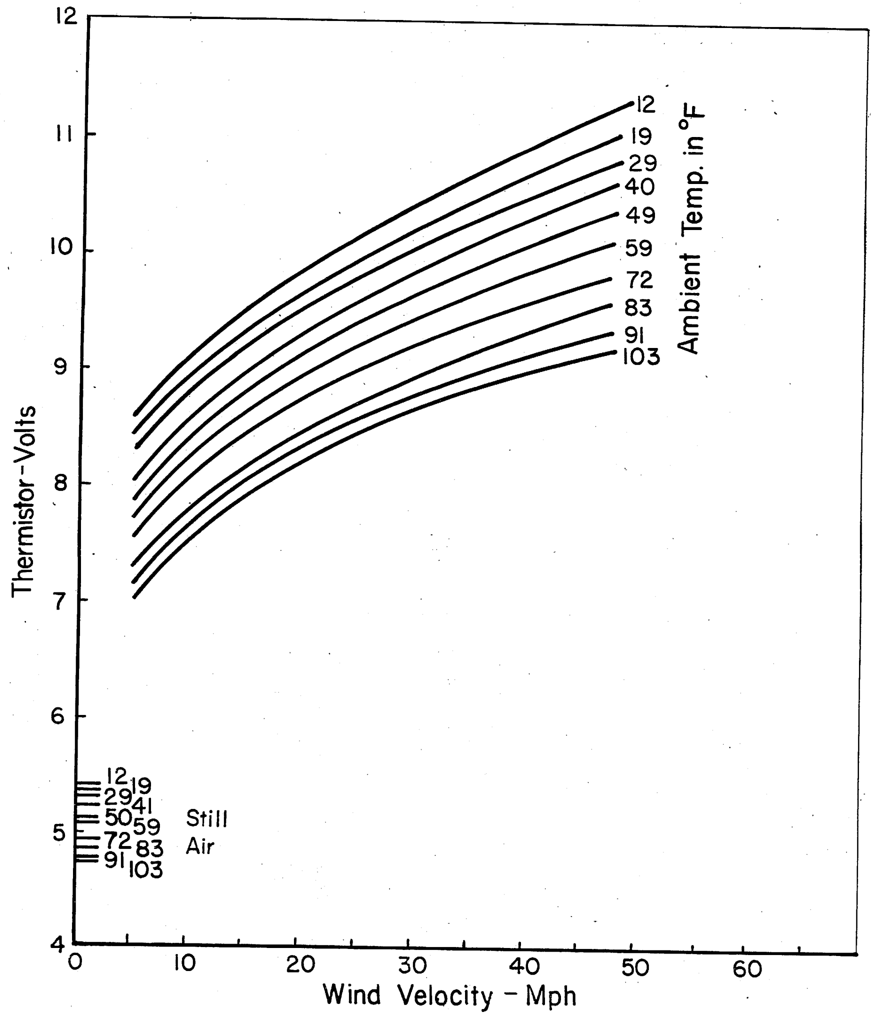


Fig. 33 - Voltage Output of a Bead Thermistor vs Wind Velocity [17]

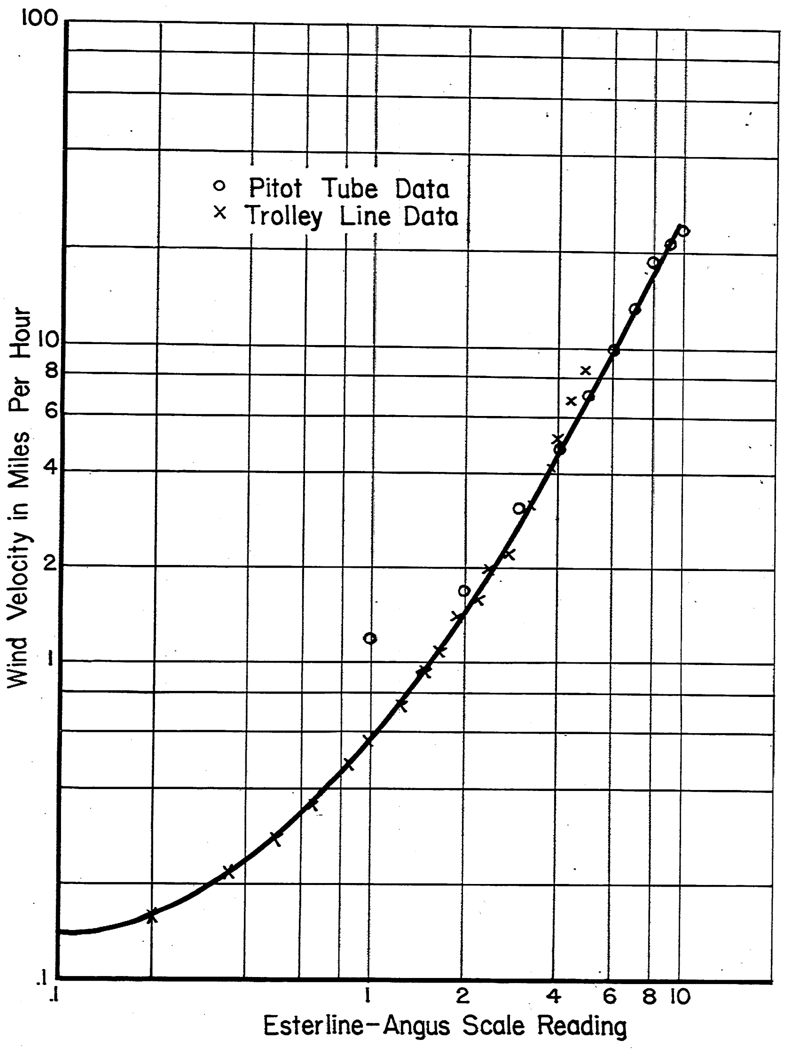


Fig. 34 - Calibration Curve for a Bead Thermistor [16]

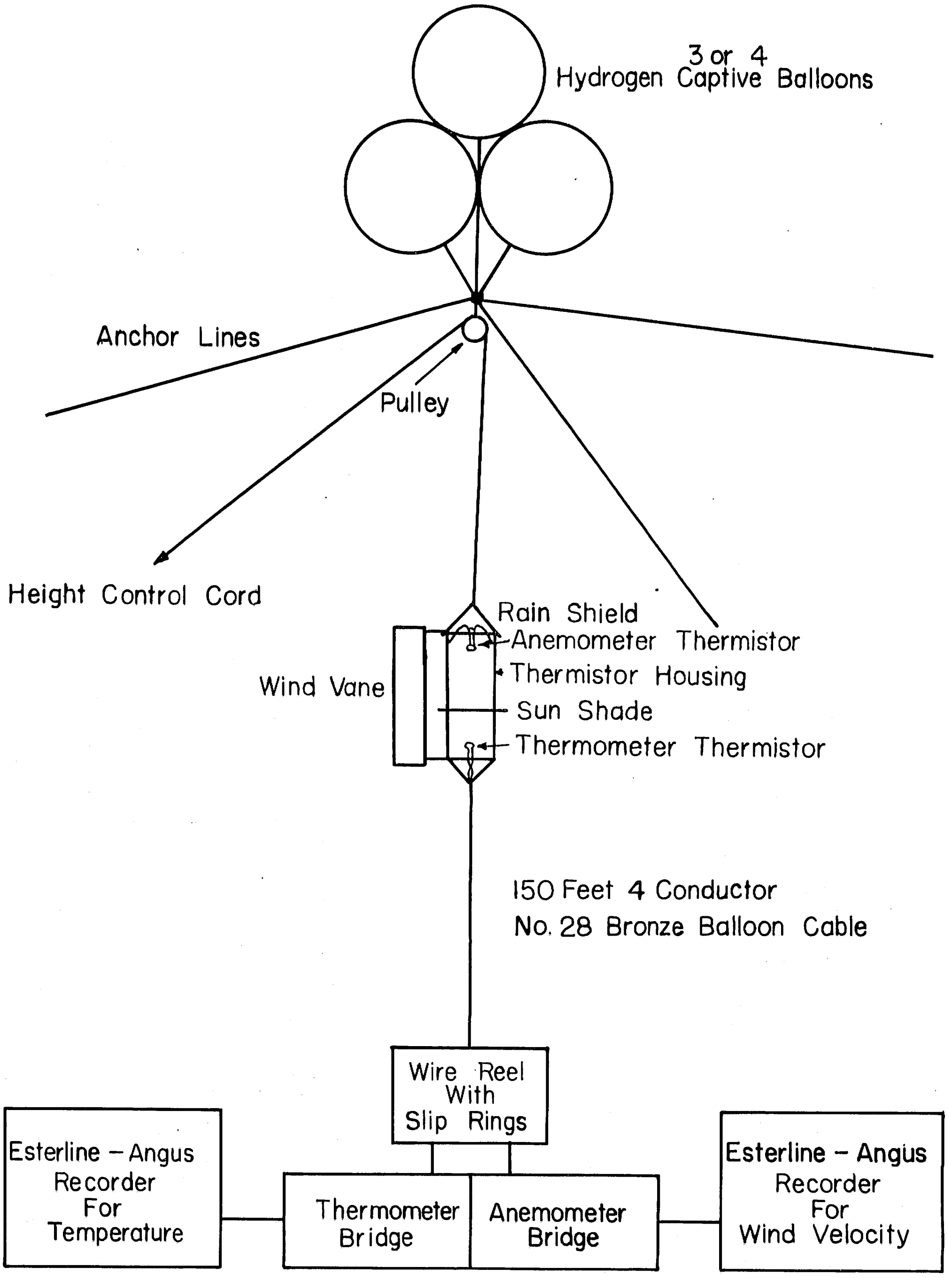
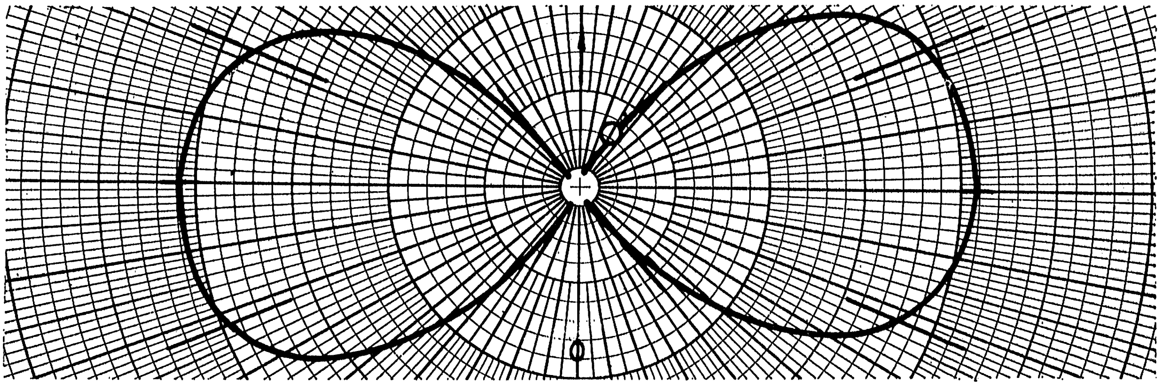
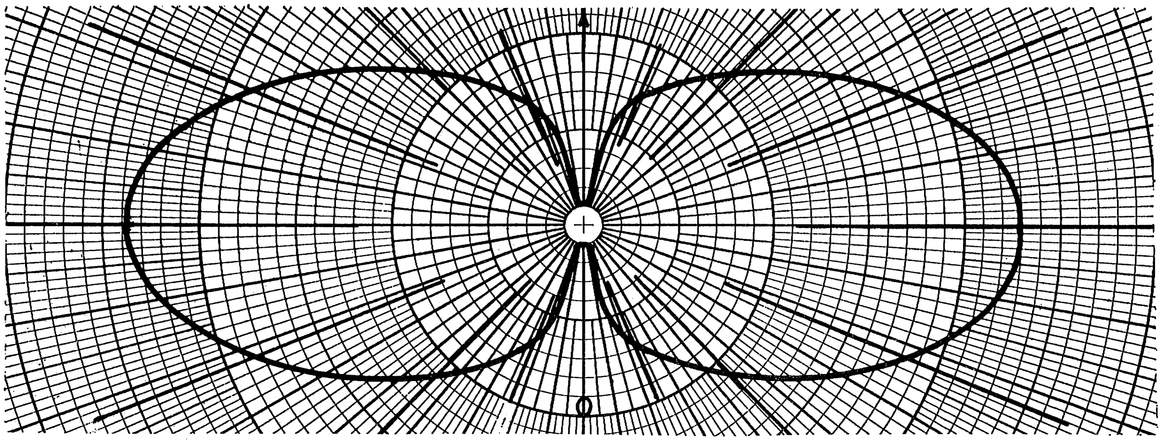


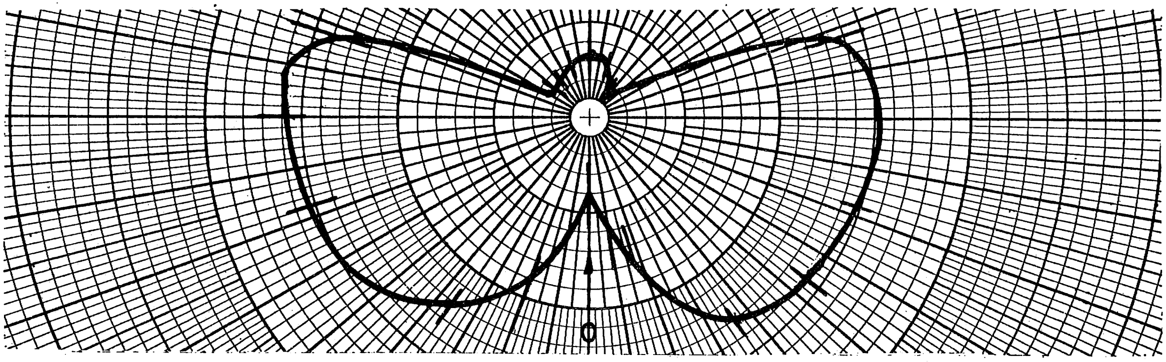
Fig. 35 – Thermistor Anemometer Arrangement as Employed by Hales [16]



a. A Western Electric rod Thermistor Type 13A was revolved in a plane parallel to a wind stream. Galvanometer readings are plotted against angular position of the Thermistor with zero corresponding to the Thermistor axis parallel to the wind.



b. Two Western Electric rod Thermistors Type 13A were placed parallel to and in close proximity with their mutual axis normal to the wind stream. Angular values are for revolution about the mutual axis with zero occurring when both rods face the wind.



c. A Bendix-Friez rod Thermistor 517613-1 was mounted 1/8 in. from surface of and parallel to the axis of a 1-in. diameter cylinder. Cylinder axis was normal to wind. Angular values are for rotation of Thermistor about cylinder axis with zero corresponding to the Thermistor facing the wind.

Fig. 36 - Variation of Velocity Indication with Angular Positions of Thermistors Placed in a Steady Wind

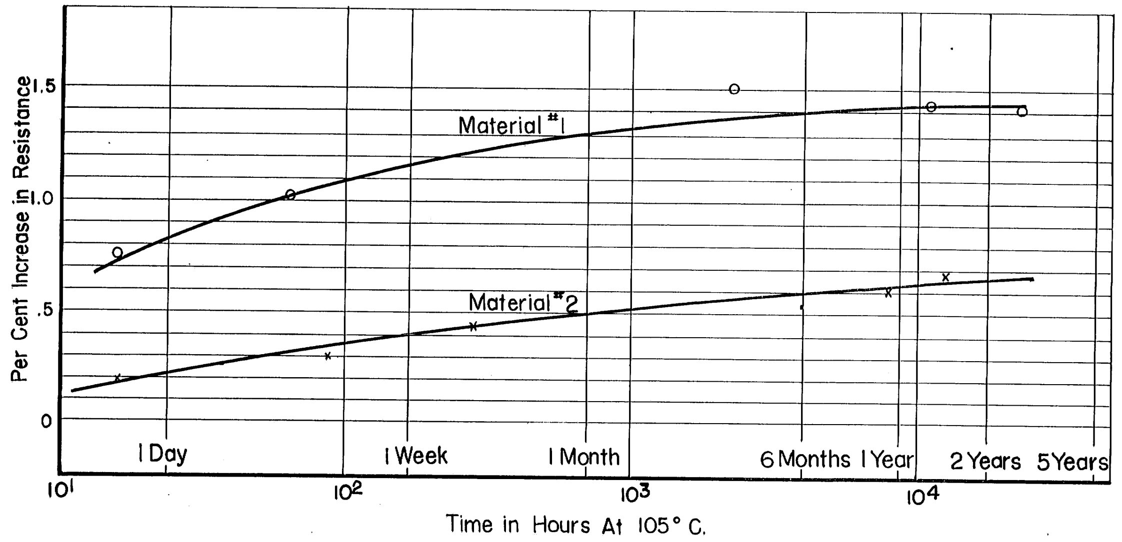


Fig. 37 - Aging Characteristics of Thermistor Materials [19]

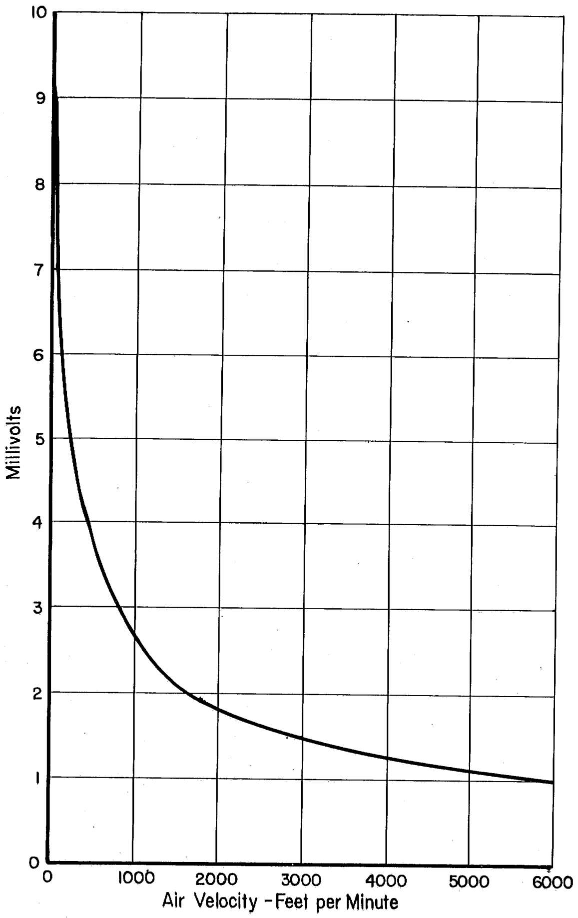


Fig. 38 - Effect of Air Velocity on the Voltage Output of a Two-Element Thermopile [28]

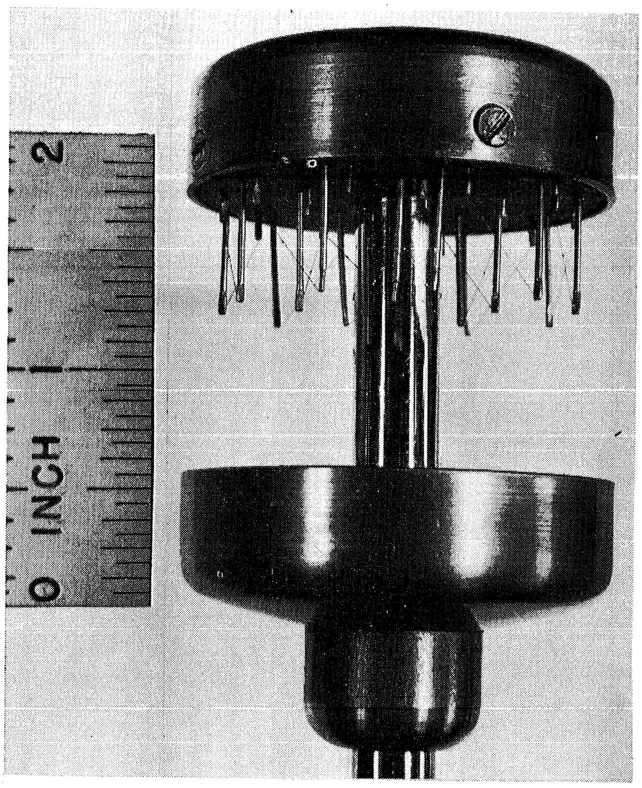


Fig. 39 - Nondirectional Anemometer Probe of the Heated Thermopile Type as Made Commercially by the Hastings Instrument Company

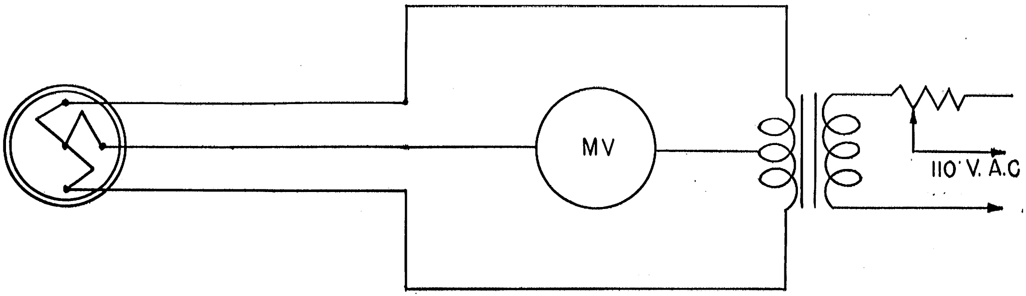
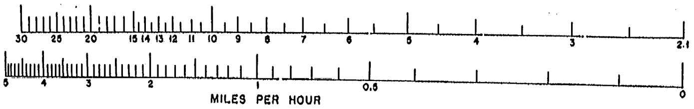
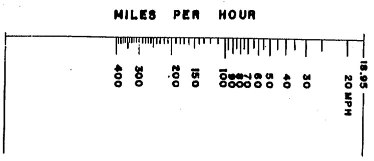


Fig. 40 - Circuit Diagram for Elementary Heated Thermopile Anemometer [22]



(A) 2 RANGE LOW VELOCITY CALIBRATION ON A BROWN 11" STRIP RECORDER



(B) HIGH RANGE VELOCITY CALIBRATION ON AN ESTERLINE — ANGUS 5" STRIP RECORDER

Fig. 41 - Calibration Scales for Commercially Produced Heated Thermopile Anemometer Units [22]

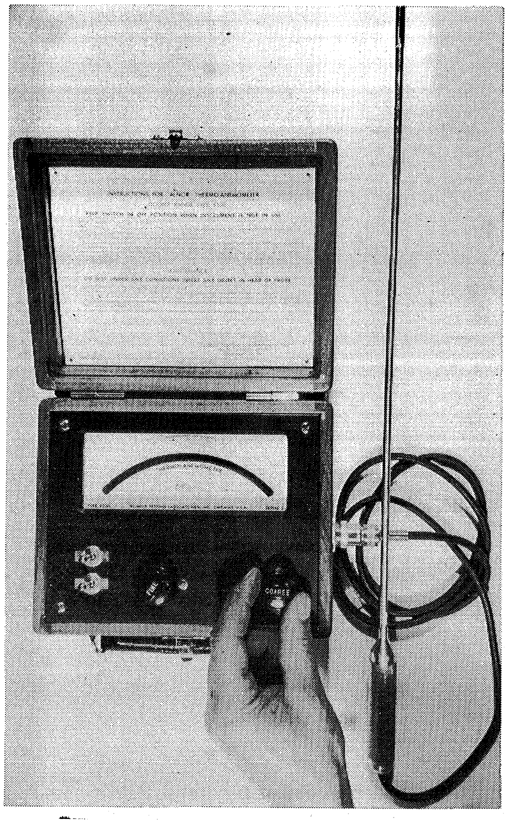


Fig. 42 - The Alnor Thermo-Anemometer

The tip of the probe is covered with a removable cap.

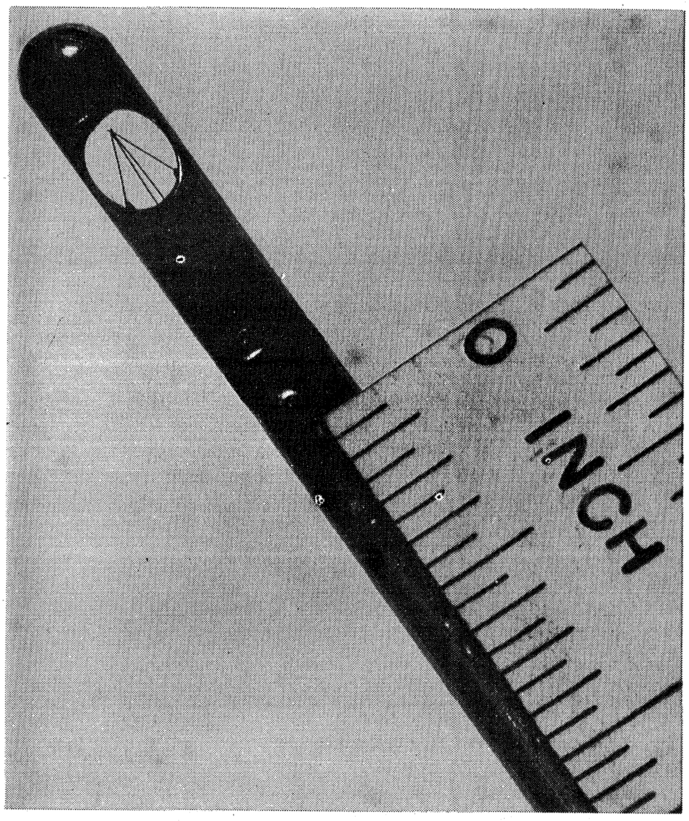


Fig. 43 - Sensory Probe of the Alnor Thermo-Anemometer with Cover Removed

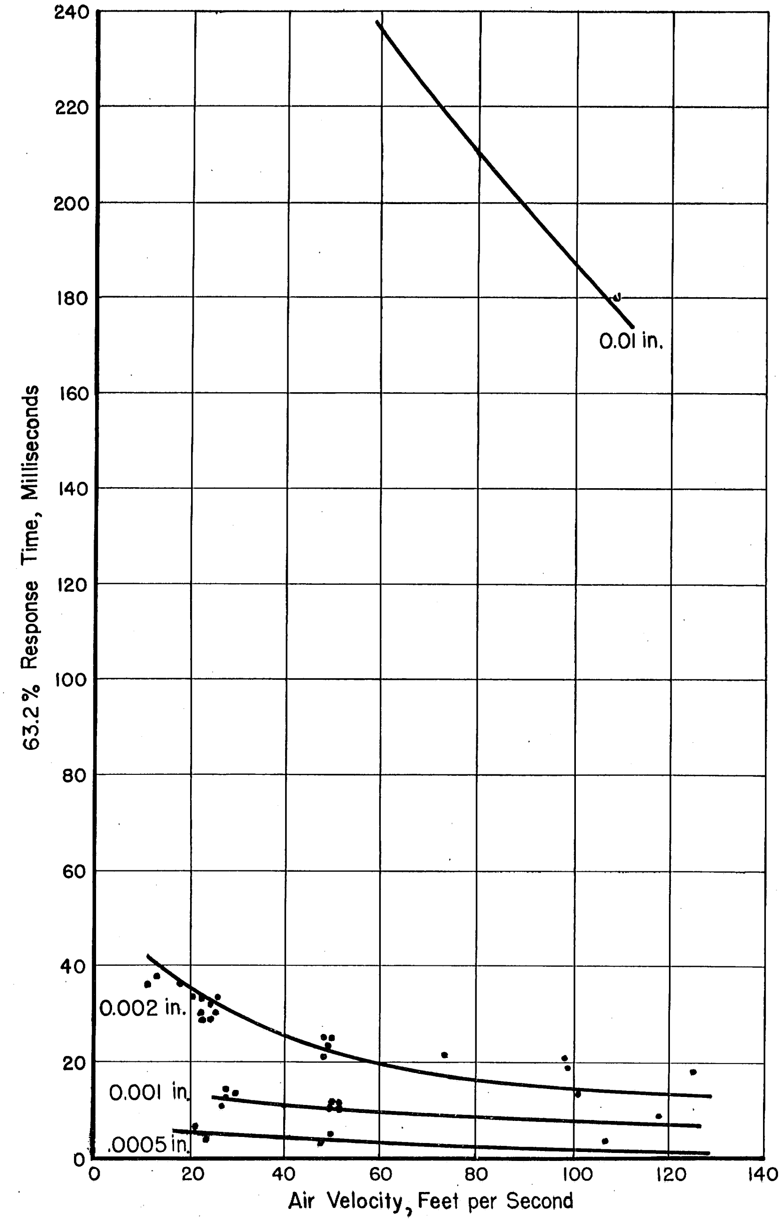


Fig. 44 – Response Time vs Velocity for Simple Platinum Thermocouples of Various Diameters [29]

IV. IONIZATION ANEMOMETERS

A. General Considerations

The use of additive tracers to determine rates of motion or motion patterns in a moving fluid stream are among the oldest and commonest of experimental techniques employed in fluid dynamic studies. While most of these methods have relied upon flow visualization such as smoke in air, dye in water, etc., for detection of motion, others have employed sensory systems utilizing tracers of a thermal, electrical, or chemical nature. It is the purpose of this section to discuss systems which produce and detect electrical tracers in a moving stream of air for the purpose of measuring the air stream velocity.

The structure of air which has been exposed to certain special electrification processes is said to be ionized if it contains a greater than normal number of free ions. Such ions are not static but possess an inherent motion. Fortunately their average motion is quite slow in the absence of a strong electrical field, thus the ions serve as quite typical electrical tracers of any bulk motion of the air. The presence of these ions in the air contributes two distinct properties which can be electrically measured in terms of velocity. These are:

(a) The charged ions of the ionized gas when placed in the electrical field of two oppositely charged electrodes will collect on the electrodes, or if continuously supplied will support a flow of electrical current between the electrodes.

(b) A moving cloud of charged ions possesses a moving electrical field capable of inducing a detectable electrical signal in a suitable electric circuit exposed to the moving field.

Anemometers based on the first principle measure the air velocity by electrically measuring the magnitude of the steady transport of ions existent between two charged electrodes; the amount of transport of such ionized particles and their paths are affected by the sweeping action of the wind as it passes between the electrodes.

Anemometers based on the second principle generally consist of a device which permits controlled ionization of some of the air stream particles in a given region or station in the flow field and subsequent detection of the presence of the ionized particles at a separate downstream station. Most of these systems have measured the time interval required for a small cloud of the ionized air to move over a measured distance between the two stations. The distinct cloud of ions is produced by an upstream pulsing or cycling ionizing device.

Anemometers utilizing ionization phenomena have been the subject of occasional investigations since about 1920 and have undergone rather intensive investigation since about 1945. To date, none of these investigations has produced a finished instrument suitable for meteorological field measurement. No apparent effort is being expended in this direction, since the principal recent development is directed toward high-velocity aeronautical research instrumentation. The latter emphasis stems from the fact that the method inherently permits:

(a) Velocity measurement from a flush-mounted boundary wall installation without disturbing the flow field with struts, probes, etc. This feature is of special value in transonic or supersonic studies.

(b) Detection of velocity pulsations or turbulence structure at frequencies far beyond those of other instruments (considerably exceeding the 40,000 cps associated with the hot-wire anemometer).

Despite the fact that the aeronautical instruments are wrapped up with physical complications and that the meteorological field is unprobed, the potentialities of the principles are deemed worthy of a moderate detail of discussion herein.

B. The Ionizer

Ionization of the atmosphere to a level sufficient to support wind-velocity measurements by means of electrical detectors can be achieved by two general types of action with numerous offshoots as follows:

1. The atmosphere may be exposed to bombardment by high-speed electrons or nuclei whose proximity of passage or impact will remove electrons from neutral molecules and form new ionized or charged particles. The usual means of accomplishing this are:

   (a) Expose the atmosphere to naturally emitted electrons (alpha or beta particles) from radioactive materials.

(b) Expose the atmosphere to artificial emissions from an electron gun.

(c) Place the atmosphere in an electric field of sufficiently high potential gradient that its normally present ions will be accelerated therein to velocities which will in turn produce additional ionization. Corona, glow, or arc conditions are representative of such action.

Ionization of atmosphere by the above means may be continuous or intermittent, as desired.

2. The atmosphere may be exposed to electromagnetic waves of sufficient strength to energize and force attached electrons from neutral atoms, thus producing ions. Gamma rays from radioactive substances and x-rays or cosmic rays have fields of sufficient strength to produce such action.

An examination of the literature relating to ionization anemometers indicates that ionizers have been employed utilizing all three of the systems under Class 1, but the shortcomings and physical complications associated with Class 2 have apparently ruled out its development. Since virtually all effective ionizers involve hazardous emissions, rays, or high voltages, their use in field operations is a subject for serious consideration.

C. The Detector

In ionization anemometers which measure ion presence on a steady or continous flow basis, the detector element is usually an inherent part of the associated ionizing device. On the other hand, unsteady or pulsing systems permit considerable dissociation of these components and a variety of integrated combinations have been evolved. Because of the variety of developments, the further discussions of this section will treat the anemometers as units involving both the ionizer and detector. These have been arbitrarily treated in the three following separate groups.

D. Steady Ion Production by Radioactive Bombardment

In the interest of providing a low-velocity (0-5 fps) air meter for use in applied physiology studies, Lovelock and Wasilewska [1] investigated and developed an instrument based on steady ion production by radioactive means. Their initial thinking proceeded along the general lines previously proven useful in fundamental ion mobility studies in the field of physics and is exemplified by their elementary meter. This consisted of two flat metal electrode plates 1.98 inches in diameter, spaced parallel, 1.98 in. apart, and with a 120-volt d-c applied potential difference. A simple series circuit containing the plates, an ammeter, a battery, and a ground connection became an effective anemometer when the volume of air between the plates was continuously ionized by irradiation with alpha particles and the test-air motion was parallel to the plates. If the ionizing action takes place within the volume confined by the plates, the selected voltage and plate spacing will produce a stable "still air" current flow which represents collection of almost all of the continuously created ions.

If the air is allowed to move parallel to the plates, some of the ions will be swept beyond the attraction of the electric field of the plates and others will have their paths elongated sufficiently so that time for ion recombination and neutralization will be provided. Both of these effects will tend to reduce the total number of ions collected on the plates and will be evident as a reduction in the current passing through the ammeter. The sensitivity of the relation between wind velocity and electric current varies directly with the distance between the plates and the level of ionization which can be maintained inversely with the area of the plates.

Since it was desired that the necessary ionization be achieved by the simplest possible process, consideration was confined to the use of natural radioactive materials emitting alpha particles. Ionization by beta or gamma radiation was deemed too small to be of practical value in the selected dimensions. This consideration included ionium, radium, polonium, radio-thorium, radium D, and equalized mesothorium I. Other natural materials were deemed to be insufficiently active or to possess half-lives too short for practical use. Consideration of the synthetic alpha-emitting materials represented by neptunium, plutonium, americurium, and curium disclosed very desirable properties but their cost was excessive. On the basis of this study, polonium was selected as the most practical material. The special properties of this material are:

(a) It has a half-life of 136 days. This is shorter than might be desired, but is still practical.

(b) It is quite cheap.

(c) It can be electroplated on silver-surfaced metal supports.

(d) It emits large quantities of alpha particles, but with a range of only 1.58 inch in air. This short radiation range makes for convenient nonhazardous handling.

(e) The quantity found necessary to activate a simple ammeter properly and steadily is quite small (between 50 and 250 μc where μc is a commonly defined unit of measure of the explosion rate within the material).

The selection of the 1.98-in. plate distance safely exceeds the maximum range of the selected alpha particle, since if the plate distance had been less than the maximum range the ionizing effectiveness of the particle would be a variable depending on its path. This path, in turn, would show some sensitivity to humidity, temperature, or barometric pressure. The 1.98-in. gap is, therefore, sufficient to provide good stability of ionization. The gap is also sufficient to provide sensitivity to low-velocity winds without excessive applied voltages.

The selection of the 120-volt plate value was intended to be a safe minimum sufficient to attract substantially all of the ions under still air conditions, but small enough to give sensitivity to low wind values and only minor voltage insulation problems.

The polarity of the plates was selected so that the plate connected to the meter was negative; thus the meter presumably measures the flow or collection of positive rather than negative ions. Additional instrument stability is thus provided because the mobility of positive ions is inherently less affected by humidity and other atmospheric contaminants than is the case with negative ions. The positive ions, however, have some sensitivity to temperature and pressure variations and compensation must be provided in precise measurements.

Since the studies of Lovelock and Wasilewska related to air movements of a three-dimensional and physiological nature, they modified the geometry of the simple two-dimensional plate meter to make it omnidirectional with the end result in the form shown in Fig. 45. This device consists of two spherical and concentric open-work, silver-plated, brass cages surrounding a small centrally placed sphere. The outer cage of 3.55-in. ID acts as a grounded screen, the inner cage of 3.16-in. ID is grounded through a meter, and the small silver-plated brass sphere of 0.4-in. diameter is electroplated with 250 μc of the alpha-emitting polonium. The parts are separated at their supports by polythene, a British high-dielectric-strength insulating sleeving. This separation is necessitated by the high circuit resistance and low circuit current.

This unit was connected to an electrometer, and wind values were read on a simple moving coil meter calibrated in a wind tunnel test. The results of such a calibration, using a 105-volt positive potential on the sphere, are shown in Fig. 46 and cover a velocity range of about 0 to 5 fps. If higher velocities were to be used, the applied voltage would be increased accordingly since it was established that winds removing more than 30 per cent of the ions deformed the linearity and accuracy of the velocity - current relation. The sensitivity was found to vary linearly and inversely for voltages ranging from 100 to 500 volts.

The arbitrary geometry of the cage system of Fig. 45 was proven to be quite comprehensive in its ion-collecting ability and fairly nondirectional despite its rugged, well-ventilated construction, as is shown by the test plotting of Fig. 47. The ±4 per cent variation indicated therein was found to be largely due to an unevenness of the polonium coating on the central electrode.

Tests of the influence of ambient changes of temperature and pressure are shown in Fig. 48. Tests of ambient humidity effects established that variations of ±40 per cent in relative humidity from a mean of 50 per cent produced only a ±1 per cent meter shift.

The rapidity of response of this instrument is largely governed by the selection of component values in the amplifier circuit and was established as 0.03 sec for the equipment used. Higher or lower values were indicated as being obtainable.

The very low output ionization current of 10^{-8} amps was apparently handled without special difficulty in the compactly packaged laboratory-type gear utilized in the original tests. No description was given of tests conducted in out-of-doors weather conditions or utilizing transmission of signals for remote indication, but with a current signal of this weakness it seemed questionable whether field insulation problems would permit any appreciable distance of separation of the sensory head and amplifier unit. It also seemed questionable whether the electrical insulation of the head could remain permanently unaffected by atmospheric contamination and vapor condensation effects.

In view of a number of important questions regarding the field practicability of this interesting type of unit, it was deemed advisable to make at least a few screening tests at the St. Anthony Falls Hydraulic Laboratory before advancing any evaluation. To this end a nondirectional unit was constructed as shown in Fig. 45 and tested in the low-velocity range with the results shown in Fig. 49. The cause of the deformation at the lower end of the curve was not determined. Some difficulty was encountered in adjusting the circuit to yield readable values of the innately weak signal.

It is believed that the simpler disc geometry of the two-dimensional form of the anemometer would probably be just as effective in measuring natural winds as the more complex three-dimensional cage form of Fig. 45. Time did not permit conclusive tests of this attractive possibility.

In theory this ionization principle appears to have good possibilities for achieving accurate velocity measurements with an all-electric, nonmechanical system. In practice the system appears to have a number of shortcomings which generally lead to physical complications or lack of accuracy. There is, however, reason to believe that eventual results may be quite favorable, for the history of serious development is confined to the very recent past.

E. Steady Ion Production by Corona, Glow, or Spark Devices

Anemometers in this class are quite similar to the previously described unit. In each a steady tracer ionization is created in the atmosphere and its change by the passing wind is electrically indicated. These units differ, however, in that the ionization is created in the atmosphere by exposing it to the high potential electric field existing between suitably charged electrodes. Ionization thus created may occur in a variety of physical forms depending on the nature of the electrodes, the air gap, and the voltage and amperage applied to the electrodes. Morgan and Vrebalovich [2] compared the various possibilities in this direction with the result shown in Fig. 50 and defined the zones in a generally accepted manner as follows:

1. The dark current or Townsend discharge occurs under conditions of high voltage (6 to 12 kv) and very low current (10^{-12} to 10^{-9} amps). There is insufficient ionizing effect to support a constant flow of current and an external source of excitation such as cosmic rays or x-rays must be applied.

2. The corona occurs under conditions of very high voltage (8 to 15 kv) and very low current (10^{-7} to 10^{-6} amps), and visible light is emitted near the negative electrode. The corona is a self-sustaining flow without external excitation.

3. The glow discharge occurs under conditions of low voltage (300 to 700 volts) and high current (2 to 25×10^{-3} amps), and is characterized by a constancy of voltage over a substantial range of current. It is self-sustaining without external excitation and visible light is emitted.

4. The arc discharge is self-sustaining and is accompanied by low voltages (20 to 100 volts) and large currents (2 to 15 amps). The electrodes operate at their boiling temperature and ionization is associated with the very high temperatures achieved. Strong visible light is emitted.

The difficulty of handling the very high voltage of the dark-current range, together with the lack of self-excitation, eliminates this type from serious consideration, as do the high current demands and very unstable electrode erosion of the arc type. The efforts of the various investigators have, therefore, been concentrated on the corona and glow discharge phenomena as being most promising for anemometer development.

This development was first described by Lindvall [3] in 1934 and is expanded in the writings of Fucks [4, 5], 1942-1947; Mettler [6], 1949; Werner [7], 1950; and Morgan and Vrebalovich [2], 1950. The findings and conclusions which follow were derived from these works.

Werner worked in the corona range of values using steady ion production and electrode systems of very small physical size. He found such devices markedly sensitive to ambient pressure changes of the order to be expected in the atmospheric range. The sensitivity to ambient humidity effects was slight and to ordinary temperature variations it was negligible. The sensitivity to velocity was, however, quite low; and aside from offering some promise in its response to high-frequency variations (more than 10^6 cps) for turbulence studies, the potentialities for use as an anemometer were not favorable.

The influence of an air stream on the electrical properties of a glow discharge to be used as an anemometer appears to involve a complex physical mechanism based on the loss of ions to the air stream. This relation is not subject to analysis and must be determined by calibration. The nature of such a calibration is typified by Fig. 51, which represents the result of applying a d-c current of 10 milliamperes with 350 volts to platinum electrodes of 0.01-in. diameter, spaced about 0.008 in. apart. The figure clearly shows the useful region of velocity sensitivity and near linearity together with the sensitivity to electrode spacing. A decrease in current is accompanied by a steeper voltage curve and general raising of the entire curve. Lindvall's [3] preliminary work does not indicate a questionable stability for the calibration, but the work of Morgan and Vrebalovich [2] gives evidence of a so-called pseudo-hysteresis effect as shown in Fig. 52 and a random and unaccountable deviation as shown in the middle of Fig. 51.

In contrast to Werner's findings on the corona discharge, Morgan and Vrebalovich concluded that a glow discharge was only slightly influenced by ambient pressure conditions. Temperature influences were again deemed negligible, but it is noteworthy that quantitative data were not given for these conclusions and they presumably apply to a limited range of laboratory conditions rather than the wider range of all-weather field conditions.

The glow discharge is accompanied by a bombardment of the cathode leading to disintegration of its surface. The disintegration is believed due to minute irregularities which concentrate the electron flow causing high local temperatures, melting, burning, and material transport which are accompanied by sputtering or irregularity of glow. This results in a scattering of test data and inability to reproduce calibration curves. Refinements in electrode polishing, spacing, and material selection reduce but do not eliminate this instability and progressive change.

Fucks and Schumacher [4] conceived of operating the glow with an alternating rather than a direct current with the thought that the symmetrical use of the electrodes in an a-c system would reduce the sputtering difficulties attending the nonsymmetrical use of the electrodes in the d-c system.

Their findings, together with those of Morgan and Vrebalovich, confirm that good stability resulted from such a shift but the voltage - velocity relation was complicated by the fact that de-ionization of the air tended to occur during the current reversal. Consequently, the voltage wave shape was adversely affected. It was suggested that revised circuits and high frequencies (100 kilocycles per sec) might rectify this and eventually lead to a good turbulence meter.

On the basis of the foregoing it may be concluded that the present state of development of anemometers based on continuous ionization by high potential electric fields does not justify their application to the measuring problem under consideration.

F. Pulsed Ion Production and Detection

As previously mentioned, anemometers based on this principle produce a finite ionized cloud of air at an upstream ionizing station and measure the windswept time of traverse of this cloud over a measured downstream distance between two stations. The measured distance may be between the ionizing station and a downstream electrode pickup station or between two separate downstream electrode pickup stations. The principal instrumental problems center on production of a strong and clearly defined ion cloud and a detector of adequate sensitivity and transit-timing accuracy.

The NACA [8] studies of this type of instrument found that a flush-mounted, very small, single electrode centered in an insulated plug and supplied with a 15,000-peak-voltage pulse produced a corona discharge which gave a good signal and an abundant supply of ions. The electronic circuits finally selected for the study proved to be of a rather conventional nature with the pulsing and timing circuits employing radar range units.

The circuit supplying the pulse included the ion signal generator, a synchronizer, a high voltage pulser, and the ionizing electrode. The synchronizer repetitively generated a dual pulse at a frequency of 400 to 800 cps. One of these pulses served to trigger the ionizer for a pulse of 7- to 10-microsecond duration, while the other pulse triggered the driven sweep of the oscilloscope which served as the time indicator.

The receiver began with an electrode assembly in which a signal was induced when the ion cloud and its associated electric field passed over the electrodes. These electrodes were in circuit with an amplifier, a timer, and the oscilloscope indicator previously mentioned.

The oscilloscope received two distinct wave forms, the first of which was directly induced in the receiver circuit by the ionizing voltage pulse and the second of which was induced through the pickup electrodes by the cloud passage. The first wave form occasionally failed because not every pulse fired. The proportion of strikes to misses varied depending on the existent combination of voltage, current, and pressure. The second wave form also occasionally occurred as a shifted inversion. This inversion was believed due to the ion cloud possessing directional characteristics in the disposition of its positive and negative charge. The occurrence of the inversion also depended on a suitable combination of voltage, current, and pressure.

Suitable manipulation of the calibrated timer unit and the oscilloscope yielded a reading for the time interval occurring between the two wave forms. This time value, in combination with the known or established distance between the ionizing and the pickup electrodes, permitted the velocity of cloud passage to be calculated.

Lack of a clear understanding of the disposition of form and strength of the ion cloud created at the ionizer precluded an analytical solution to the time function and required comparative physical measurements for calibration. These tests were conducted with a speed range from Mach 0.3 to 3.8 (the Mach number of interest in this study is from 0 to 0.05), a substantial pressure range (atmospheric to 0.25 in. of mercury), a substantial range of humidities and temperatures, and both single and double detector stations. As a result of the tests it was concluded that an instrument containing two detector stations could be built to achieve reliable velocity measurements with an error of not more than 1 per cent and a virtual independence of the ambient pressure, temperature, and humidity. A spacing between electrode stations of as little as 1/2 in. proved workable.

Mellen [9] describes studies by the National Research Corporation of Cambridge, Massachusetts, which are somewhat similar to those conducted by the NACA. They differ in that the earlier studies employed a simple spark gap as the ionizer and an ion collector rather than an induction detector station. Later investigations under this program are described in [10] and include a discussion of ionization tests with an electron gun. These studies also indicate that ion collectors are probably less desirable than induction detector stations because the electric field of the collector may exert a lateral force on the ion stream sufficient to disturb the basic flow. There was also some indication that voltages sufficient to produce an effective strength in the collector field caused random discharges and secondary signals. On the other hand, the induction detector was not considered ideal because of the occasional false signal that it produced when subjected to an adverse distribution of the negative and positive parts of the charge in the cloud. Despite the latter objection the induction detector appeared to be quite feasible and an extensive examination of its various characteristics is included in the reference.

Cooley and Stever's [11] methods and findings were quite similar to those of the NACA study with the principal difference occurring in the details of method used to trigger the ionization pulse.

It would appear from a review of the foregoing that pulsed ion production and detection for velocity measurements can be a practical and accurate way of measuring gas velocities of a high value in laboratory studies. The rather extensive electronic assembly is not, however, well adapted to compact packaging for field use.

The most important deterrent to consideration of this principle for the current meteorological study is the observation by Mellen [9] that the gas velocity must be large relative to the inherent diffusion velocity of the ions in the cloud. Tests indicated that the radial and axial ion diffusion and recombination destroyed the measurable character of the free ion cloud if the gas velocity was less than about 30 fps.

G. Summary

Ionized air particles in an air stream may be used to trace the motion of the stream either by the manner in which the wind deflects the steady flow of ions between two exposed electrodes or by marking the progress of a series of drifting ionized portions of the stream.

The method employing deflection of a steady stream of ions appears to offer interesting possibilities for low-velocity wind measurements but has not been investigated for a full range of weather conditions. A simple but mildly hazardous method of achieving the necessary ionization with radioactive material has been established, and a quite simple electronic circuit suffices to measure the electric signal current. The signal is so weak, however, that local amplification must be accomplished near the sensory head before remote transmission may be attempted. This problem may present some complications in certain types of field mounting. The method offers an adequate, quite stable, and nearly linear sensitivity to velocity but retains some sensitivity to ambient pressure and temperature. Its time of response is very good. No development of inherent directional measuring characteristics is evident, but possibilities do exist. No commercial development activity is known.

Ionization anemometers similar to the foregoing but using a corona, glow, or arc to achieve ionization have not proven sufficiently stable to warrant further consideration in this study.

The method employing time - distance measurements of a series of ionized gas clouds has recently been intensively investigated and appears to offer excellent potentialities for extremely high-frequency wind turbulence studies and nondisturbing supersonic velocity measurements. The associated hazards, physical complications, instability, and insensitivity to low velocities do not, however, recommend its use in the measuring problem under consideration.

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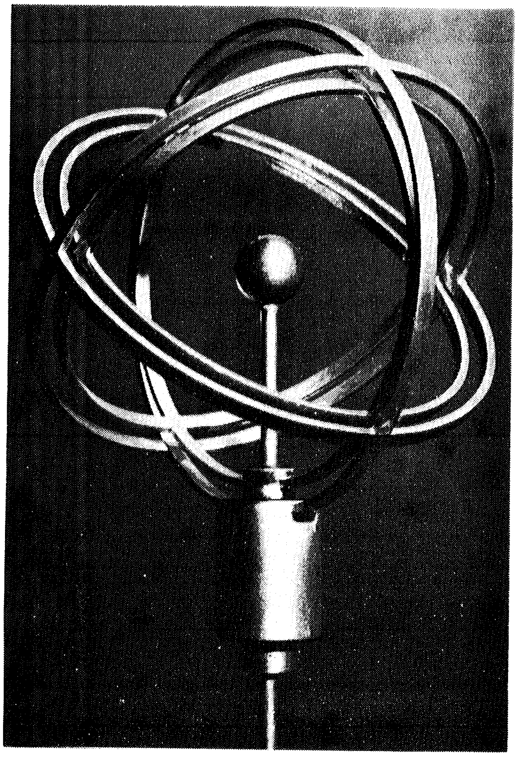

Fig. 45 - Three-Dimensional Ionization Anemometer as Designed by Lovelock and Wasilewska

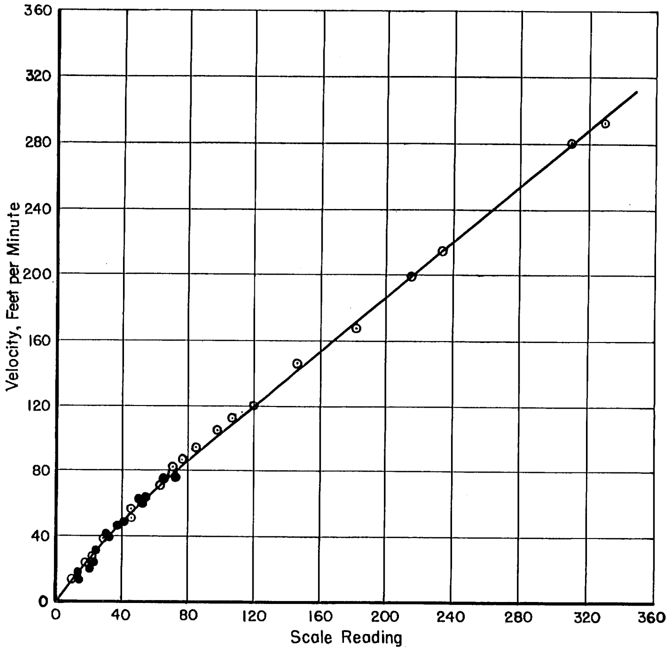

Fig. 46 - Calibration Curve for the Ionization Anemometer of Fig. 45 [1]

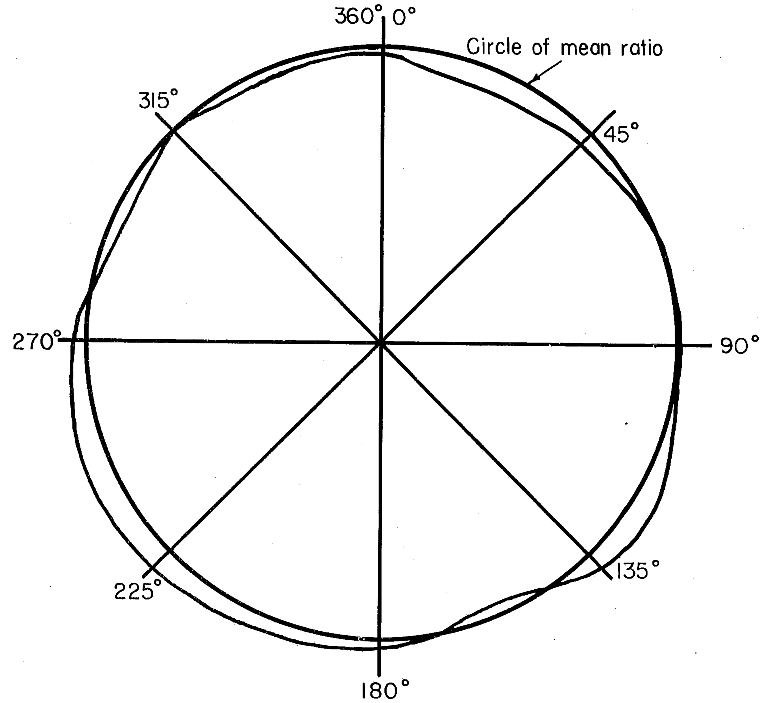

Fig. 47 - Sensitivity of the Anemometer of Fig. 45 to the Direction of Horizontal Winds [1]

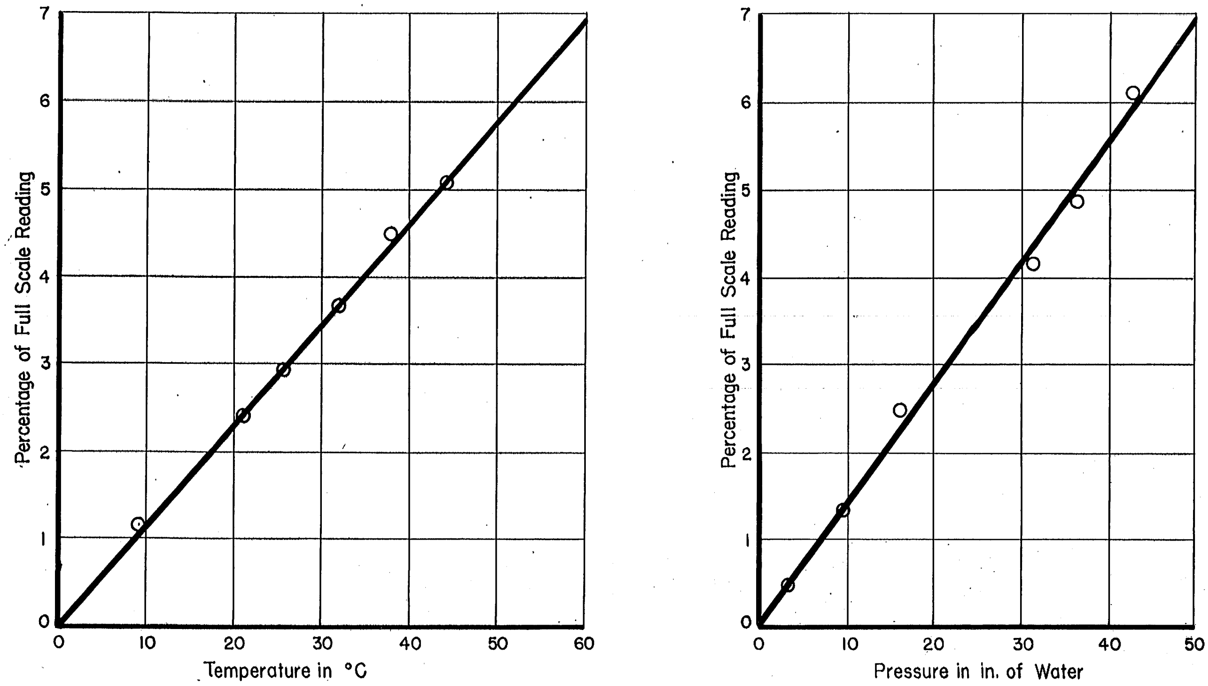

Fig. 48 – Effect of Temperature and Pressure Variations on the Anemometer of Fig. 45 [1]

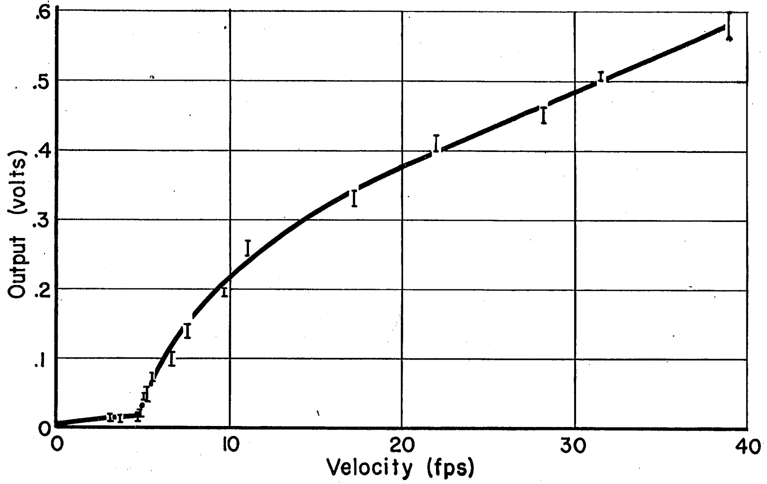

Fig. 49 – Velocity Calibration for the Ionization Anemometer of Fig. 45 as Determined at St. Anthony Falls

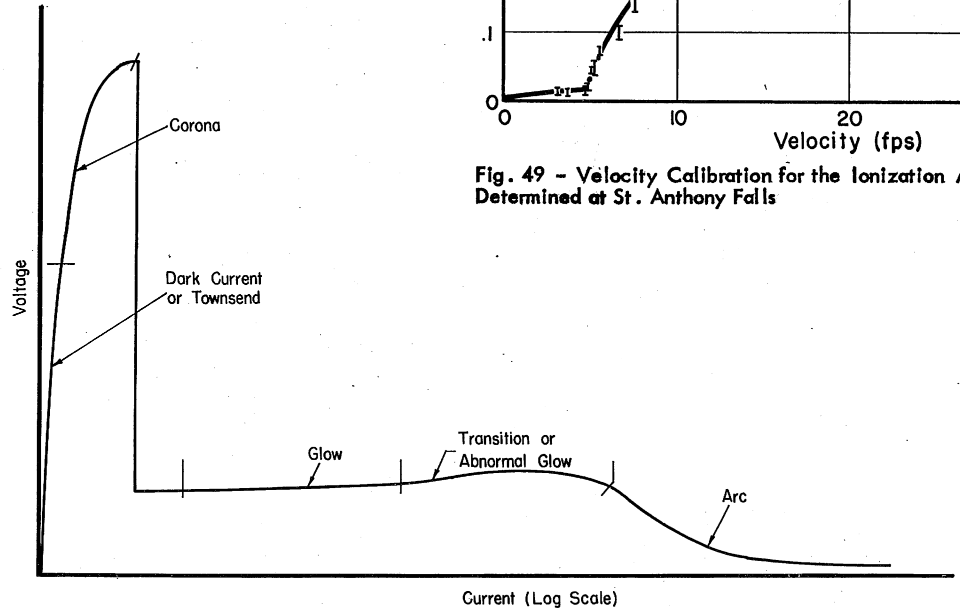

Fig. 50 – Voltage vs Current for Discharge Across an Air Gap at Atmospheric Pressure [2]

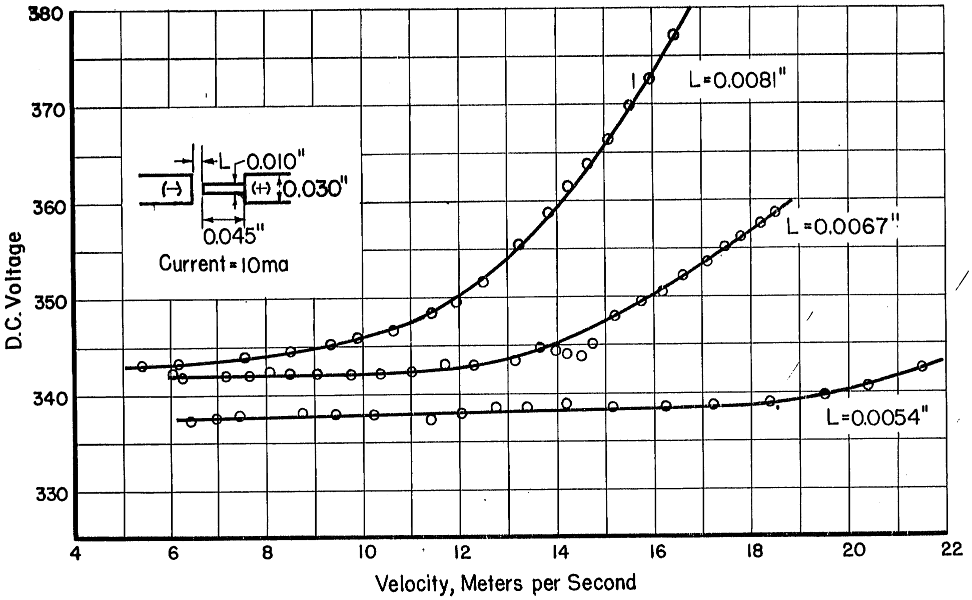

Fig. 51 – Voltage vs Velocity for a Glow Anemometer [2]

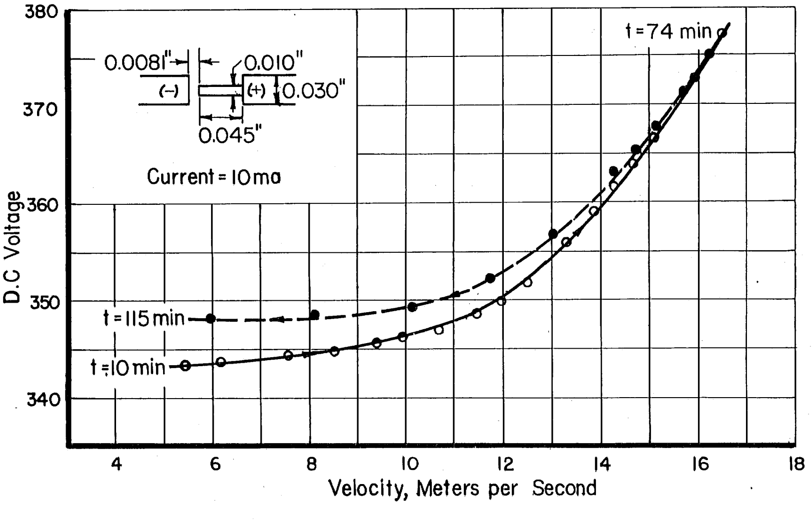

Fig. 52 – Pseudo-Hysteresis Effect of Sputtering on a Glow Anemometer [2]

V. MISCELLANEOUS ANEMOMETERS

A. Sonic Phasemeter Anemometer

If a sound wave of velocity v is impressed upon a moving air stream of velocity V, the wave will travel with the stream at a velocity $(v + V)$ and against the stream at a velocity $(v - V)$. If the transmitted sound wave is compared with the wave received at a detector a fixed distance s from the transmitter, the difference in phase of the two waves may be compared to yield a time difference which may, with proper interpretation, serve as a measure of the wind magnitude and direction.

The wind velocity in such a case will be a function of the velocity v of sound in air under the existing conditions, the established base line distance s between the transmitter and detector, and the time difference Δt between the phasing of two waves.

The velocity of sound in air, for practical purposes, is 1087 fps at 0° C, and is relatively insensitive to most of the commoner atmospheric variations with the exception of temperature. The sensitivity to ambient temperature is, however, significant and is given by the comparative relation $v_1/v_2 = \sqrt{T_1}/\sqrt{T_2}$ where T is the absolute temperature. While the variant influences on v are not large, the use of a low wind velocity V in differential evaluations of $(v - V)$ or $(v + V)$ will require that the instrumentation minimize these variations if good accuracy is to be expected.

Establishment of the base line distance s is somewhat arbitrary. However, as indicated in the earlier discussion of wind structure, any measurement of the small-scale eddies which might influence small-scale ordnance bodies will require a velocity measurement of a relatively short running length of the wind which in turn may require s to be no more than a few feet in length. It is anticipated that normally s could be easily measured with any requisite accuracy.

The value of the time difference Δt involved in measuring wind velocities of 1 to 50 fps over a base line of a few feet may be roughly calculated to yield time values of the order of 10^{-3} to 10^{-5} sec. While these are small physical values, they are practically measurable by electronic means or phasemeters where the signal is of a repetitive wave nature. There is evidence that considerable thought has been given to the development of this electronic instrumentation, but the complexities of the problem have been such that only two published reports of activity have been disclosed by this study.

In the first of these disclosures Corby [1] briefly described an instrument which consisted of a central pulsed sound source surrounded by four electro-mechanical-transducer listening stations oriented at the four cardinal compass points 5 ft from the sound source. The four receiving stations were connected to an amplifier and then to a discriminator. The latter resolved the vector components of any wind into its cardinal components to yield directional indication and also served to produce a secondary square wave pulse with a width proportional to the time differential of the received signals. The square waves were imposed as voltages on the deflection plates of an electrostatic cathode-ray tube and resulted in a line image on the screen. The polar direction of this line served to indicate the wind direction, while its radial length was a measure of the wind speed. Since the pulsing sound source operated 60 times per sec, the instrument readily followed rapid changes in the wind. No factual data on the accuracy or operational limits of the instrument were given, but it was stated that reliable continuous operation was achieved and the signals would readily be transmitted for remote indication.

It would appear that use of this instrument at low velocities under a wide variety of atmospheric conditions might disclose a greater error than would be tolerable. The instrument also has the disadvantage of requiring a rather extensive collection of apparatus for a single anemometer and would impose serious field problems if multiple anemometers were employed. Further development might, however, materially reduce the physical problems and thus permit advantage to be taken of a system which is inherently fast in time response and capable of securing both wind speed and direction without exposed moving components.

In the second of these published treatments [2], a development at the Bureau of Standards by Kalmus is described. The phasemeter assembly of this device is somewhat similar to that of Corby, but the prime difference is in the physical arrangement of the transmitter and receiver. In Corby's instrument, upstream and downstream receivers are placed an s distance from the transmitter and two distinct circuits are required. Kalmus, on the other hand, employed two units which could serve as either transmitter or receiver, and alternated their function by a switching device. By so doing he was able to balance out any assymetry of the circuit or unknown shifts which might occur in the sonic velocity. He accomplished switching initially with a 10-cps mechanical commutator and later with an electronic switch at 1000 cycles. The published account was very brief and without factual data, although it was indicated that very low air velocities could be measured and that the time response at 1000 cycles is very brief. No mention was made of the possibility of adding components and sorting circuits for directional measurements.

The sonic phasemeter type of anemometer appears to have attractive possibilities in a number of aspects. It is, however, a complex and bulky equipment and not currently deemed practical for multistation field anemometer applications. Subsequent developments may establish this as a very useful instrument.

B. The Vortex Trail Anemometer

Occasional references in the literature and the personal observations of most individuals substantiate that many audible sounds in nature have a pitch which is quite obviously some function of the wind velocity. No technical discussions of this occurrence were disclosed in this study,* but it may be presumed that all such phenomena are evidence of the pulse period of the flow separation eddies which trail from behind various geometries when exposed to a flow. A common and long recognized form of this phenomenon is the eddies which periodically form and are shed from both downstream sides of a cylinder held normal to a wind. This shedding phenomenon, known as the Karman vortex trail, has a shedding frequency which is usually expressed in a dimensionless quantity known as the Strouhal number S. In this quantity, $S = nd/V$ where n is the shedding frequency from one side of the cylinder, d is the cylinder diameter, and V is the stream velocity. The Strouhal number will apparently depend on all of those quantities which influence separation, including body geometry, Reynolds number, stream turbulence level, body roughness, etc.

The principal influence in the case of a selected cylinder appears, however, to be the Reynolds number. Roshko [3], working with a variety of cylinders in a low-turbulence wind tunnel, determined the relation to be in accord with Fig. 53. In these studies the frequency was determined with a

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*An extensive bibliography of related material has since been found in "Vortex Streets in Incompressible Media," by M. Z. Krzywoblocki, Applied Mechanics Review, Vol. 6, No. 9, pp. 393-397, September, 1953.

hot-wire anemometer and the velocity - frequency relation proved to be sufficiently reliable to permit a cylinder to be used as an anemometer for part of the experimental data. It may be concluded from Roshko's data that an anemometer may be based on the relation that S is approximately equal to 0.2 for a substantial range of conditions or that $V \approx 5\ nd$.

In view of this relation it is apparent that if a vertical cylinder is equipped with a pulse-sensing device it may directly serve as an anemometer. Practical development of such an anemometer would hinge on selection of a pulse-sensitive device (this might be either pressure or velocity sensitive) with a greater ruggedness than is offered by the hot-wire anemometer employed by Roshko. The frequency meter should preferably permit the cylinder to remain stationary and not require orientation into the wind; for this reason it would appear that a pressure-sensitive device might be more fruitful in development than a velocity-sensitive frequency meter. Whether or not the frequency meter could distinguish between the rather impotent eddy trail signal and other turbulence pulses is problematical and not considered worthy of recommended development at this time.

C. Visual Tracers

In the discussion of ionization anemometers based on tracer techniques, it was pointed out that visual tracers may be added to a wind stream to permit recording its path and velocity. While students of meteorological techniques are familiar with the use of balloons and smoke for such purposes in large-scale studies, the aeronautical sciences [4] have made good use of tracer techniques based on observance of variations in the refractive index of air. These data are most simply and directly obtained by repeatedly discharging a point spark source in the flowing stream, thereby creating a series of local "hot spots" whose abnormal density and refractive properties are evident under suitable lighting conditions. Photographic recording of such tracers will permit subsequent analysis of the wind speed and direction. Unfortunately, there appears to be no simple way to convert these optical traces in a transmittable electrical signal.

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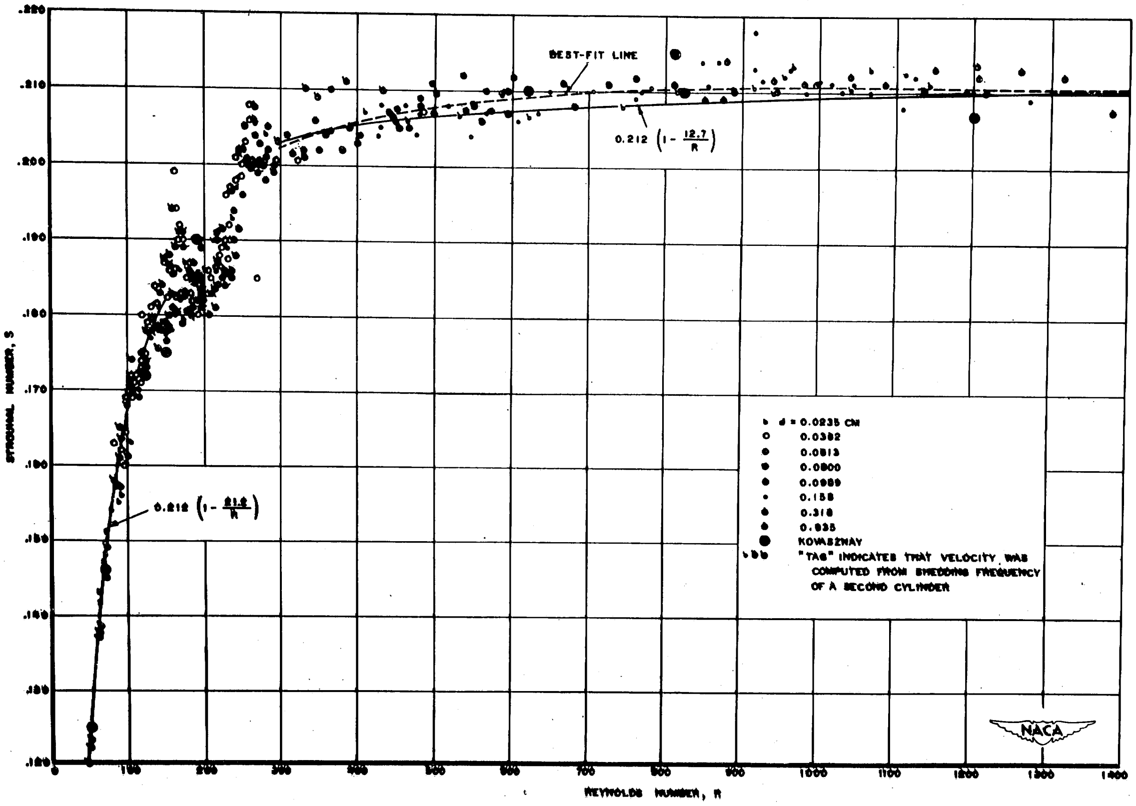

Fig. 53 – Strouhal Number (S = shedding frequency x cylinder diameter/velocity) Plotted Against Reynolds Number (R = velocity x cylinder diameter/kinematic viscosity) for a Circular Cylinder [3]

VI. DIRECTIONAL DEVICES

For the wind-measuring problem dealt with in this report, the measurement of the wind direction is equally as important as the measurement of the wind velocity. Accordingly, the foregoing material, which has detailed the methods whereby velocities may be measured, has also included supplementary assessments of the direction-measuring properties of each of the velocity devices discussed. This section will not, therefore, repeat the previous assessments but will attempt to expand briefly on certain other phases of the direction-measuring problem and then summarize the general picture.

At the present time most instrumental wind-direction measurements are made with some form of dynamic pressure wind vane device. In general, these consist of an area or body form placed at the end of a horizontal rod which is supported on a bearing and vertical spindle near its center. The design objective of such a device is to orient the area exposed to the wind in such a manner that the dynamic lift or drag of the wind will provide a strong responsive steering torque for any degree of misalignment without providing an unstable flutter about the neutral or aligned position. If rapid response to variable winds is to be expected, this objective should be achieved with a disposition of mass and torque arm providing a minimum angular moment of inertia. The size of the parts should be only sufficient to provide torque or energy to overcome the spindle-bearing friction and energize the signal transmitter.

While the older and more common wind vane forms have apparently developed along empirical lines, there is evidence [1, 2, 3] that in recent years aerodynamic analysis and wind tunnel testing have led to more rational designs. This development has been accompanied by improvements in the rotor bearings and signal transmission systems comparable to those previously discussed relative to the cup and windmill anemometers.

A modern version of such a development is represented by the Bendix-Friez Aerovane unit [4], which was previously discussed under windmill anemometers. This directional unit is moderately sensitive and responsive but has a considerable inertia because of the windmill mass which it serves to orient. On the other hand, the Beckman and Whitley [5] and The Instrument Corporation [6] units dissociate the velocity and directional components, with the result that the latter component is of small dimension and mass and the units are correspondingly more sensitive and responsive.

While the current study is concerned only with the horizontal component of the wind, it is noteworthy that design developments have also successfully evolved three-dimensional wind vane units [7].

There is no indication that the wind-vane type of directional unit has been developed to operate with accuracy and sensitivity on anything but a rigid mounting. It is conceivable, however, that an instrument might be developed to operate from a balloon suspension with fair accuracy. Such a device would, of course, require an index of orientation with respect to the earth which is capable of wire transmission to the earth. Such orientation can be provided by a magnetic compass with an associated electrical condenser which produces an electrical directional signal. This type of device has already been developed for other service uses and should be adaptable to providing orienting signals for any type of freely suspended directional sensing unit.

Promising possibilities for directional instruments may be found in the previous discussions of the drag sphere, Thermistor, thermocouple, ionization, and sonic anemometers. These devices are especially attractive in that they appear to be capable of producing a directional signal without resort to moving mechanical parts exposed to the weather. Unfortunately, relatively little development work has been done on the directional aspects of these devices and the ancient weather vane remains as the most available current offering.

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VII. SUMMARY AND CONCLUSIONS

The literature and pilot experimental studies conducted at St. Anthony Falls indicate that while a wide variety of instruments has been developed, no one wind-measuring instrument is currently available to answer the needs of the problem under study. There are, however, indications that several sensory devices may be capable of development to meet the requirements. The more promising of these may be summarized as follows.

The dynamic pressure type of device which has served so well for other air velocity-measuring problems is poorly adapted to production of a stable signal for the low velocities involved in this problem. This is particularly true for the Pitot type of device and to a lesser degree for the rotating cup and windmill anemometers. The latter rotary devices have a long history of use and development and constitute the most available instruments for the problem despite their inability to give complete coverage of the extreme low end of the velocity range. They also possess some sluggishness of response to wind variations at the lower speeds. The principal work with these devices has been with a rigid support but there is some evidence that they may operate satisfactorily with nonrigid or balloon support.

The dynamic pressure drag sphere offers considerable promise for a combined speed- and direction-measuring device with a number of desirable properties. It would, however, require considerable further development and calls for a rigid mast mounting.

Thermal anemometers which derive their sensory electrical signal directly from the cooling effect of the wind are believed to constitute the most promising type of anemometer. This is true because they are most sensitive in the low-velocity range and directly produce a workable electrical signal.

The Thermistor, which is one type of thermal sensory unit, is of quite recent introduction and has not been fully developed for field anemometer use. It is, however, fairly sensitive, stable, simple, compact, and reasonably rugged. In addition, it possesses a time response of as low as 0.04 sec. With adequate development this device is believed capable of evolving into a practical field velocity-measuring unit. The efforts to date have not exploited the possibility of measuring the wind direction with this device, but pilot studies indicate that considerable promise exists. The device has the advantage also of not requiring a rigid mounting.

The heated thermocouple is a sensory unit which varies an electric voltage as the result of the cooling action of a wind. It is based on long established thermoelectric principles which have recently been commercially exploited to produce a practical velocity-measuring anemometer. The device has good accuracy and stability and a time response of the order of 0.1 to 0.3 sec. The electrical output can be practically measured and transmitted. The development of a directional measuring unit has not been disclosed but some possibilities do exist. The device does not require a rigid mounting.

An anemometer based on the electrical signal produced by the wind's deflection of a stream of ions passing between two electrodes appears to offer considerable promise. Ionization of the air is achieved by the use of a very simple arrangement including a quite stable, low-hazard, radioactive material. The wind deflection signal is very weak, but existing data indicate that amplification and transmission are quite practical. The accuracy and stability basic to the system are quite good and the time response of less than 0.03 sec is very good. The instrument has not been fully developed for field use nor has consideration been given to directional measurements. There is, however, a fair possibility that practical success could be achieved with such development. The device does not require a rigid mounting.

It is recommended that additional research be devoted to a fuller exploitation of the above-described thermal and ionization anemometers.