U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU

KEY TO METEOROLOGICAL RECORDS DOCUMENTATION NO. 3.151

HISTORY OF WEATHER BUREAU WIND MEASUREMENTS

U. S. DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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PREFACE

The Key to Meteorological Records Documentation Series has been established to provide guidance information to research personnel making use of climatological data.

Frequently users of such data have found it necessary to spend a great deal of time establishing whether the criteria for observing or computing various elements have changed over the period of record. It is therefore hoped that the presentation of this series may not only conserve valuable time but may have a direct influence in improving the accuracy of research results.

ACKNOWLEDGMENTS

Recognition is given for the review and inclusion in this paper of pertinent material processed by Messrs. M. D. Baliles and J. P. Kohler and their efforts toward having this paper published as a part of the Key to Meteorological Records Documentation Series. Acknowledgment is also given to W. A. Wood for help in compiling historical facts and for editorial assistance in the preparation of this paper. Thanks are also due to several other colleagues in the Central Office of the Weather Bureau for reading the manuscript and submitting helpful suggestions.

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HISTORY OF WEATHER BUREAU WIND MEASUREMENTS

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ABSTRACT

Rotating cup type anemometers have been used by the United States Weather Bureau principally for the measurement of wind speed. Before and including December 31, 1927, wind speeds were recorded by means of 4-cup anemometers for which no instrumental corrections were made either in the records or in the published data. (To correct these values to true wind speeds, corrections must be applied as indicated in the 3d column of Appendix V, under the caption "By 4-cup anemometer".)

From January 1, 1928, through December 31, 1931, a 3-cup anemometer was generally used. Although Column 2 of Appendix V shows the corrections required, no corrections were made either in the record or in the published data; but whenever a 4-cup anemometer was employed during this period, the readings were reduced to the equivalent which would have been yielded by a 3-cup instrument. (See Appendix I-C.)

Since January 1, 1932, all manuscript records and published data from Weather Bureau anemometers have been corrected to true wind speeds. Appendices V and VI show the corrections applicable to the various types of cup anemometers used by the Bureau.

While the contact-type anemometers described in Chapter II were generally used, data pertaining to the "5-minute maximum wind speed" and the "fastest single mile wind speed" were determined during certain periods as mentioned in Chapter V. A multiple register (triple register or operation recorder) was required. Due to the increased interest in aviation during the decade beginning with 1940, direct reading designs of anemometers (such as the magneto type) and wind measuring systems (such as the condenser-discharge type) were developed and employed on a wide scale, especially at airport stations.

Magneto types which give direct readings require no correction to true values when switched on single scale operation. The employment of instruments of this type permitted gust data to be obtained, but prohibited the determination of the "fastest single mile wind speed" or of the "5-minute maximum wind speed".

Descriptions are given concerning the methods of determining these data, and the operation of the wind direction indicators and transmitters.

I. INTRODUCTION

The purpose of this paper is to give an account of the methods employed by the Weather Bureau for the determination of wind speed and direction. It discusses the equipment used, the corrections applied to observed wind speed data for the various types of anemometers, the character of the observed data and the techniques of recording these data.

Since the beginning of Weather Bureau records, the instrumentation used for the ascertainment of wind speed and direction has remained basically the same, inasmuch as the speed has been been consistently measured by means of a rotating-cup type anemometer. At certain times changes were introduced in the number of cups and their design, as well as in the length of the supporting arm, which necessitated revisions in the applicable corrections. While the anemometers employed by the Bureau during the first portion of the period under consideration were of the so-called "contact type", which permitted a rather simple method of recording, more recent years have seen the introduction of modern designs based on electrical methods of response, such as magneto and condenser-discharge types, which allowed the use of different techniques for obtaining wind-speed data. Differences in design and techniques brought about the need for the Weather Bureau to issue from time to time information regarding changes in the corrections appropriate to the observed wind-speed data, depending upon the equipment used. Consequently, it is deemed desirable to incorporate in this paper a complete reproduction of the original instructions and tables of corrections applicable to the readings of the various types of anemometers.

Considering the fact that advances in the art of wind measurement and observation may be confidently expected, one can anticipate that additions will be necessary to the material embodied in this paper. Furthermore, as information not currently available comes to light regarding the older or present types of wind-measuring equipment and their relevant corrections, suitable revisions will be justified. Therefore, the author and the Weather Bureau will be grateful to anyone who will supply information which will fill gaps in the material presented herein or which will enlarge its scope by the inclusion of summaries of advances in the field of wind measurement.

Anemometers operating upon a number of different principles have been developed. The type most commonly used by meteorological services in North America, and to a considerable extent also in other parts of the world, is the rotation type "cup anemometer" (see fig. 1-3). The earliest mention in the literature of a rotation anemometer relates to 1720, whereas more is known concerning a windmill-type wind instrument due to d'Ons-en-Bray reported in 1734. (see Appendix VII). Experiments were conducted by many investigators over a period of years with a view to determining the aerodynamic and hydrodynamic characteristics, such as the resistance per unit area per unit wind speed, of windmill sails, rectangles of various sizes, disks, spheres, pendulums, and other forms, which provided information of scientific value for the design of anemometers (see Refs. 1 and 24).

The development and introduction of the first real cup anemometer by Robinson was announced in a publication dated 1846 (Ref. 66); and this instrument had its antecedent in a suggestion made to Robinson many years earlier by Edgeworth (1783).

Since the cup anemometer in its various forms as used by the Weather Bureau is a matter of paramount interest in the present context, no effort will be made to cover here types of anemometers which function on the basis of other principles, except perhaps to make brief mention of them in the list below. Wind-speed measuring equipment can be classified under the following headings which are based largely on the categories listed by Middleton and Spilhaus (Ref. 57):

I Rotation Anemometers
- (A) Propeller or windmill anemometers
- (B) Cup anemometers
- (C) Special types

II Pressure-Plate Anemometers
- (A) Plate allowed to swing
- (B) Plate held normal to the wind

III Bridled Anemometers and Airdrag Anemometers (based on torque measurements)

IV Pressure-Tube Anemometers (based on the Pitot tube, such as the Dines instrument)

V Anemometers Depending Upon Cooling
- (A) Hot-wire anemometer
- (B) Kata anemometer
- (C) Heated-thermometer anemometer
- (D) Heated thermocouple and thermopile anemometers

VI Ionization or Ion-Transit Time Anemometers

VII Sonic Anemometers

VIII Miscellaneous Types of Anemometers

For those who are concerned with the history of the subject, especially in modern times, we have included Appendix VII, entitled "Discussion of Matters of Historical Interest Regarding Anemometers". Some particular attention is devoted therein to the development of the 3-cup anemometer which has generally replaced the 4-cup instrument, the value of the so-called "bead" (or beaded edge) on the cups, the merit of the semi-conical cup as contrasted with that of the hemispherical cup, and the effect of fine-grained turbulence on the tendency of the cup-wheel to yield over-estimates of the wind speed when exposed to a wind stream whose speeds fluctuate.

Readers interested in obtaining information regarding the comparative characteristics of the various types of anemometers, together with a brief account of the history of these instruments, will want to consult the paper by Sheppard (Ref. 82). Additional material of a historical nature pertinent to the subject is contained in publications by Abbe (Ref. 1), Laughton (Ref. 46), and Bentley (Ref. 3).

Those persons concerned with the problem of "The Measurement of Air Flow" and the instrumentation relevant to this branch of science will find a wealth of material on the subject in a book of this title by Ower (Ref. 60). The principal emphasis in Ower's book is upon industrial applications including information regarding the pressure tube anemometer, the Pitot-static tube, the Venturi tube, the vane anemometer, the manometer, and the various methods of flow measurement based upon the rates of cooling of hot bodies.

II. CONTACT-TYPE ANEMOMETERS FOR WIND SPEED INDICATION

The cup anemometer has been accepted by the Weather Bureau as the standard instrument for wind speed measurement. Several variations of this device have been developed and tried in order to obtain the maximum degree of accuracy and to adapt the apparatus to suit particular requirements. It is necessary to make a distinction between the contact-type cup anemometer and cup anemometers which yield their indications by virtue of a magneto or condenser-discharge operation. The ensuing description is limited in scope to the contact-type instrument; for information regarding the others, the reader is referred to Chapter VIII.

Figure 1 illustrates the 4-cup anemometer, which was the type most widely used in the United States from 1870 through 1927. In this design the cups are 4 inches in diameter, and the supporting arms of the cup wheel, arranged at right angles, are 6.72 inches long from the axis to the center of the cups. Later designs employed arms 6.68 inches long (see Ref. 55).

The 3-cup anemometer (designated as "S" type) introduced in 1928 is shown in figure 2. This instrument also has cups of hemispherical design, 5 inches in diameter on arms 6.29 inches long arranged at 120° angles (see Ref. 55).

Cups with beaded or rolled edges were used in some anemometers issued to a limited number of stations at various times since July 1, 1932; but cups of this design have not been employed for the 3-cup "S" type anemometer. Marvin has presented a discussion and some comparative data relating to the effect of using beaded or rolled edges on the cups (see Ref. 56). According to tests made in a wind tunnel with different degrees of turbulence, anemometer cup forms run faster in a turbulent than in a non-turbulent wind stream, and the overrun caused by increased turbulence is much less with beaded cups than with smooth cups. (Refs. 54 and 56).

In the case of the "SA" type anemometer generally used at airport stations, which is illustrated in figure 3, the cup wheel has 3 cups, conical in form with beaded edges. The diameter of the face of the cup is 2.875 inches, and the arm length is 4.75 inches. Scrase and Sheppard (Ref. 80) have drawn the following conclusion regarding the comparative performance characteristics of the two designs of cups: ". . . that conical cup anemometers over-estimate the mean speed of a gusty wind to a much less extent than do hemispherical cup anemometers" (see also Ref. 81).

As may be inferred from the accompanying figures, the contact-type cup anemometer most commonly used by the Weather Bureau involves hemispherical or conical cups mounted on supporting arms which are attached to a vertical spindle. The cups are driven by wind pressure due to the horizontal motion of the air. Accordingly, the cups rotate about the spindle at a rate which depends not only upon the wind speed in the plane of the cups, but also upon a number of other factors including: the diameter and shape of the cups (taking cognizance of whether their edges are sharp or beaded), the length of the supporting arms, the moment of inertia of the rotating system, the density of the air, the viscosity of the air, the small-scale turbulence in the air flow, the speed of the air motion perpendicular to the plane of the cups, and the effects of precipitation, if any.

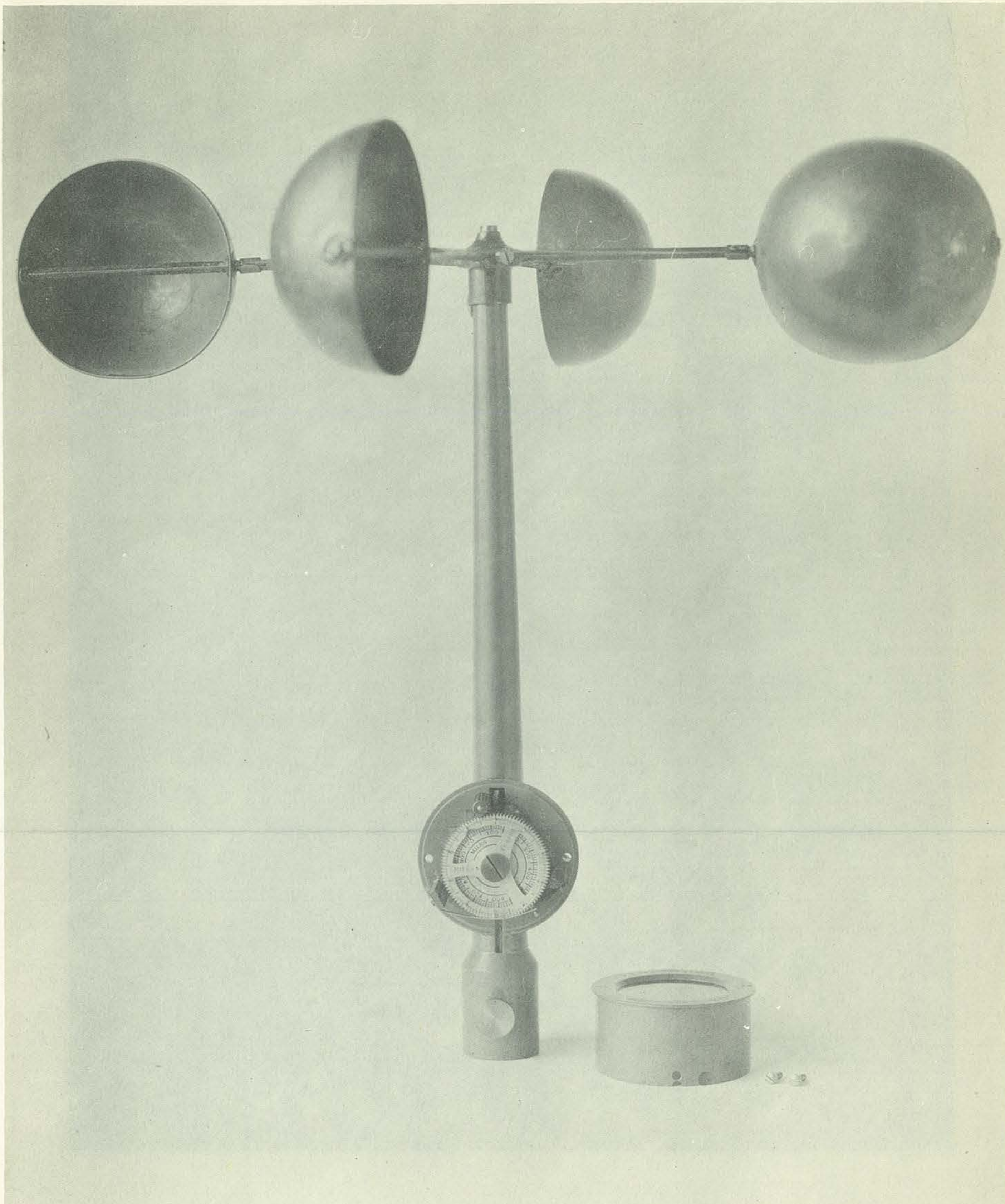

FIGURE 1

Four-cup anemometer; 4-inch diameter, smooth hemispherical cups with straight (unbeaded) edges, equipped with 1-mile contacts and circular totalizing dial.

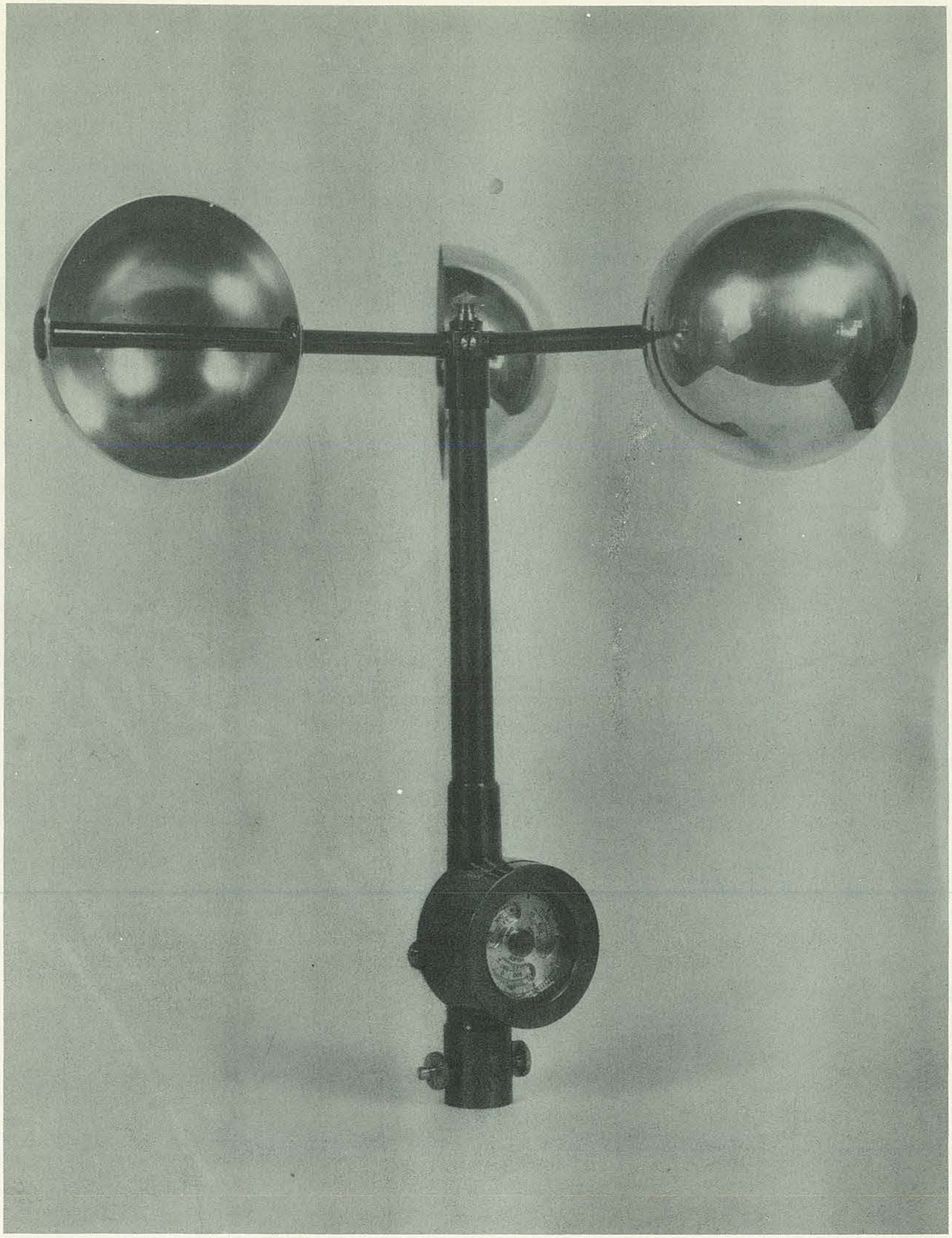

FIGURE 2

Three-cup, "S" type anemometer; 5-inch diameter, smooth hemispherical cups with straight (unbeaded) edges; equipped with 1-mile and 1/60-mile contacts and circular totalizing dial. (Stock No. F102)

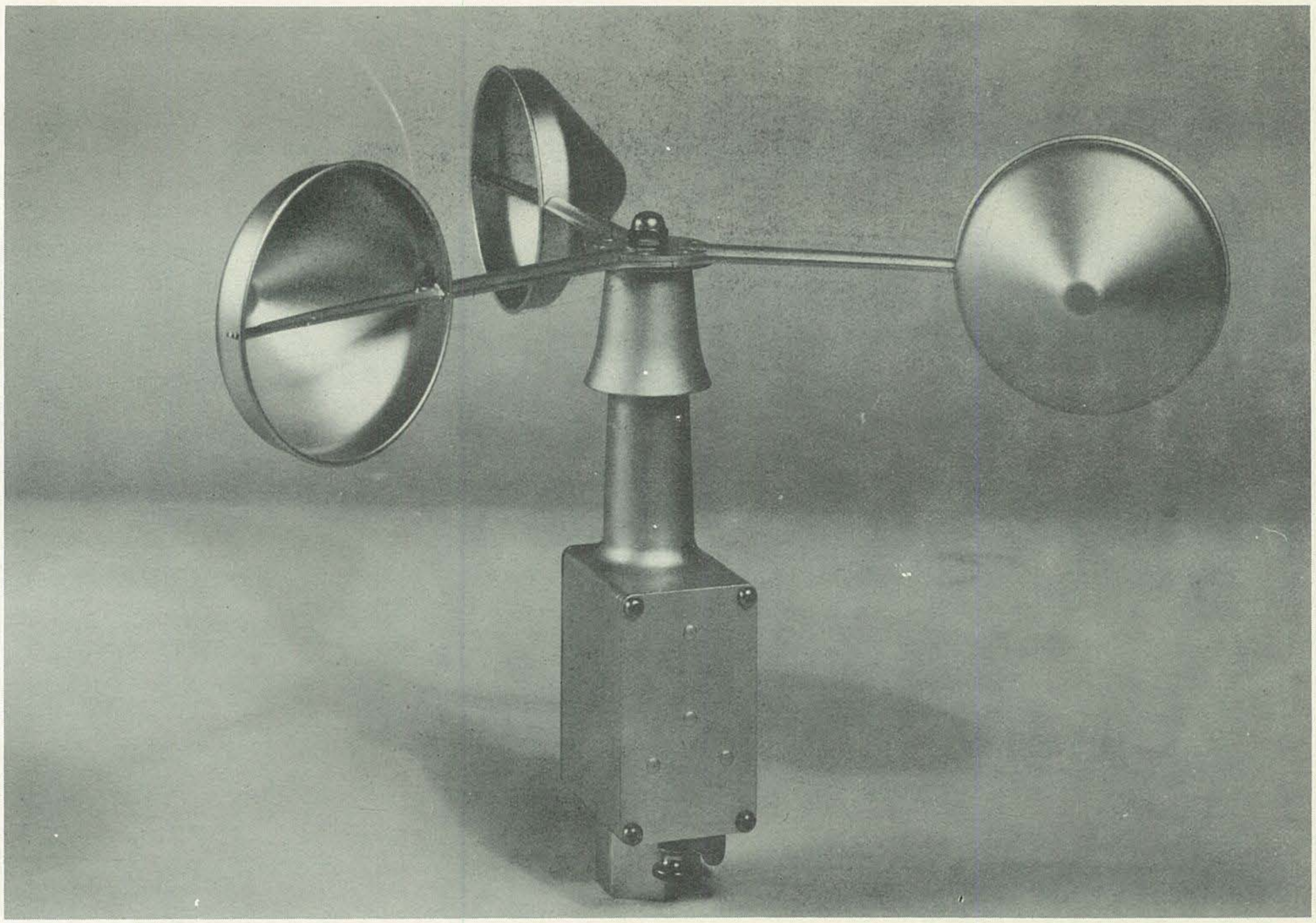

FIGURE 3A

Three-cup, "SA" type, small airway anemometer; 2.875-inch diameter semi-conical cups with beaded edges; equipped with 1/60-mile contact only but not provided with totalizing device. (Stock No. F103)

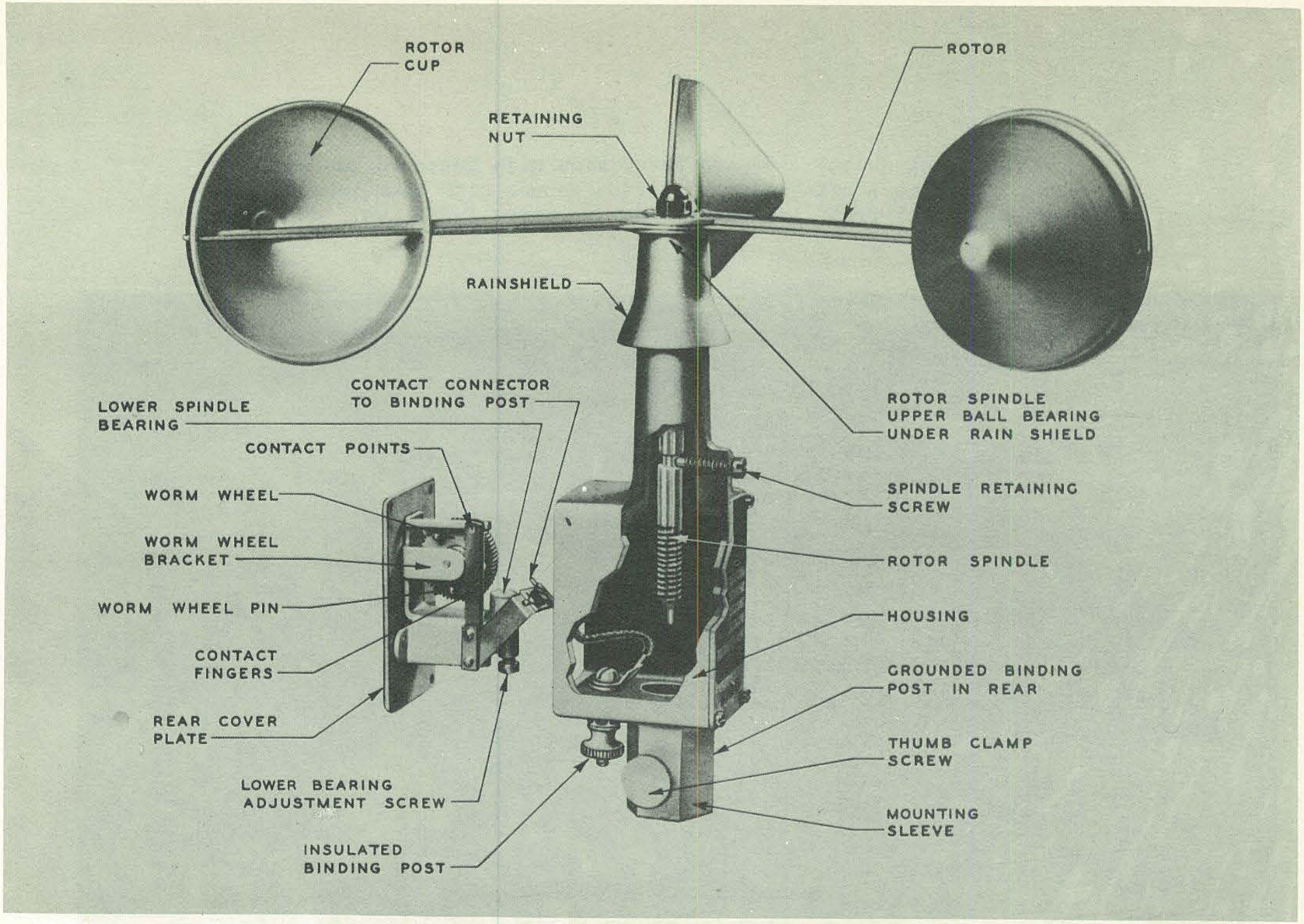

FIGURE 3B

Cut-away view of "SA" type anemometer, shown in figure 3A.

Before proceeding with the presentation of additional information concerning the mechanical aspects of obtaining wind speed with the aid of the contact-type anemometer, it is considered worth while to give a general, fairly brief account in the next three paragraphs relative to the recording and correcting of wind data. We may mention at this point that further details regarding the matters touched upon in these paragraphs will be found in Chapter VII and in the Appendices.

The change in design from the 4-cup to the 3-cup instrument was adopted owing to the fact that calibrations of the two designs in the wind tunnel revealed that, generally speaking, the errors in the readings of the three-cup instrument were smaller than those pertinent to the four-cup instrument. (See Appendices; summary in No. V.). During the earlier period of use of the 4-cup anemometer, corrections to overcome these errors were not generally employed; and likewise beginning with January 1928, whenever the 3-cup anemometer was used, and continuing until the end of 1931, corrections were not applied to the readings of the latter instrument, on the assumption that the errors of the 3-cup instrument were negligible. During the four-year interval just mentioned (1928-1931), the best 4-cup anemometer at the station was designated as "extra", to be used only when the 3-cup instrument was being cleaned or when it was damaged. It was an adopted practice during the four-year period to make a notation on the record when the 4-cup anemometer was substituted for the 3-cup instrument and to apply corrections to the readings of the former in order to reduce them to the equivalent of readings of the latter.

Beginning with January 1, 1932, the 4-cup anemometer was again generally employed for official wind-speed measurements at first-order and other stations of the Weather Bureau at which automatic records were maintained, but after a lapse of several years the 3-cup anemometer was once more put into general use by the Bureau. However, there has been this important difference in practice since January 1, 1932: all readings of anemometers, both 3- and 4-cup types, have been corrected to true wind-speed values.

Wind directions were originally observed to 8 points of the compass (N, NE, E, etc.) and the data were tabulated accordingly in climatological records. However, since about the year 1940, a new practice was established and maintained of observing and recording wind directions to 16 points (N, NNE, NE, ENE, E, etc.). Specifically, the U. S. Synoptic Code effective June 1, 1939, provided for the reporting of wind direction to 16 points.

The conventional cup anemometer was originally provided with 1-mile contacts. These electric contacts were so arranged in relation to the circumference of the cup wheel that an electrical contact was made momentarily at the completion of each respective whole mile of wind movement. At the instant of contact an electric current was caused to flow in a connecting circuit. This pulse of current served as an indication that a mile-long horizontal column of air had moved past the anemometer as wind since the previous contact. Instruments designed on this basis of operation were termed "1-mile contact anemometers", because the wind speed could be indicated in miles per hour if the horizontal distance of 1 mile were divided by the time which had elapsed between successive contacts, the hour being used as the unit.

The "1-mile contact anemometer" was adapted to the recording of wind-speed data by means of either a "single register" or a "triple register". The method employed will be explained in detail in the next section. The "triple register" is still extensively used at first-order Weather Bureau stations for the automatic registering of wind speed data. It is obvious that the "one mile contact anemometer" was not designed to permit the accurate determination of wind movements for fractions of 1 mile, hence it could only provide wind-speed values over intervals of time at least as great as the period covered by 1 mile of wind movement, and it could not give precise indications of small-scale variations in the wind speed. On account of the need, especially at airport stations, for a method of securing wind-speed information somewhat more rapidly than at city-office stations and in consideration of the requirement for data regarding short-period wind fluctuations (turbulence and gustiness), a modification of the system of contacts was developed. (See fig. 2). This consisted of contacts in the anemometer for each 1/60th-mile of wind movement, in addition to the contacts for 1 mile. Assuming that one-sixtieth of a mile of wind flow actually occurs between each successive pair of the former contacts, it may be easily seen that the number of 1/60th-mile contacts made per minute will equal the same number of miles per hour of wind speed. Thus, if the 1/60-mile contact-type of anemometer is connected to an electric buzzer (see fig. 4), the count of the number of buzzes in a time interval of 1 minute yields the wind speed, in miles per hour. Such a system of wind-speed indication was employed at many airport stations during the 1930's, but its use declined subsequently, as more modern methods of recording were applied (see for example Chapter VIII). When the "9-light wind direction and speed indicator" as shown in figure 4 was introduced during that period, it permitted estimation of the wind direction to 16 points of the compass; and these data were used in airway meteorological reports.

III. RECORDING OF WIND DATA BY MEANS OF THE TRIPLE REGISTER

The triple register, illustrated in figure 5, consists essentially of a clock-driven drum on which is securely wrapped a chart, so arranged that several pens actuated by electric impulses controlled by certain equipment can make suitable records automatically on the chart. The equipment included an anemometer for the measurement of wind speed, a wind vane for the indication of wind direction, an automatic tipping-bucket type of precipitation gage for measuring rain, and a device for indicating periods when the sun was shining. A helical screw (worm drive) operated by clockwork causes the cylinder to be displaced parallel to its axis at a uniform rate while the cylinder rotates simultaneously with the turns of the screw. The relationship of the rate of rotation to the screw thread is such that one revolution of the cylinder is accompanied by an advance of the cylinder parallel to its axis by a distance corresponding to one-fourth its length during a time interval of 6 hours. Thus, four complete revolutions of the drum occur in 24 hours as the drum advances by its full length. In view of this relationship, the time at which any record mark is made on the chart by one of the pens can be determined from the position of the mark with respect to the original position of the pen at a known time when the chart record was begun.

The pen controlled by the anemometer makes a pair of marks transverse to the helical line on the chart each time that an additional mile of wind moves past the anemometer, except that for every successive tenth mile one of the lines in the pair is omitted in order to facilitate the counting of the number of marks made within various time intervals. Thus, each tenth contact is longer when compared to the other nine, and permits the observer to distinguish readily between them. (See fig. 6 which illustrates two different methods employed in this regard). Since the rate of movement of any point on the line is known, the distance between any two consecutive marks made by strokes of the pen in the same direction provides an indication of the time elapsed between the beginning and ending of the mile of wind movement shown by the consecutive marks. Accordingly, if the linear displacement of 1 mile of air passing the anemometer is divided by the time elapsed in hours, the result is the wind speed in miles per hour.

To accomplish this a line is printed on the chart in such a manner that it produces a helix when the chart is wrapped around the cylinder, since it has the same distance of advance as the metal screw which causes the displacement of the cylinder. Therefore,

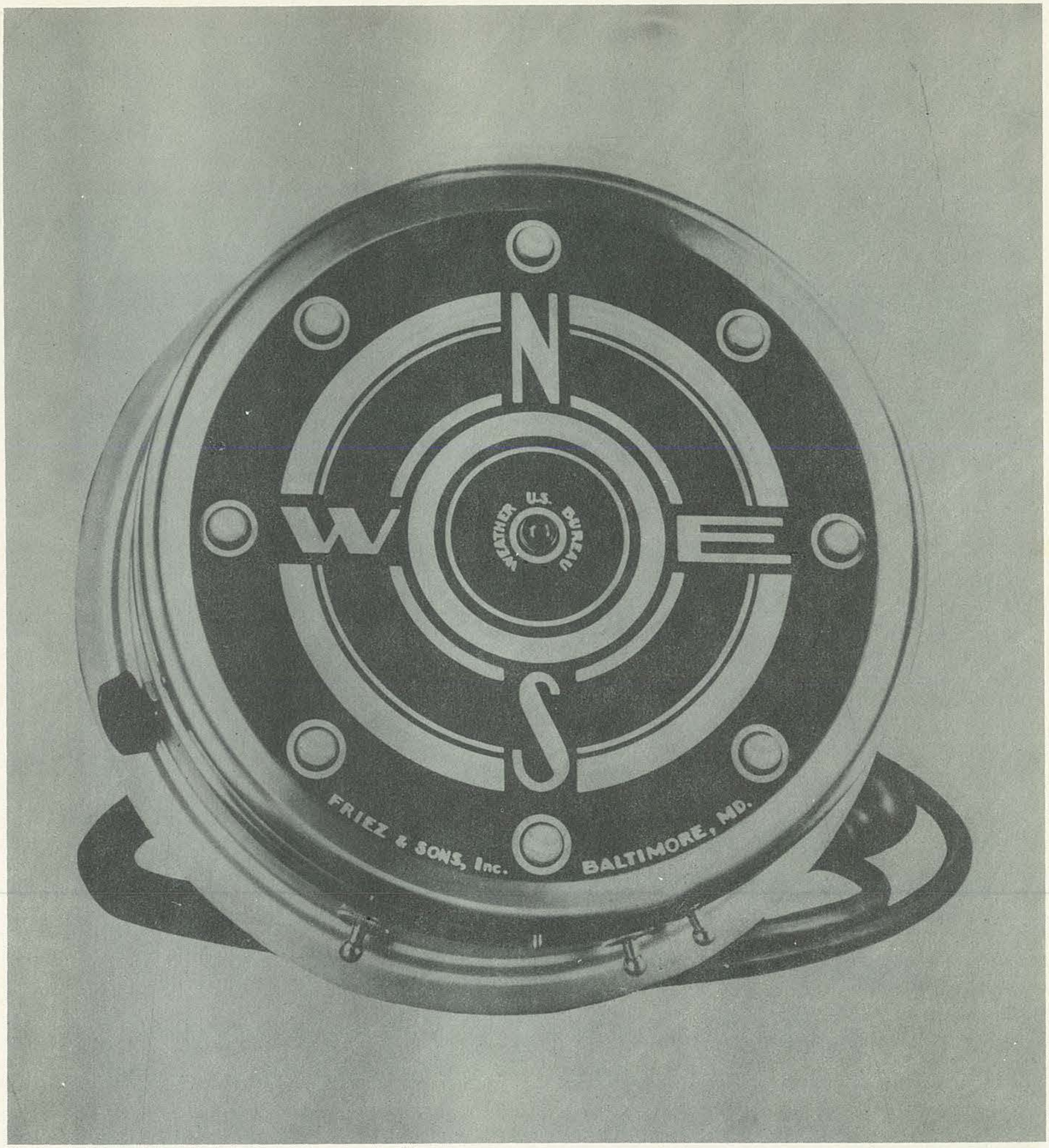

FIGURE 4

Wind speed and direction indicator, 9-light with buzzer; for use with 8-contact wind direction transmitter and 1/60-mile contact anemometer. (No. F221A)

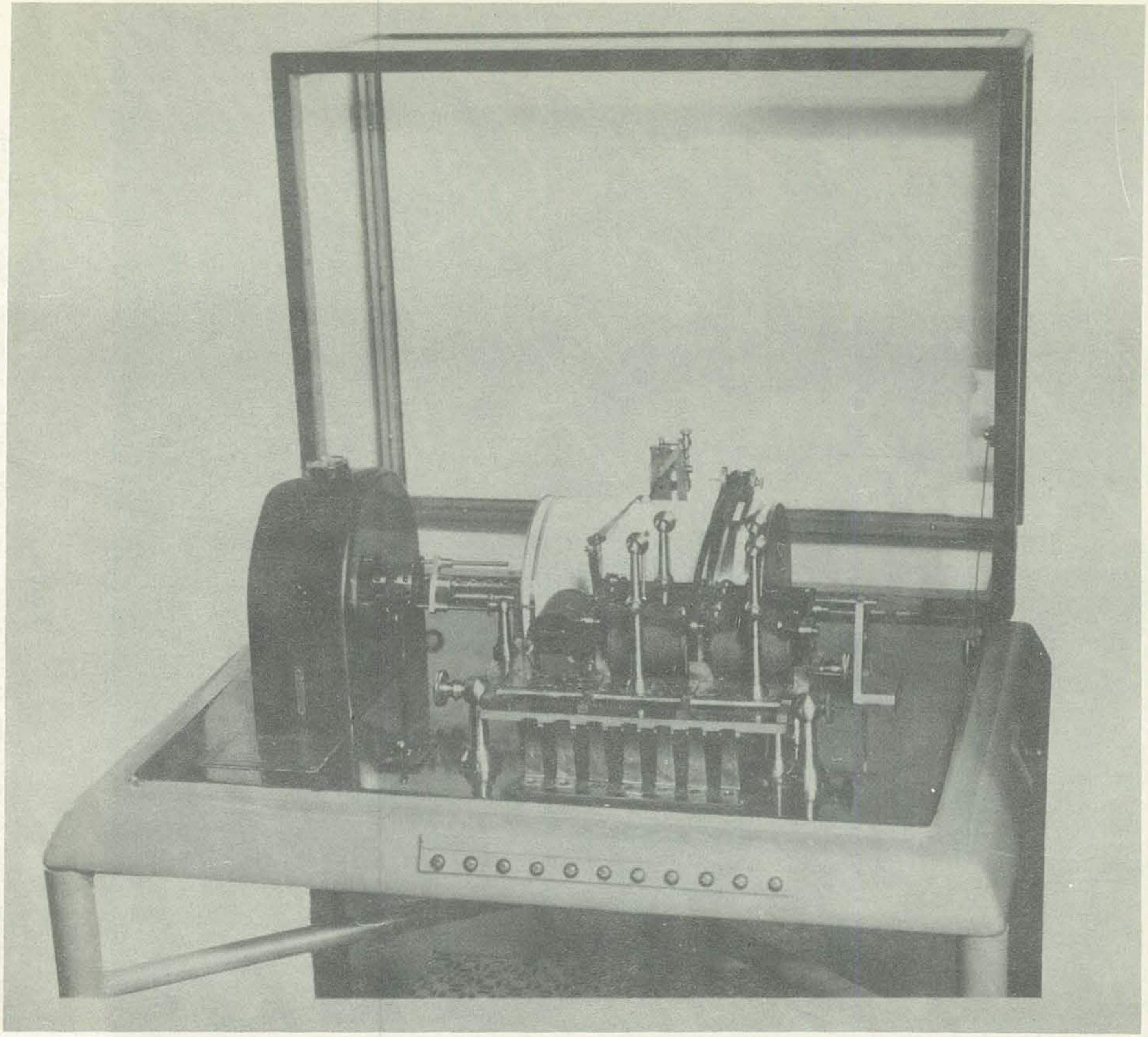

FIGURE 5
Triple register, to yield record of wind speed, wind direction, rain, and sunshine; for use with 4-contact wind direction transmitter, one-mile contact anemometer, tipping bucket rain gage and sunshine switch. (No. M000)

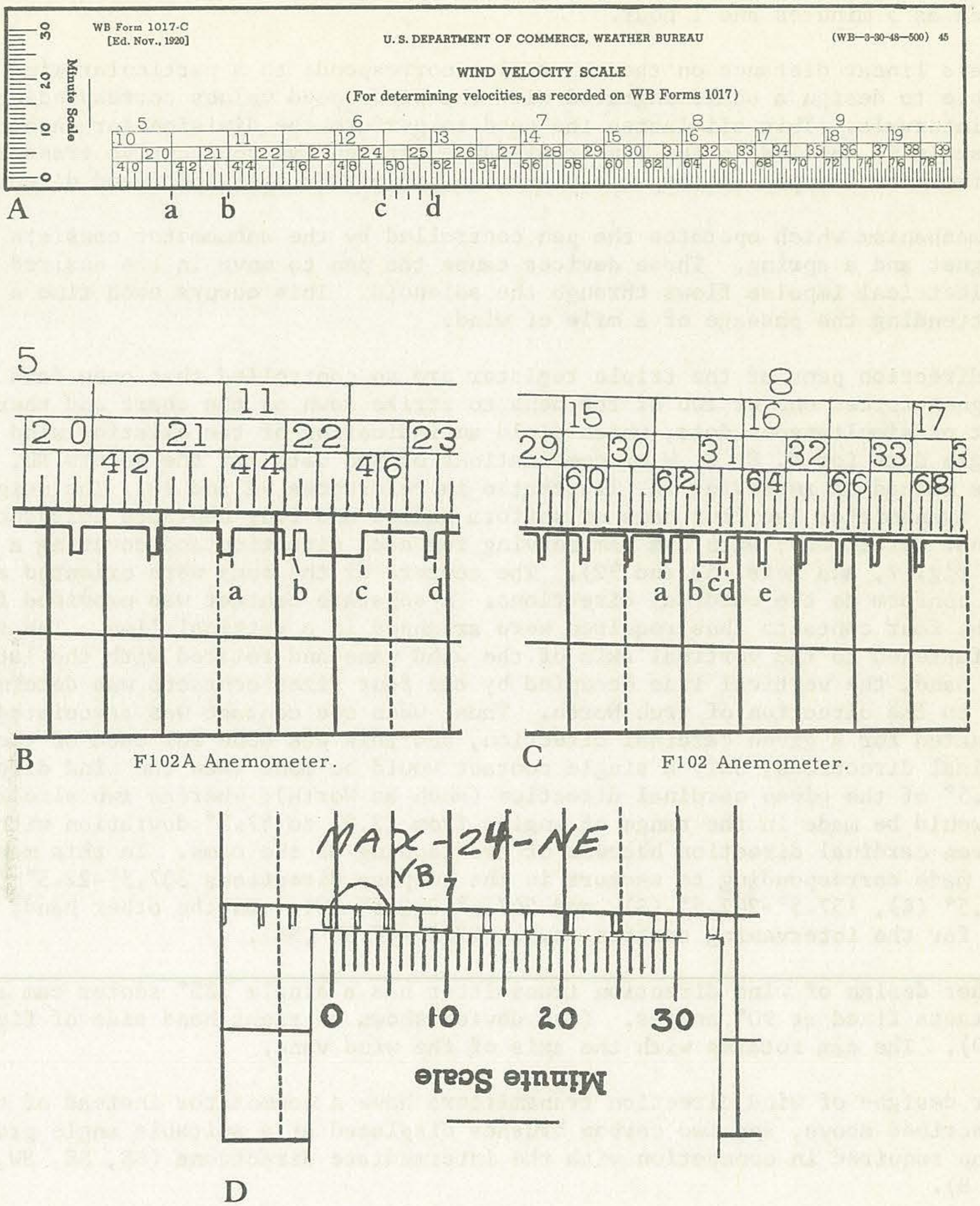

FIGURE 6

A is a wind speed scale for use with triple register records. B, C, and D show the application of the scale in evaluation of typical records from the register.

Explanation: The scale shown in A has four ranges of speed. For example, the smallest scale divisions between a and b represent 42 m.p.h., two such divisions represent 21 m.p.h., four represent 10.5 m.p.h., and the space from a to b which contains eight small scale divisions represents 5.25 m.p.h. In B the wind speed corresponds to 11 m.p.h. for the interval a b. In C the wind speed is 31 m.p.h. (in this case the increment b c was taken as approximately 92% of b d which is the length of the distinctive mark at the end of the 10-mile cycle). In D the "Maximum Average Five-Minute Wind Speed" is 24 m.p.h. (2 miles in 5 minutes, computed as 2 miles divided by 1/12 hour equals 24 m.p.h.).

positions on this line serve to indicate time. The known rate of motion of the cylinder permits lines to be printed on the chart which correspond to pre-established time increments, such as 5 minutes and 1 hour.

Since a linear distance on the chart also corresponds to a particular wind speed, it was possible to design a scale engraved with the wind speed values corresponding to various time intervals. This eliminates the need to perform the division for each reading. When the scale is applied to the linear distance between two consecutive transverse marks made by stroke of the pen in the same direction, it yields the wind speed directly.

The mechanism which operates the pen controlled by the anemometer consists of an electromagnet and a spring. These devices cause the pen to move in the desired manner when an electrical impulse flows through the solenoid. This occurs each time a contact is made attending the passage of a mile of wind.

The direction pens of the triple register are so controlled that once each minute an electromagnet forces one or two of the pens to strike down on the chart and thereby produce a dot or simultaneous dots, which yield an indication of the existing wind direction (e.g. single dots for N, E, S, W or combinations of two dots for the points NE, SE, SW, NW). This method of recording is illustrated in references 92 and 94. The original wind direction transmitter had four cams of uniform radius and four contacts corresponding to the cardinal directions; with one cam serving for each direction and covering a sector of 135° (see fig. 7, and Refs. 53 and 92). The centers of the cams were oriented at 90° angles to conform to the cardinal directions. A separate contact was provided for each cam and the four contacts thus required were arranged in a vertical line. The system of cams was fastened to the vertical axis of the wind vane and rotated with the latter. On the other hand, the vertical line occupied by the four fixed contacts was determined with reference to the direction of true North. Thus, when one contact was associated with a cam designated for a given cardinal direction, and this was done for each of the respective cardinal directions, only a single contact would be made when the wind direction was within 22.5° of the given cardinal direction (such as North); whereas two simultaneous contacts would be made in the range of angles from 22.5° to 67.5° deviation with respect to any given cardinal direction because of overlapping of the cams. In this manner single dots were made corresponding to sectors in the compass directions 337.5°-22.5° (N), 67.5°-112.5° (E), 157.5°-202.5° (S), and 247.5°-292.5° (W). On the other hand, two dots were made for the intervening sectors, e.g., 22.5°-67.5° (NE).

Another design of wind direction transmitter has a single 135° sector cam and four point contacts fixed at 90° angles. (See device shown on right hand side of fig. 9 and in fig. 10). The cam rotates with the axis of the wind vane.

Later designs of wind direction transmitters have a commutator instead of the cam system described above, and two carbon brushes displaced at a suitable angle provide for the overlap required in connection with the intermediate directions (NE, SE, SW, and NW). (See fig. 8).

Information concerning the wiring of the triple register was published by Covert (Ref. 93).

When an operation recorder is employed instead of the triple register, a tooth-like mark is made on the autographic record sheet in place of the dot indication used in the triple register.

For more details regarding the triple register and the wind vane mechanisms the reader is referred to Weather Bureau Addendum to "Manual of Surface Observations", Circular N,

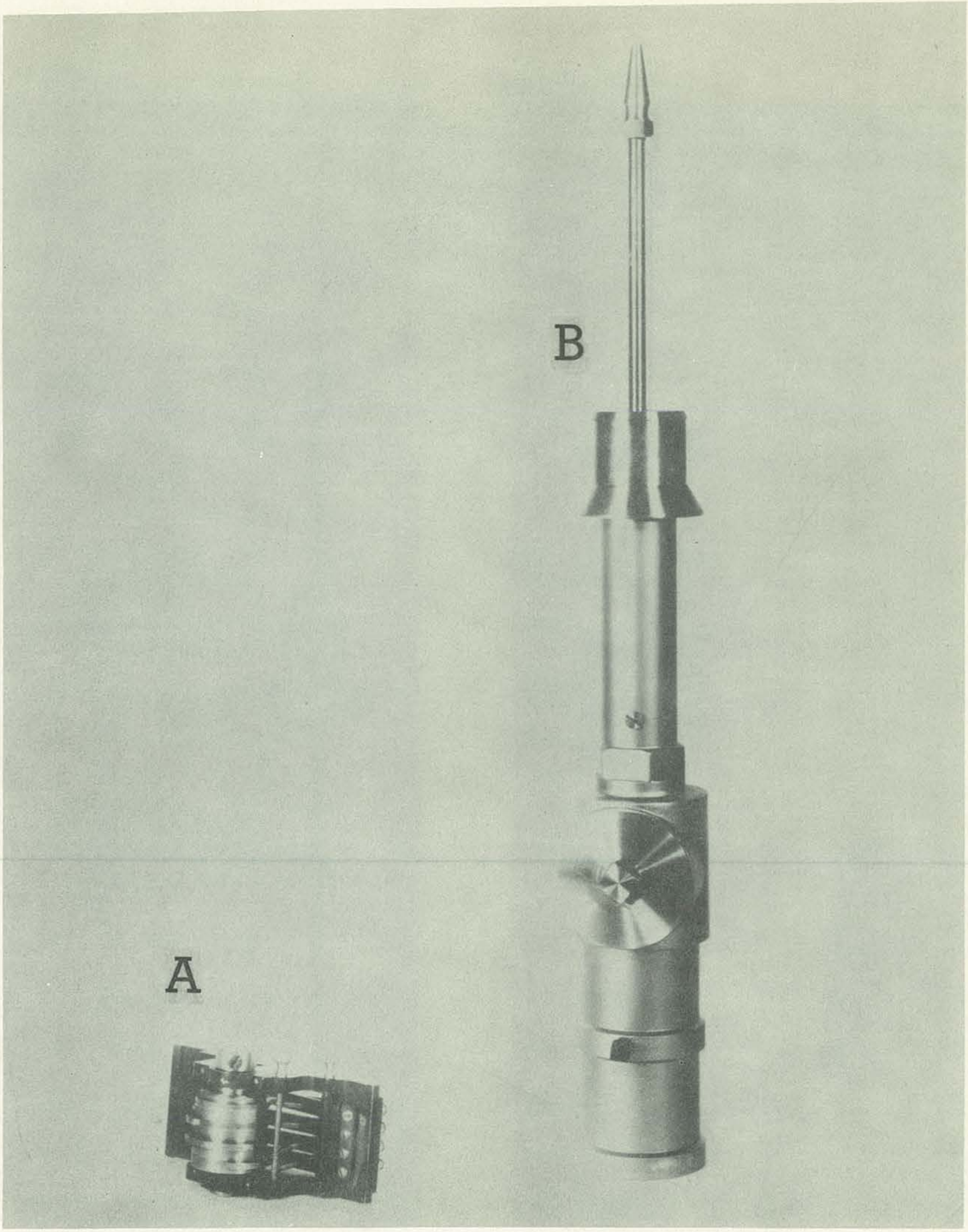

FIGURE 7

Wind direction transmitter "A" is cam assembly with four electrical contacts and "B" is Fergusson bearing for wind vane, used with contact assembly shown in "A". (Contact assembly No. F001-1, Bearing No. F001-4)

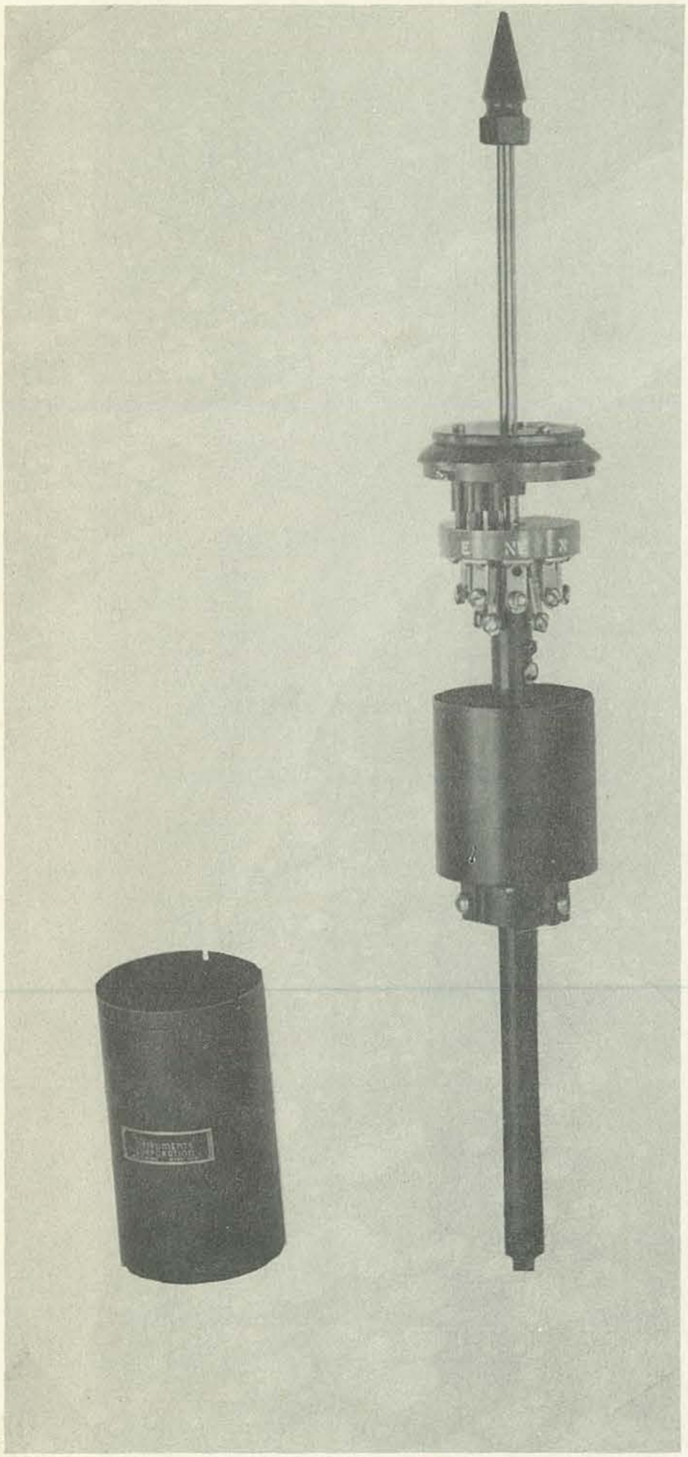

FIGURE 8

Wind direction transmitter, 12-point commutator-type switch (No. F005). The outer shield is removed and the inner shield lowered to reveal the commutator and carbon brushes.

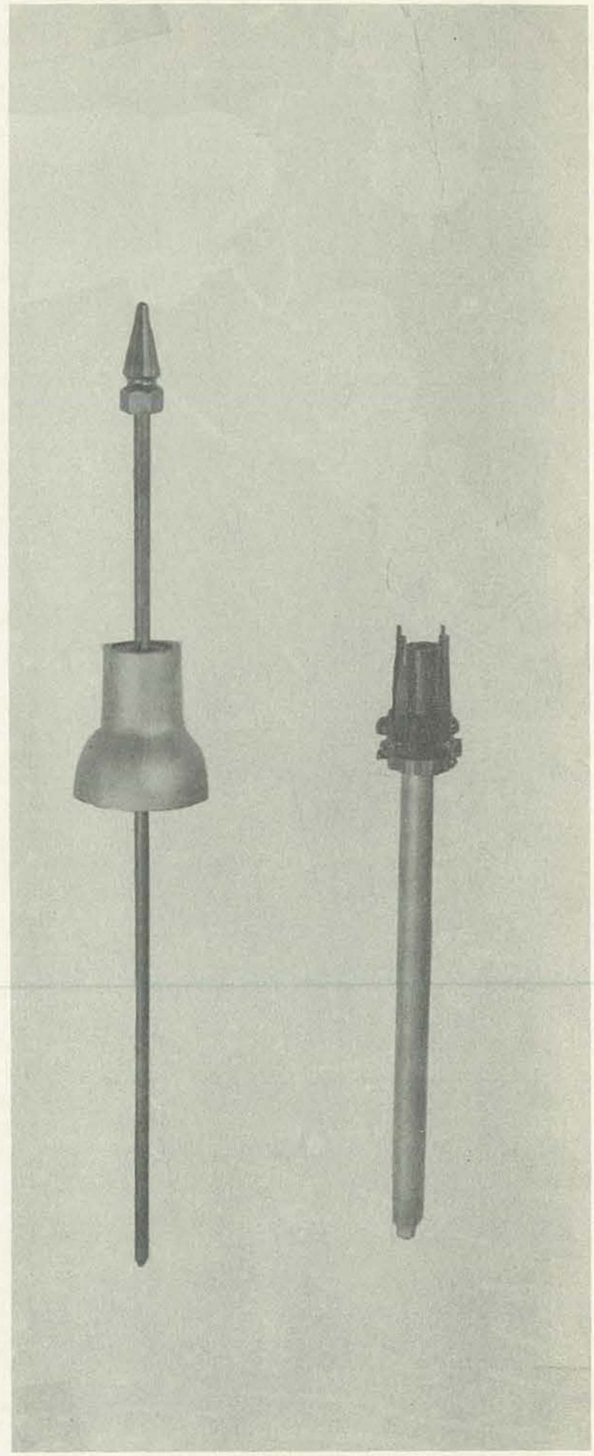

FIGURE 9

Wind direction transmitter, 4-point contact type. On the left is the spindle and shield, on the right the bearing and contact assembly. (No. F002)

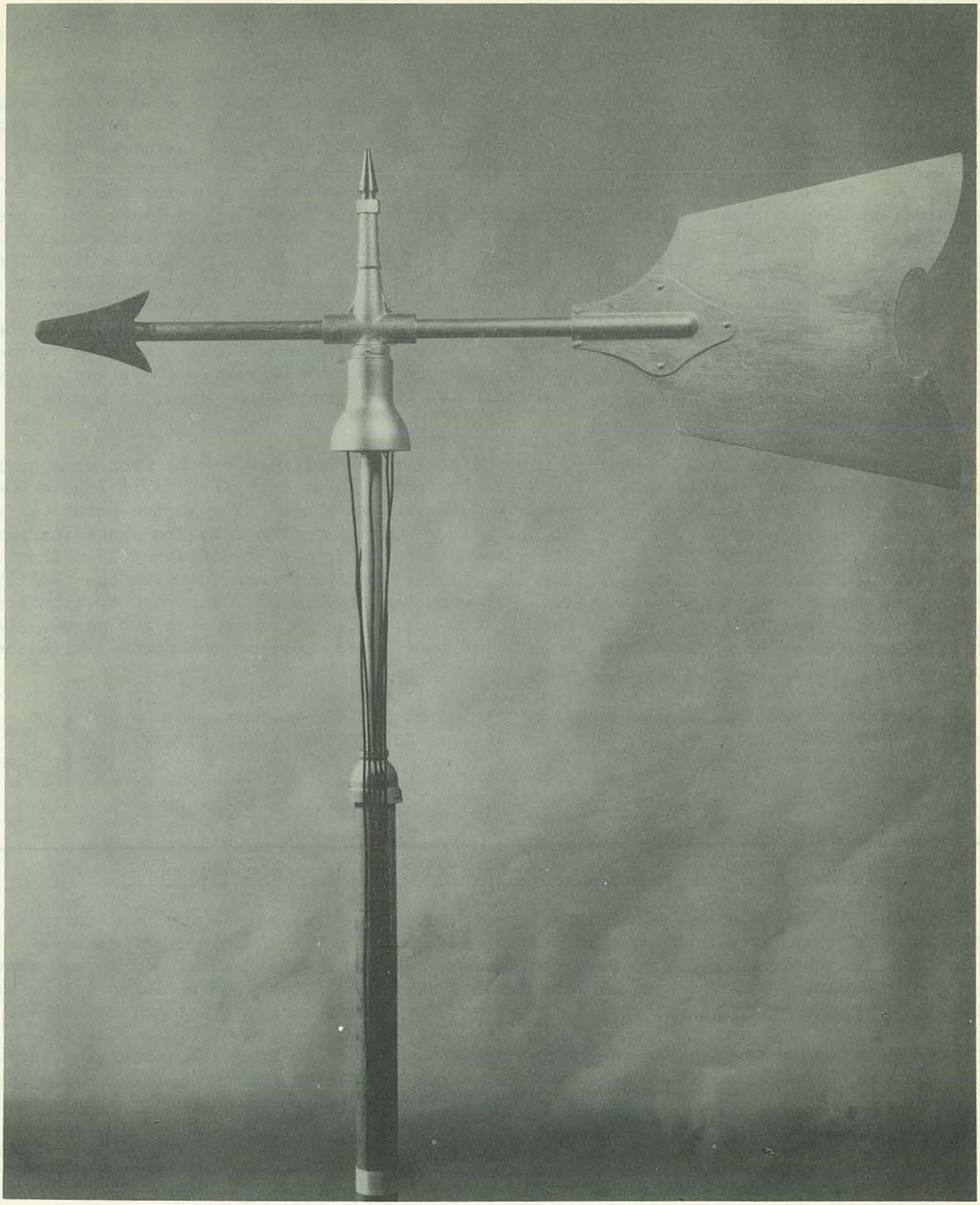

FIGURE 10

Wind vane (No. F010) with 4-point wind direction transmitter similar to that in figure 9.

Sixth Edition Revised, November 1951; Chapter A8 on Wind, and Chapter A13 on Multiple Registers and Sunshine Switch. The latter chapter illustrates the type of record produced by the anemometer on the triple register chart.

In some cases stations are equipped with wind vanes that have a wind direction transmitter consisting of a 12-point commutator-type switch. Four of the points refer to the four sectors for the cardinal directions as previously explained, and the other eight refer to combinations pertaining to the 8 points of the compass, viz., N, NE, E, SE, S, SW, W, NW. The first four points mentioned are employed in connection with the triple register; while the remaining eight points are used for the so-called "9-light wind speed and direction indicator" (see fig. 4 and paragraph A8310 of the Weather Bureau Addendum referred to above). The latter device consisting of 8 lights in the form of a direction dial plus a center one is employed at airway stations to indicate the wind direction according to which light or pair of lights is incandescent, depending upon orientation of the wind vane with relation to the contacts pertaining to the respective 8 points of the compass. The ninth light, in the center of the dial, is connected to a 1/60 mile contact-type cup anemometer. This center light flashes once for each contact. Therefore, a count of the number of flashes within 1 minute indicates the average wind speed, in m.p.h., during the minute.

Some stations are equipped with a wind direction transmitter for the wind vane having either a twelve-point switch or an eight-point switch. These are pictured in figure A8-11 of the Weather Bureau Addendum to Circular N, referred to above. The twelve-point switch serves the same purpose as the 12-point commutator switch mentioned in the preceding paragraph, but the mechanical details of its construction are somewhat different from those of the latter. The eight-point switch (see fig. 11) is used in connection with the "9-light wind speed and direction indicator" (fig. 4), when no triple register record is required. These switches contain a contact for each point, adjustable by means of a set screw. Cam rollers actuated by the orientation of the wind vane serve to close the circuit with these contacts.

Information relative to installation of wind measuring equipment may be found in various Instrument Division Circulars (see References at end of this survey).

IV. REPLACEMENT OF THE TRIPLE REGISTER BY MORE MODERN RECORDERS

The triple register was a useful piece of equipment which served its purpose quite adequately during the early days. It was fairly limited as to the number of elements that could be recorded, and the chart covered only a period of 24 hours. In modern times, operation recorders have been developed, capable of recording many more elements than was possible by means of the triple register and yielding their records on continuous rolls of paper so that the periods covered were not so limited. In view of these considerations, the 20-pen operation recorder manufactured by Esterline-Angus Co., has been introduced at some stations to replace the triple register. One of the pens of the operation recorder is actuated by the anemometer, producing transverse marks (like jogs) for each mile of wind movement, practically in the same fashion as in the case of the triple register (see Chapter A13 of Weather Bureau Addendum of Circular N). Four of the pens of the Esterline-Angus operation recorder are employed to indicate the cardinal wind directions. The functioning of these pens is such that when contact is made in the wind-direction transmitter for any particular wind direction a circuit which is closed once each minute (or two minutes) permits an electric current to flow into the electromagnet

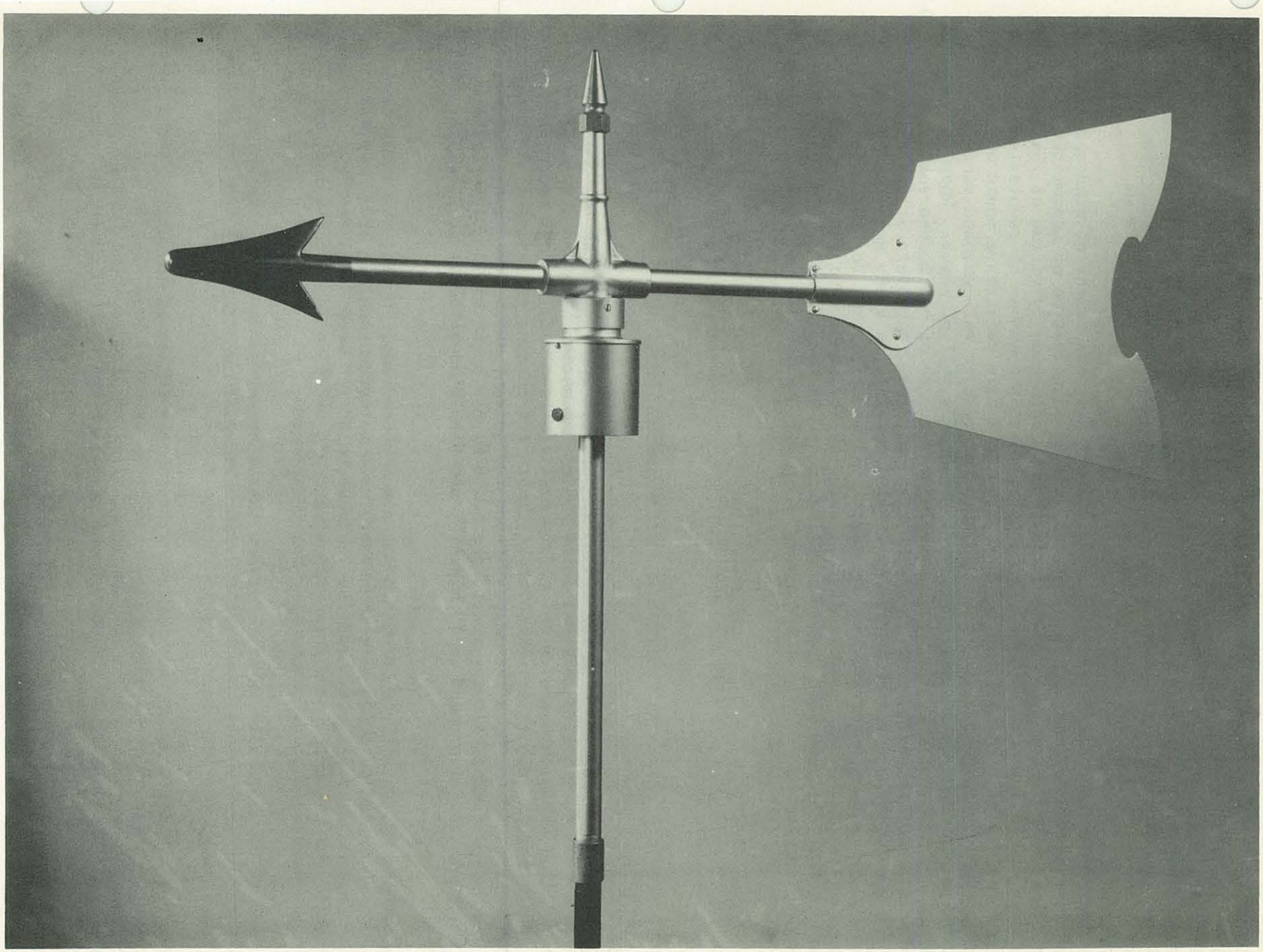

FIGURE 11
Wind vane (No. F010) with 8-point wind direction transmitter (No. F003), having adjustable contacts.

controlling the particular pen so that the pen is momentarily pulled aside, thus producing a sharp tooth-like mark. Consequently, the occurrence of such a mark for any of the four specified pens is indicative of the wind direction. Combinations of the marks show the occurrence of intermediate directions (e.g., NW).

Five of the remaining pens are employed to indicate the record of the tipping bucket precipitation gage, and another of the pens is used for the recording of the duration of sunshine. Information concerning the various Operation Recorders manufactured by the Esterline-Angus Co., Inc., may be found in literature issued by the company (see Refs. 22 and 23).

In addition to the contact-type anemometers for the measurement of wind speed another class of instrument employed is the generator-type or magneto-type of anemometer (see Chapter VIII). The latter type yields a continuous indication by virtue of the d.c. electric current which it generates in direct proportion to the number of revolutions per second of the spindle of the instrument. Therefore, this type requires a means of continuous recording. For such purposes the speed and gust recorder is well adapted since it permits indications of the wind speed on a chart consisting of a roll of paper. When the chart drive is in the low position, the paper travels at the rate of two inches (or three inches) per hour; and when the chart drive is in the high position, it travels at the rate of two inches per minute. Thus, in the latter case it is possible to study gust structure. At the normal, low rate of paper travel, the chart roll is sufficient for two weeks of recording; whereas at the high rate it is only adequate for about five and one-half hours. A picture of the speed and gust recorder will be found in Chapter A8 of the Weather Bureau Addendum of Circular N.

V. DEFINITION OF WIND SPEED TERMS

Modern usage among physicists and engineers indicates that the term "speed" pertaining to any object or fluid undergoing motion is employed when referring to "the ratio of distance traveled to the time interval during which the motion occurred", regardless of the direction of the path taken by the object or fluid involved. Proper usage of the term "velocity" in modern scientific nomenclature limits its meaning to a vector quantity; that is, the specification of both the magnitude and the instantaneous direction. For example, if the wind were observed blowing toward the north with a speed of 10 miles per hour, we should say that "the wind speed is 10 m.p.h.", and "the wind velocity is 10 m.p.h. from the south".

Unfortunately, this distinction has not always been made. During the early days of meteorology speed and velocity were frequently used interchangeably. Thus, expressions like the "maximum wind velocity" and the "extreme velocity" were often employed in regard to quantities for which only the speed was given. In order to avoid confusion, this paper will always indicate a proper equivalent for these terms.

It should be understood in what follows that whenever we speak of the "multiple register" the reference is either to the "triple register" described in Chapter III or to the "operation recorder" described in Chapter IV.

From the descriptions already given concerning the method of operation of the multiple register, it may be readily seen that a register actuated by a "1-mile contact anemometer" is capable of indicating the number of miles of wind movement passing the instrument during various intervals of time. Since the chart was changed daily at local noon or midnight, the number of miles of wind movement during the 24-hour period could be ascertained immediately after the time the chart was replaced. A count made of the number of whole mile wind passages from the total number of transverse marks on the daily chart yielded the "24-hour wind movement", which is of interest for various types of investigations, such as the intensity of the general circulation, the average evaporation effects of wind, etc.

Another element determined from the record on the register was the so-called "maximum wind velocity", also termed the "5-minute maximum wind speed". This represented the wind speed corresponding to the greatest number of miles of wind movement past the anemometer during a one-twelfth hour (5 minute) interval. For example, suppose that the chart record for a given 24-hour period was examined, and that the maximum number of miles of wind movement found to occur during any 5-minute period was 6.0, then the corresponding 5-minute maximum wind speed was calculated as: 6.0 miles/(1/12 hour) = 72 miles per hour. The 5-minute maximum wind speed was taken from the chart of the register each day, and the resultant value was entered in the daily record form. At the end of the month the greatest value of the 5-minute maximum wind speed which had been observed during the month was noted down in climatological records; and similarly, at the end of the year, the annual maximum was reported on the basis of the greatest value observed during the year.

Beginning with the year 1912, still a different element obtained from the register chart was the so-called "extreme wind velocity", also termed the "fastest mile" or the "fastest single-mile wind speed". This quantity represents the wind speed corresponding to the whole mile of wind movement which has passed by the 1-mile contact anemometer in the <u>least amount of time</u>. Therefore, it was determined from the triple-register chart by observing the shortest time interval between consecutive pairs of transverse marks made by the pen actuated by the anemometer. On this basis the "fastest single-mile wind speed" could be calculated as the quotient of 1 mile and the minimum time interval (in hours) elapsed during the passage of 1 mile of wind movement. Records of this element were made in accord with the data shown on the daily charts, and at the end of every month and year the highest extremes were indicated on climatological forms pertaining to the stated periods. This practice has been maintained wherever multiple-register equipment is still in use.

During the period 1910-1948, monthly and annual summaries prepared for Weather Bureau stations contained data regarding the observed 5-minute maximum wind speeds. Effective January 1, 1949, the fastest single-mile wind speed data were included in the published summaries; and the 5-minute maximum wind speeds were <u>not</u> given in those summaries. During the period January 1, 1949 - September 30, 1957, inclusive, daily values of the following elements were recorded at stations where multiple registers were available: 5-minute maximum wind speed, associated wind direction, and time of beginning of this speed to the nearest minute; also, fastest single-mile wind speed, associated wind direction, and time of beginning to the nearest minute. At City Offices, where aviation observations were not made, these data were entered in columns 34-37 of Form 610-10 (formerly 1001 B); and at stations where aviation observations were made they were entered in column 90 of Form WBAN-10. <u>Beginning October 1, 1957, the data pertaining to the 5-minute maximum wind speed were omitted; hence after September 30, 1957, no records of the latter data are kept.</u> However, records pertaining to the fastest single-mile wind speed are continued and maintained for stations equipped with the multiple registers subsequent to this time.

VI. VERIFYING VELOCITY

The term "verifying velocity" requires some explanatory remarks. (Note: References pertinent to this matter are given in Weather Bureau Instructions No. 15 of December 9, 1927, which is presented in Appendix I of this paper, also in Appendices I-B and I-C). Each station which rendered synoptic or climatological reports, was assigned one or more so-called "verifying velocities". In the case of a station making synoptic reports, if the 5-minute maximum wind speed observed since the previous synoptic report attained or exceeded the assigned value of its "verifying velocity", the actual amount of the 5-minute maximum wind speed during that intervening period together with the accompanying wind direction were expressed by a special code term reported in the synoptic message. Stations located on the Atlantic, Pacific, or Gulf coasts, or on the Great Lakes were individually assigned specific values for the verifying velocities; whereas stations not located in those areas employed the value 40 miles per hour for the verifying velocity in connection with the synoptic message (see Weather Code, 1924, paragraphs 83-88). The assigned values of verifying velocities were published in "Station Regulations", while changes in the values were published from time to time in Weather Bureau "Instructions". In some cases the assigned values of the verifying velocities depended upon the direction of the wind at the time of the maximum. The reports of 5-minute maximum wind speed received in synoptic messages were used in part for the purpose of verifying the accuracy of Storm Warning forecasts.

In the case of climatological records, each station was assigned a verifying velocity. The application of this datum was as follows: for every hour during which the 5-minute maximum wind speed equaled or exceeded the verifying velocity the observed 5-minute maximum wind speed was determined and entered in red ink in appropriate places on Weather Bureau Forms 1001 and 1014. Form 1001 was the monthly record which included data for each day, and means and extremes of certain elements for summary purposes. Form 1014 was a record book kept at each station with much the same sort of data on a daily basis, together with notes regarding observations of unusual local phenomena. At stations not located on the above-mentioned coasts or on the Great Lakes, the Official in Charge at the station would establish a velocity limit at and above which the hourly entries of 5-minute maximum wind speed would be made in Forms 1001 and 1014 at his station. This velocity limit, which was indicated on the page of Form 1001 where hourly wind movement was entered, varied from station to station and from time to time. For example instructions for the year 1905 suggested that the specified hourly maxima not be evaluated unless they exceeded 24 m.p.h. (uncorrected); while the 1936 instructions suggest that they not be evaluated unless they exceeded 21 m.p.h. (corrected). Some stations did not evaluate the hourly maxima unless they exceeded 33 m.p.h. (uncorrected) 3-cup or equivalent 4-cup reading.

The 12-hour maxima were also evaluated when they exceeded the assigned verifying velocity. In such cases the maxima were encoded in the synoptic reports and entered on the observational pages (pp. 2 and 3) of Form 1001. At coastal and Great Lakes Stations these maxima were recorded when they equaled or exceeded 33 m.p.h. From January 1, 1928 through December 31, 1931, the uncorrected 3-cup or equivalent 4-cup reading was used in determining when 33 m.p.h. was reached. See Appendices I-A, I-B, I-C, and II for further details. At stations not on the coast or Great Lakes the 12-hour maxima were evaluated when they exceeded 21 m.p.h. by the 3-cup anemometer or equivalent 4-cup reading (January 1928 through December 1931).

VII. CORRECTIONS TO INDICATED WIND SPEEDS GIVEN BY CONTACT-TYPE ANEMOMETERS

The regular 4-cup anemometer was employed at all first-order stations of the Weather Bureau until the very end of the year 1927 for the purpose of determining wind speed in the manner previously described. In the Annual Report of the Chief Signal Officer, 1890, a table of corrections to the indicated readings of this instrument in order to obtain true wind speeds was published for the range up to 90 m.p.h; and a copy of this table is reproduced in Reference 53, page 9. However, these corrections were not applied in general practice by the Bureau for record purposes up to the close of 1927. Comparison of the data given in the table of 1890 with those adopted in 1927 and 1931 reveals some discrepancies.

A notable departure from older practice occurred following the issuance of Weather Bureau Instructions No. 15, dated December 9, 1927, effective January 1, 1928. This publication contained two tables which may be briefly described in these words: Table 1 - Correct or true velocities corresponding to velocities indicated by the 4-cup anemometer, covering the range 2-189 m.p.h.; and Table 2 - Correct or true velocities corresponding to the velocities indicated by the standard 3-cup anemometer (for use as indicated in paragraph 9 of Instructions No. 15, 1927, and covering the range 2-140 m.p.h.).

In order to make abundantly clear the exact nature of the changes put into effect by Instructions No. 15, 1927, a copy of those Instructions is attached as Appendix I. Special attention is invited to paragraphs 1, 2, 3, 4, 6, 9, and 10 thereof for information pertinent to the present discussion.

It will be seen from the information in Appendix I that the 3-cup anemometer generally replaced the 4-cup anemometer at first-order stations in the continental United States effective January 1, 1928, and that the indicated readings of wind speed obtained with the aid of this 3-cup instrument were generally used uncorrected. Also, indicated readings of the 4-cup anemometer, when obtained, were corrected by means of Table 1, Instructions No. 15, 1927, to what was regarded as true wind speed; however some slight revisions were found to be necessary in the corrections at a later date (see Appendix II). Appendices I-A through I-E give further information regarding the use of corrected wind speeds.

Referring to paragraph 6 of Instructions No. 15, 1927 (also to the appendices referred to in the last paragraph above) it will be seen that under certain conditions the 5-minute maximum wind speeds obtained by means of the 4-cup contact-type anemometer during the period January 1, 1928 - December 31, 1931 were converted to the equivalent 3-cup anemometer results by means of a combination of the correction tables for the two types of instruments. It would appear that in general such conversion from 4-cup to 3-cup equivalents was made in connection with 5-minute maximum wind speed reported in synoptic messages when the maximum equaled or exceeded the so-called "verifying velocity" (see Weather Bureau Weather Code, 1924).

Comparing the corrections shown in Tables 1 and 2 of Instructions No. 15, 1927, it is obvious that for indicated speeds exceeding 7 m.p.h. the corrections applicable to the 3-cup contact-type anemometer are smaller in magnitude than those applicable to the 4-cup type.

Since January 1, 1932, all wind speed records reported by the Weather Bureau have been corrected to true wind speeds. This rule was put into effect under authority of Weather Bureau Instructions No. 14, dated December 18, 1931. These Instructions had appended to them 3 tables, described as follows:

Table 3 - Correct or true velocities corresponding to velocities indicated by the 3-cup anemometer (C. F. Marvin, 1931. Range covered: 0-200 m.p.h.)

Table 4 - Correct or true velocities corresponding to velocities indicated by the 4-cup anemometer (C. F. Marvin, 1931. Range covered: 0-209 m.p.h.)

Supplementary Table 5 - Corrections for indicated velocities derived from Tables 3 and 4.

In order to make clear the pertinent details of the information contained in Instructions No. 14, 1931, we present those instructions as Appendix II. Special attention is invited to paragraphs 1, 2, 3, 4, 5, 6, 9, 10, 11, 12, 13, and 16. In paragraph 4 of Instructions No. 14, dated December 18, 1931, the following information was presented regarding Table 2 on the basis of a limited number of tests: "Corrections for the 3-cup anemometer, published as Table 2, Instructions No. 15, 1927, have been found by further analysis to be in error". On comparing the corrections for the 3-cup anemometer given in Instructions No. 15, 1927, with those in Instructions No. 14, 1931, it will be observed that the differences may be summarized by the statement that for indicated speeds of 29 m.p.h. and less the true speeds given in the 1927 table were lower than those given in the 1931 table, whereas for higher indicated speeds the relationship was reversed. To give some idea of the magnitude of the discrepancies we may cite several representative figures:

Indicated Speeds (3-cup Anemometer)	True Speeds according to -	
	1927 Table 2	1931 Table 3
m.p.h.	m.p.h.	m.p.h.
2	2.2	3.48
10	10.0	11.14
20	19.6	20.16
30	29.1	29.08
50	48.1	46.84
75	71.8	68.99
100	95.5	91.13
140	133.5	126.5

While the reader of paragraphs 2 and 3 of Instructions No. 14, 1931, may get the impression that the 4-cup anemometer might have eventually superseded the 3-cup instrument, at least at first-order stations where automatic records are obtained, this has not been the case. Some years after 1931, procurements of the 4-cup anemometers ceased, and subsequent procurements were only of the 3-cup variety. At the time of writing this survey (May 1958), it appears that few, if any, 4-cup anemometers remain in service at Weather Bureau stations. The reason for this may be seen from the fact that the corrections for the 3-cup anemometer are generally smaller in absolute magnitude and vary more slowly with change in indicated speed than those of the 4-cup instrument. The latter fact yields a significant advantage for the purpose of obtaining more reliable corrected speeds averaged over a period when the wind is variable, since the corrections for the 3-cup type differ relatively little between the extremes of gust and lull so that an average correction for the middle of the range is usually quite representative.

Weather Bureau Instructions No. 1, dated January 2, 1935 (See Appendix III), were issued to provide revisions and extensions to the anemometer correction data presented in Instructions No. 14, dated December 18, 1931. Apart from three minor revisions in the data for Tables 3 and 4, the following additions were given:

Table 3a - Correct or true velocities corresponding to velocities indicated by the 3-cup anemometer (range 0-24.9 m.p.h., for the intervals of 0.1 m.p.h.)

Table 4a - Correct or true velocities corresponding to velocities indicated by the 4-cup anemometer (range 0-24.9 m.p.h., for the intervals of 0.1 m.p.h.)

Table 6 - Correct or true velocities corresponding to velocities indicated by anemometer equipped with 4-hemispherical cups with beaded edges. (Put into service at some stations beginning July 1, 1932; range 0-200 m.p.h. for intervals of 1 m.p.h.)

Table 6a - Correct or true velocities corresponding to velocities indicated by anemometer equipped with 4-hemispherical cups with beaded edges. (Put into service at some stations beginning July 1, 1932; range 0.0-24.9 m.p.h., for intervals of 0.1 m.p.h.)

Supplementary Table 5a (Revised) - Corrections for indicated velocities derived from Tables 3, 4, and 6. (Corrections were given in whole miles per hour).

From Supplementary Table 5a, Appendix III, it is evident that generally the corrections for the 4-cup anemometer with beaded cups are smaller in absolute magnitude than the corrections for the regular 4-cup anemometer <u>without</u> beaded cups. Table 8-6, attached as Appendix IV, from "Manual of Surface Observations (WBAN)", Circular N, Seventh Edition, October 1957, presents the corrections employed for various contact-type anemometers (1/60 or 1 mile contacts). It is clear from the data that the corrections to the 3-cup anemometers are generally smaller in absolute magnitude than those for the 4-cup types listed. A few words concerning the descriptions and designations of these instruments are necessary: (1) the 3-cup anemometer ML-80 is apparently the same as the 3-cup "S" type anemometer (for a discussion of the question concerning this matter see Note accompanying Appendix V.); (2) the 3-cup "S" type anemometer has hemispherical cups, <u>not</u> beaded (see Appendix II); (3) the 4-cup anemometer has hemispherical cups <u>not</u> beaded (see the same Instructions); (4) the 4-cup anemometer with beaded cups is briefly described in Weather Bureau Instructions No. 1, January 2, 1935; (5) the small airway "SA" type anemometer has 3 conical beaded cups and is provided with 1/60-mile contacts for use with the 9-light indicator. All anemometers of the "S" type are equipped with 1/60-mile contacts in addition to the usual 1-mile contacts. At time of writing (May 1958), it is apparently a general policy to procure no more 4-cup anemometers, and to employ 3-cup anemometers wherever practicable.

VIII. DIRECT-READING MAGNETO ANEMOMETERS AND CONDENSER-DISCHARGE TYPE OF ANEMOMETER

In an earlier chapter we have mentioned the contact-type anemometers which make their records by the closing of electric contacts for each mile or 1/60-mile of wind passage. A different method of recording is employed in the direct-reading type of anemometer. It contains a magneto or small electric generator involving a permanent magnet. A spindle is connected to the armature of the magneto so that the number of revolutions per minute of the spindle as determined by the rotation of the anemometer cups governs the magnitude of the electric current generated by the magneto (see fig. 12 for the cup-type and fig. 13 for the propeller-type). Calibration of this type of anemometer in the wind tunnel indicates that to a close degree of approximation the true wind speed is linearly related to the electric current produced by the magneto. The pertinent relationship is given by the equation:

$$U = K \cdot I + C \qquad (1)$$

where U = true wind speed, I = current, in amperes, yielded by the magneto, and K and C are appropriate constants, determined by wind-tunnel calibrations. Both K and C depend upon the units in terms of which U is given, and upon such factors as the construction and size of the cup-wheel system, friction in the mechanism, characteristics of the magneto, electrical resistance in the circuit, air density and viscosity, etc. The quantity C may be considered to represent the lowest wind speed at which the magneto yields a just-perceptible electric current when it is gradually slowing down. Accordingly the dial of the direct-reading magneto anemometer has a linear graduation, on the basis of equation (1). The general practice is pursued of graduating the dial in such a manner that the rest position of the needle indicates the value C. Therefore, when the electric current produced by the magneto just becomes perceptible, the direct reading of the dial yields true wind speed without the need to apply any correction. On the same basis, the dial under normal operating conditions should indicate true wind speed without requirement of any correction for higher values of current. However, many of the magneto-type anemometers are designed to read on a double range, and in this condition a correction is necessary. This means that by throwing a switch to the double-range position the true wind speed will be determined by multiplying the observed reading on the dial by the factor 2 and applying a suitable correction to the result thus obtained. The corrections, which all have a negative sign, are listed in Appendix VI. It is of interest to understand the reason for the need of these corrections. Thus, the action of throwing the switch to the double-range position is equivalent to doubling the resistance of the circuit outside the terminals of the magneto; hence the electric current in this external circuit which enters the ammeter controlling the dial indications is reduced to one half of its previous value, provided the number of revolutions per minute of the magneto remain constant (as in the case of a wind of uniform speed). Therefore, since the current is reduced by a factor of 1/2, the appropriate value of K must be doubled in order to obtain the true wind speed in accord with equation (1). It follows that when one doubles the indicated dial reading with the switch in the double-range position the resulting numerical value will exceed the true wind speed by the amount C; hence a correction equivalent to -C must be applied in such cases (see Appendix which shows that the correction is the negative of the reading of the needle in the rest position).

Appendix VI which shows the corrections pertinent to anemometers of the types under consideration is based on Table 8-5 of "Manual of Surface Observations (WBAN)", Circular N.

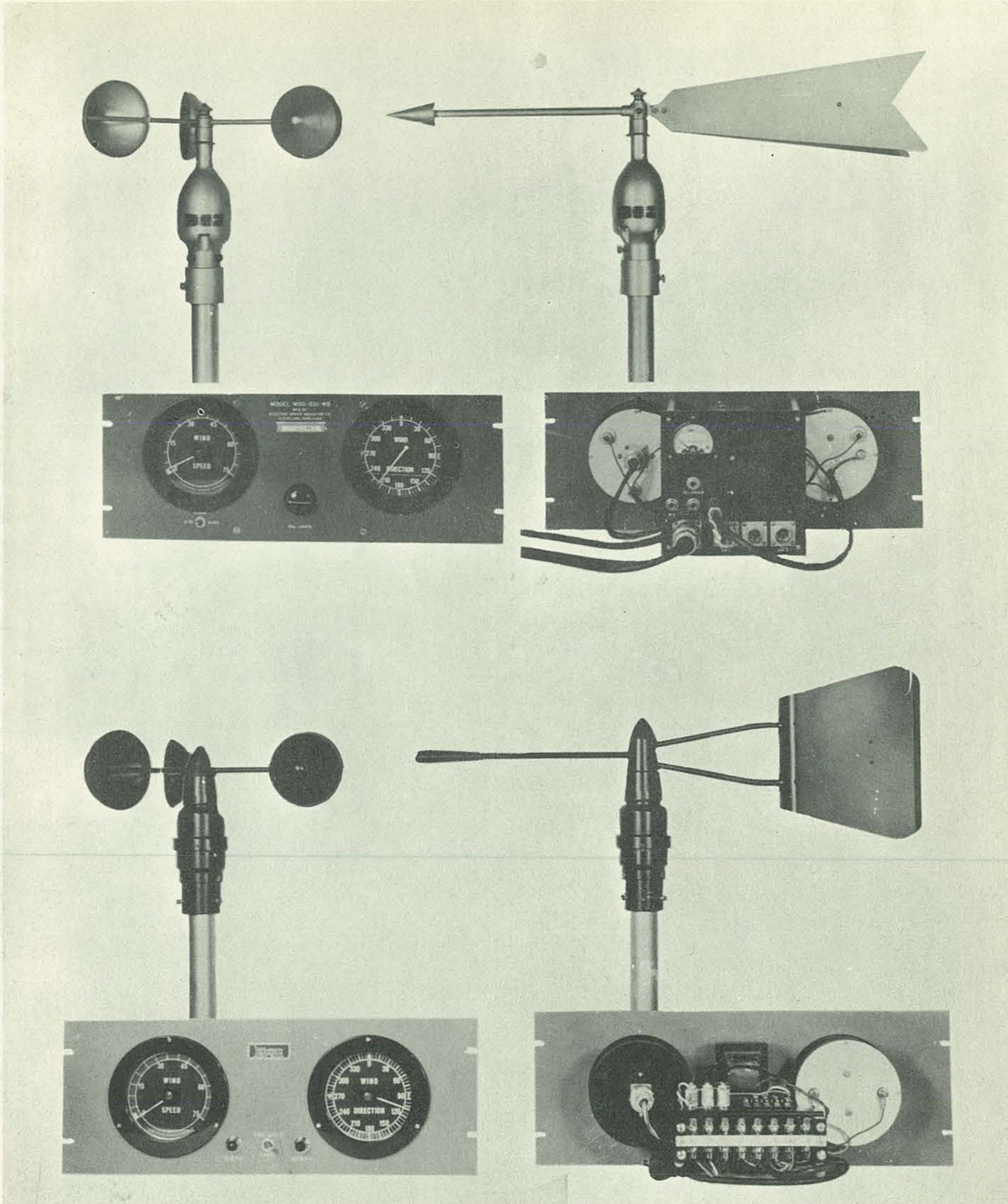

FIGURE 12

Magneto-type anemometers and wind vanes, with transmission systems and indicators (front and back views). For direction a d-c synchro transmitter is used. (F420 system in upper half, and F420A in lower half.)

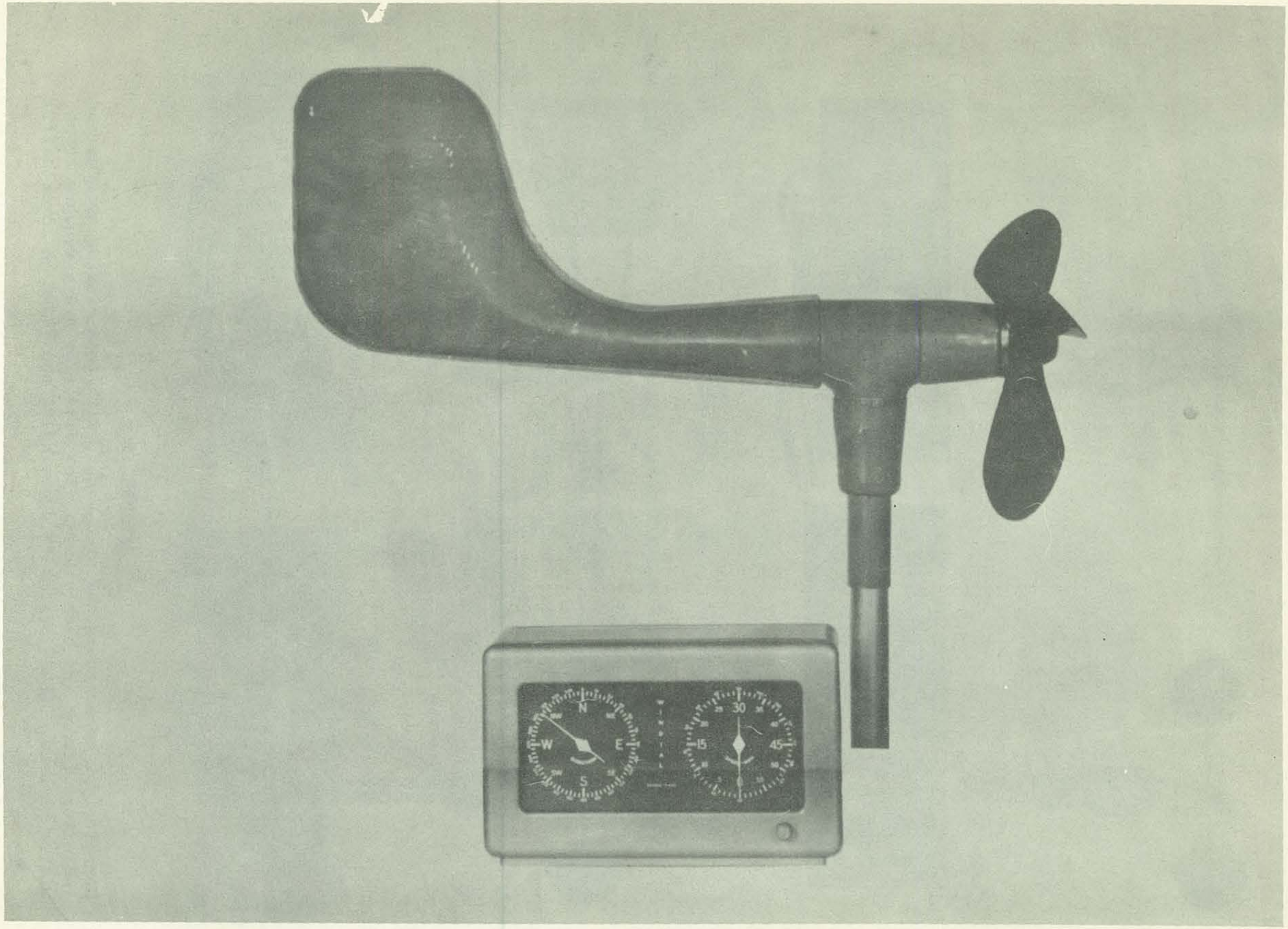

FIGURE 13
Propeller-type anemometer, with d-c synchro speed and direction transmitters; showing indicator unit below (Windial, No. F431).

Anemometers designated as F420, F420A, F420B, F420C, and F430 are of the magneto, direct-reading type. Indicators or wind systems designated as F210 and F222 are of the condenser-discharge type; while the anemometer referred to as F102 is the S-type, and F103 is the SA-airway type. Both the F431 (also called "Windial") and the "Aerovane" are propeller-type anemometers, the latter having a generator to yield an electric current for indication purposes. The "Windial" anemometer indicates by means of a direct current synchro speed transmitter.

In the light of the foregoing information, reports and records of wind speed based upon the indicators and wind systems referred to above are given in terms of true wind speed; i.e., whenever a correction is required and known, it is applied in accord with the data in the published table (e.g. Appendix VI; see "Manual of Surface Observations (WBAN)".

It should be noted that the results yielded by the magneto-type anemometers are not readily expressed in terms of the "5-minute maximum wind speed" or of the "fastest single-mile wind speed" as was possible in the case of the contact-type anemometers which provided a record on the triple register. However, the magneto-type of anemometer gives a continuous indication of the wind speed. If the indications are shown on a dial, the observer can keep the dial of the instrument under scrutiny for periods of the order of one minute and estimate the mean wind speed for the specified period. Commonly, the wind-speed data obtained for synoptic messages from the magneto type represent the results observed over time intervals of 1 minute. It is clear that when the wind is very gusty during the period of observation, some difficulty may arise in the effort to obtain a representative value of the mean wind speed, especially if the gust amplitude is large and the wind accelerations are relatively great. The direct-reading anemometer is often connected to a mechanism which provides a continuous record of the wind speed. The latter device involves generally a roll of paper driven by electric clockwork at a uniform rate. On the roll there are printed parallel lines along the direction of motion of the paper, and each line is labeled with the corresponding wind speed. A pen, actuated by the current from the magneto in the anemometer, makes a continuous record on the paper, enabling the wind speed readings to be made directly by comparison of the position of the pen point with the labels on the parallel lines. When the wind speed is required for a regular observation, the observer determines the average value for a 1-minute period.

Another type of anemometer sometimes employed involves the charging of a large condenser at a switching rate which depends upon the r.p.m. of the instrument. Indications are determined by the continuous discharge of this condenser. Thus, condenser-discharge indicators give an uncorrected average value at the highest point reached on the scale during a single pulse. When making a reading, one observes the indicator (see fig. 14) over a period of 1 minute and takes the average of the corrected highest points reached during successive pulses. Corrections are applied in order to obtain true values. This instrument has a small condenser which is maintained at a fixed potential by virtue of its connection with a controlled source of constant voltage. A switching mechanism conveys small increments of electric charge from this small condenser to the large condenser at a rate governed by the angular speed of the anemometer spindle. This rate thereby controls the voltage of the large condenser, whose potential determines its current flow or rate of discharge which permits direct readings of the wind speed (see Appendix V, Table 8-5 for the corrections).

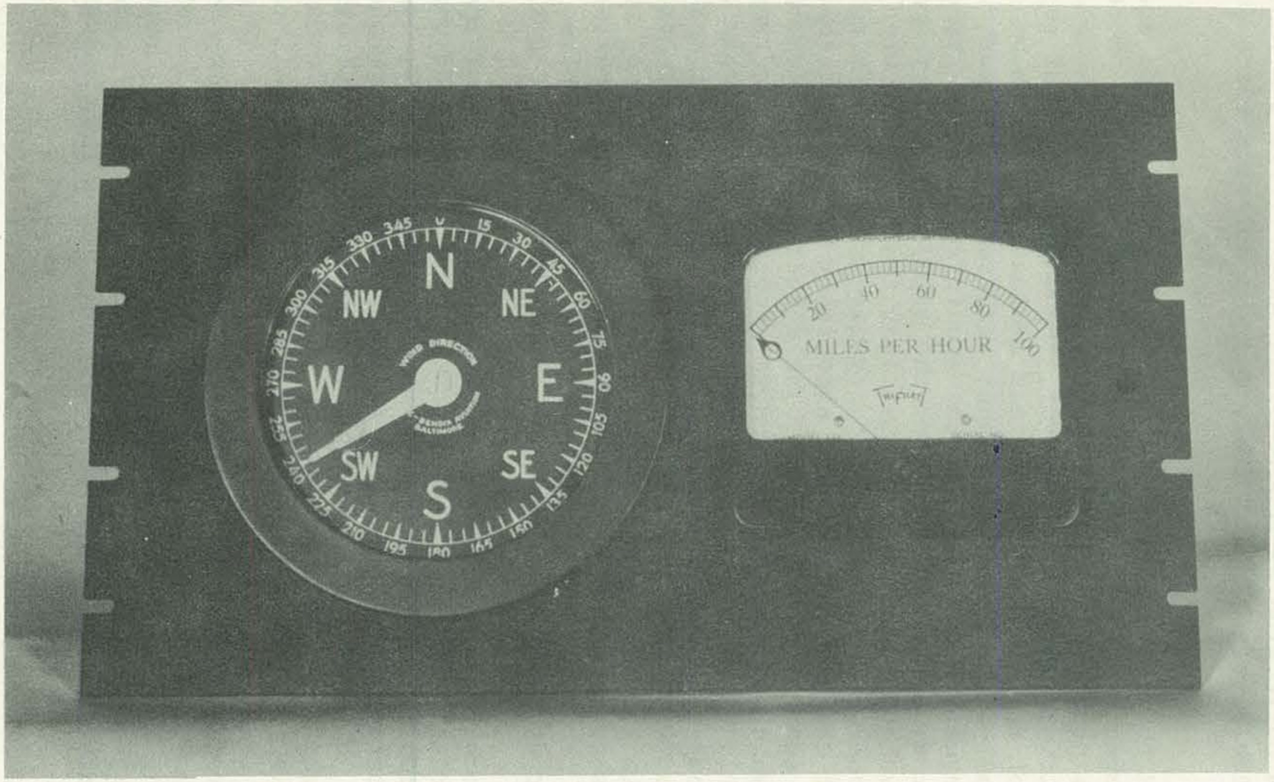

FIGURE 14
Wind-speed indicator (on right) for condenser-discharge type of measurement using 1/60-mile contact anemometer.

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U. S. DEPARTMENT OF AGRICULTURE

WEATHER BUREAU

INSTRUCTIONS No. 15

Washington, D. C., December 9, 1927

1. A new 3-cup anemometer has been furnished to each first-order station in continental United States. These instruments will be put into use as station anemometers beginning with January 1, 1928.

2. This anemometer runs so close to the true velocity of the wind that errors in the anemometer itself are smaller in magnitude than errors from other sources, such as those due to exposure, variability in velocity during the time period chosen, the mechanical condition of the anemometer, and limitations in making and interpreting the record. Hence, the indicated values from the new instrument will be recorded, reported, and published without correction. A brief description of the instrument is published in the Monthly Weather Review for April, 1924, pages 216–218. Conversion Tables 1 and 2, in slightly modified form, are taken from this description.

3. The best 4-cup anemometer on the station will be designated as "extra" and will be used only when the 3-cup anemometer is removed for cleaning and in emergency. At such times appropriate notation that the record is made by a 4-cup anemometer will be made on the record sheet, and interpretations therefrom will be corrected, as indicated in Table 1 herewith, before being transcribed to forms or reported in observations. Stations at which the new anemometer is not received on time will likewise correct the 4-cup anemometer record before transcribing values to forms or reporting them in observations, and will make notation on the face of each record sheet. Storm-warning substations using anemometers, and Alaskan and West Indian stations, will be equipped as early as practicable. It will be impracticable to furnish two of the new instruments to one station for a year or so.

4. At evaporation stations where, because of the location of the anemometer near the ground, the velocities are so low as to be practically the same from either the 4-cup or the 3-cup instrument, it will be sufficient to note on each monthly form the fact that the record is made by a 4-cup anemometer. The 4-cup instruments at evaporation stations can not now be replaced.

5. The date and hour of beginning the new system should be entered in station records, including the Daily Local Record, both copies of Form 1001, the Station Memorandum Book, and the Climatological Record.

6. Paragraph 86 of the Weather Code, paragraph 439-11R of Station Regulations, and instructions for the preparation of Form 1069C, pertaining to maximum wind and verifying velocities, will not be amended and reprinted at the present time; but in all cases equivalents in 3-cup anemometer records will be utilized. For example, when 36 miles is the verifying velocity according to existing instructions, velocities of 29.4 (30) or more (3-cup record) will be telegraphed and otherwise considered as the verifying velocity.

7. Officials exercising supervision over substations at which anemometers are used are charged with the duty of acquainting substation observers with the change and making sure that automatic records are properly annotated and interpreted.

8. Appropriate action should be taken to acquaint the public, through the press and otherwise, of this change in Weather Bureau methods of reporting wind velocity.

9. Table 2 is included for possible use upon the infrequent occasions when it may become desirable to know the small corrections of the 3-cup anemometer. Examples are the presentation of data to engineers as a basis for wind pressure computations, or comparison of an unusually high velocity with a former high velocity for local information.

10. While mechanically similar to the old anemometer, the new instrument differs materially in dimensions. The cup arms have a length of 6.29 inches, and make 640 revolutions per mile of wind. The wind travels two and one-half times as fast as the centers of the cups.

11. An automatic oiler has been provided for each instrument. This oiler is, in effect, an oil container concentric with a tube that leads downward through the top end of the spindle and laterally through the side of the spindle to the top bearing surface. A piece of *oil-soaked* cotton thread serves to siphon oil from the well to the bearing surface. The end of the thread projecting into the spindle must be lower than the oil container, just as with any siphon Experience with the oiler is limited, and hence existing regulations for the care of anemometers remain in effect. A nut for optional use in place of the oiler has been supplied.

12. A few stations have received anemometers equipped with $\frac{1}{60}$-mile contacts in addition to the usual 1-mile contacts. These instruments, originally obtained for a special purpose, are identified by the letter "S" following the serial number. The $\frac{1}{60}$-mile contact mechanism and short piece of wire may be removed, but should be carefully preserved and labeled and should be included with the instrument in case of future transfer.

Table 1

Correct or true velocities in miles an hour corresponding to velocities indicated by the 4-cup anemometer.

Indicated velocity	0	1	2	3	4	5	6	7	8	9
0	......	......	2.2	3.2	4.2	5.1	6.0	6.9	7.8	8.6
10	9.3	10.2	11.2	12.0	12.8	13.5	14.3	15.0	15.7	16.5
20	17.3	18.1	18.9	19.7	20.5	21.3	22.0	22.7	23.4	24.2
30	24.9	25.7	26.4	27.2	28.0	28.7	29.4	30.2	30.9	31.6
40	32.3	33.1	33.8	34.5	35.2	36.0	36.8	37.5	38.2	38.9
50	39.7	40.5	41.3	42.0	42.7	43.4	44.1	44.9	45.6	46.3
60	47.0	47.8	48.6	49.2	50.0	50.7	51.5	52.2	52.9	53.7
70	54.4	55.1	55.8	56.5	57.2	58.0	58.7	59.4	60.1	60.9
80	61.7	62.4	63.1	63.8	64.5	65.3	66.1	66.9	67.6	68.3
90	69.1	69.8	70.5	71.3	72.1	72.9	73.6	74.3	75.0	75.7
100	76.5	77.2	78.0	78.7	79.4	80.2	80.9	81.6	82.3	83.1
110	83.8	84.5	85.2	85.9	86.7	87.5	88.3	89.0	89.7	90.5
120	91.3	92.0	92.7	93.5	94.2	95.0	95.8	96.4	97.1	97.9
130	98.7	99.5	100.2	101.0	101.8	102.6	103.3	104.0	104.7	105.4
140	106.2	107.0	107.8	108.6	109.3	110.1	110.8	111.5	112.2	113.0
150	113.8	114.5	115.2	115.9	116.6	117.4	118.2	119.0	119.7	120.5
160	121.3	122.0	122.7	123.4	124.1	124.8	125.5	126.3	127.1	127.8
170	128.5	129.2	129.9	130.7	131.5	132.3	133.0	133.8	134.5	135.2
180	135.9	136.6	137.3	138.1	138.9	139.6	140.3	141.1	141.8	142.5

Table 2

Correct or true velocities in miles an hour corresponding to velocities indicated by the standard 3-cup anemometer.

(*For use as indicated in paragraph 9.*)

Indicated velocity	0	1	2	3	4	5	6	7	8	9
0	......	......	2.2	3.1	4.1	5.1	6.1	7.1	8.0	9.0
10	10.0	11.0	11.9	12.9	13.8	14.8	15.8	16.7	17.7	18.6
20	19.6	20.6	21.5	22.4	23.4	24.3	25.3	26.2	27.2	28.1
30	29.1	30.0	31.0	31.9	32.9	33.8	34.8	35.7	36.7	37.6
40	38.6	39.5	40.5	41.4	42.4	43.3	44.3	45.2	46.2	47.1
50	48.1	49.0	50.0	50.9	51.9	52.8	53.8	54.7	55.6	56.6
60	57.6	58.5	59.4	60.4	61.3	62.3	63.2	64.2	65.2	66.1
70	67.1	68.0	68.9	69.9	70.8	71.8	72.7	73.7	74.6	75.6
80	76.5	77.5	78.4	79.4	80.3	81.3	82.2	83.2	84.1	85.1
90	86.0	87.0	87.9	88.9	89.8	90.8	91.7	92.7	93.6	94.6
100	95.5	96.5	97.4	98.4	99.3	100.2	101.2	102.2	103.1	104.0
110	105.0	106.0	106.9	107.8	108.8	109.8	110.7	111.6	112.6	113.5
120	114.5	115.4	116.4	117.3	118.3	119.2	120.2	121.1	122.1	123.0
130	124.0	124.9	125.9	126.8	127.8	128.7	129.7	130.6	131.6	132.5
140	133.5	......	......	......	......	......	......	......	......	......

APPENDIX I-A

WIND VELOCITY RECORDS

Topics & Personnel - January 1928 - Page 276 - 277

In connection with Instructions No. 15, 1927, concerning the use of the new 3-cup anemometer, beginning January 1, 1928, the following further statements are submitted for guidance of station officials in the preparation of all forms or records containing wind data:

Pages 2 and 3, Form 1001. -- The maximum velocity will be entered only when it equals or exceeds 22 miles by the 3-cup anemometer.

Page 7, Form 1001. -- The limiting velocity for the entry of hourly maximum velocities in red ink, will as heretofore, be determined by the official in charge.

Page 9, Form 1001. -- The heading, "Winds (40 miles or over)", will be changed to read "Winds (33 miles or over)".

The date for Forms 1002, 1003, and 1014 will conform to those appearing on Form 1001, and Instructions for Preparing Meteorological Forms, 1928 edition, will be amended in accordance with the above.

The Climatological Record should be marked on each page that contains entries of wind velocities or movements of both 1927 and 1928 to show that entries for 1927 and earlier years are from the 4-cup anemometer and for 1928 and following years from the 3-cup.

APPENDIX I-B

WIND VELOCITY RECORDS

Topics & Personnel - March 1928 - Page 292

Conversion. Instead of converting 4-cup anemometer values into 3-cup anemometer values, as is required for official records, many stations are by mistake converting the 4-cup values into true velocities. Thus, when the 4-cup value is 30 miles, they enter in the record 25 miles, which is the true velocity; whereas they should enter 26 miles, the desired 3-cup value. The point to be remembered is that the reductions should be to 3-cup values and not to true velocities. In changing from the 4-cup to the 3-cup system, it is necessary at present to use both Tables 1 and 2, Instructions 15, 1927. However, the Central Office is preparing a table for converting 4-cup anemometer values directly into 3-cup values, and this table will be mailed to all stations as soon as printed.

Form 1001, pages 2 and 3. At stations on Atlantic, Pacific, and Gulf coasts, and shores of the Great Lakes, the 12-hour maximum velocity should be recorded on these pages only when it equals or exceeds 33 miles. All such records should be in 3-cup values.

Instructions on the same subject in first two lines of page 277, Topics and Personnel for January, 1928, are superseded by the provisions above.

Form 1030, station annuals, and other publications. When wind data for preceding years are presented for comparison with current, or 3-cup values, they always should be corrected to the 3-cup scale; and a note should be added to show this has been done.

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU

WIND VELOCITY CONVERSION TABLE

IN MILES AN HOUR

To convert 4-cup anemometer records into 3-cup anemometer equivalents.

4-cup record	0	1	2	3	4	5	6	7	8	9
	3-cup equivalents									
0	—	—	2	3	4	5	6	7	8	9
10	9	10	11	12	13	14	14	15	16	17
20	18	18	19	20	21	22	23	23	24	25
30	26	26	27	28	29	30	30	31	32	33
40	33	34	35	36	36	37	38	39	40	40
50	41	42	43	44	44	45	46	47	47	48
60	49	50	51	51	52	53	54	54	55	56
70	57	57	58	59	60	60	61	62	63	64
80	64	65	66	67	67	68	69	70	71	71
90	72	73	74	74	75	76	77	78	78	79

(Combination of Tables 1 and 2, Instructions No. 15, 1927.) (WB—4-7-28—250) 99

APPENDIX I-D

WIND VELOCITIES REQUIRING SPECIAL OBSERVATIONS

Topics & Personnel - March 1930 - Page 25

Paragraph 112 (5) (b), Weather Code, provides that special observations be sent when the wind reaches and maintains for 5 minutes a velocity of 40 miles an hour or more at stations that do not make stormwarning displays. Inquiry has been made as to whether or not this limitation applies to 3-cup anemometer records. It was the intent of paragraph 6, Instructions No. 15, 1927, that in all such cases the equivalent in 3-cup anemometer records be used.

APPENDIX I-E

WIND-VELOCITY RECORDS

Topics & Personnel - April 1930 - Page 34

The item, "Wind-Velocity Records", published on pages 292-293, March, 1928, "Topics", and the cardboard table entitled "To convert 4-cup anemometer records into 3-cup anemometer equivalents" are intended only to make possible a choice of values, particularly maximum velocities, for entry in Form 1001 and for telegraphic purposes, comparable, in fact, one period with the other.

Conversion of mean values should be to true velocity by use of Table 1. Instructions No. 15, 1927. (Available also cardboard for desk use.)

Hourly means in the Climatological Record book will not be converted to true velocities for the time being.

U. S. DEPARTMENT OF AGRICULTURE

INSTRUCTIONS No. 14

WEATHER BUREAU

Washington, D. C., December 18, 1931

1. Beginning with January 1, 1932, all values of wind velocity obtained from anemometers shall be corrected before being used for records, telegraphic reports, publications, or any other purpose, to the end that the best information available may be supplied to the public.

2. Beginning with January 1, 1932, the 4-cup anemometer shall be employed for official records at first-order and other stations of the Weather Bureau at which automatic records are maintained (except as indicated in paragraph 3). This anemometer is the same as used from the beginning of Weather Bureau records to December 31, 1927. It has four hemispherical aluminum cups, 4 inches in diameter, on arms 6.72 inches long from axis to centers of cups. The gearing and dials are arranged so that 500 revolutions of the cup wheel indicate 1 mile of wind.

3. The total number of 4-cup anemometers available is not quite sufficient to supply all recording stations. Hence, for some time to come, the 3-cup anemometer will be continued in use at all airways stations, at a number of stations engaged upon special projects, as station instrument at a few first-order stations, and as extra instrument where an extra is maintained.

4. Corrections to be employed for the 3-cup anemometer are presented as Table 3. These corrections are based on a limited number of tests. The instrument has three hemispherical aluminum cups, 5 inches in diameter, on arms 6.29 inches long from axis to centers of cups. The gearing and dials are arranged so that 640 revolutions of the cup wheel indicate 1 mile of wind. Corrections for the 3-cup anemometer, published as Table 2, Instructions No. 15, 1927, have been found by further analysis to be in error. Marginal notation to this effect should be made on the station copy of those instructions.

5. Corrections for the 4-cup anemometer described in paragraph 2, originally published for indicated velocities up to 90 miles an hour in Annual Report of the Chief Signal Officer, 1890, and extended to 189 miles an hour, indicated velocities as Table 1, Instructions No. 15, 1927; have been changed only slightly by careful analysis of a large number of tests. The corrections to be employed, beginning with January 1, 1932, are presented in these instructions as Table 4.

6. While the values presented in Tables 3 and 4 are by rigid interpretation applicable to anemometers with aluminum cups, their use with anemometers with copper cups is authorized. The difference in the corrections is small, there are but few copper cups in the bureau, and light-weight cups made of non-corrosive material are in prospect.

7. Each sheet of Form 1015 or 1017 shall have noted or stamped on its face the kind of anemometer employed.

8. Forms 1015 and 1017 will be prepared exactly as heretofore, including the marginal sums, and in accord with existing instructions. However, the hourly movement as registered will be counted and entered in pencil thereon and the maxima and extremes in ink. In accord with Weather Bureau practice, original determinations will be made to whole miles, fractions to be disposed of in accord with the usual custom. Futhermore, in order to simplify and expedite the application of corrections, the use of Supplementary Table 5, which presents tabulated integral values of corrections derived from Tables 3 and 4, is authorized.

9. After the appropriate correction to hourly movement, maximum velocities and extreme, in whole units, as given in Supplementary Table No. 5, has been applied, mentally or otherwise, the result will be entered in Form 1001 or other record. The daily movement will be the sum of the 24 corrected hourly movements. The monthly movement will be the sum of the daily movements.

10. Wind movement determined by dial readings over a period longer than 1 hour will be corrected on a mean hourly basis. Examples for a 4-cup anemometer: Dial reading 8 a. m., 547; 12 noon, 652; difference, 105; mean hourly, 26; correction, −4; corrected mean hourly, 22. Dial reading 8 a. m. 20th, 824; 8 a. m. 21st, 836; difference, 12. In this case the movement for each hour should be entered as 0 on Form 1017 and as 1 in Form 1001, and the direction for the corresponding hour will be entered as 0.

11. It is recognized that the method of correcting the movement for 1 hour contains imperfections in the case of thundersqualls or other winds that vary unduly within the hour. However, actual trial with such records has shown that to attempt to correct the several portions of the hour separately involves needless refinement.

12. When the anemometer cups are not moving at the time of observation, the wind will be recorded and telegraphed as calm, whether or not 1 or more than 1 mile has been recorded during the last hour.

13. Verifying velocities and other limits established for telegraphing maximum wind velocities in regular and special observations in accordance with the Weather Code, 1931, will be the corresponding corrected velocities.

14. When the movement for 1 hour is entered as 0 in pencil on Form 1015 or 1017, the direction for that hour will be entered as 0, as heretofore.

15. From these instructions it follows that no value less than 1 as the movement for 1 hour nor less than 24 as the movement for 24 hours can appear in the corrected record. However, zero may appear as the velocity for a given observation.

16. Velocities determined by one-sixtieth-mile anemometers shall be corrected before being entered on Form 1130 or used in transmitted reports.

17. On page 9, Form 1001, the heading "Winds, 33 miles or over", will be changed to read "Winds, 32 miles or over".

18. The change made in anemometers 4 years ago led to many requests for instruments which it was assumed were to be discarded. For the guidance of officials, it is stated that present plans provide for the utilization within the bureau of all anemometers, either 3-cup or 4-cup.

19. Supplementary Table No. 5 is being prepared on cardboard for distribution to substations.

ABLE 3.—*Correct or true velocities, in miles an hour, corresponding to velocities indicated by the 3-cup anemometer.* (*C. F. Marvin, 1931.*)

Indicated velocity	0	1	2	3	4	5	6	7	8	9
)..............	.67	2.43	3.48	4.52	5.52	6.49	7.44	8.38	9.30	10.23
)..............	11.14	12.05	12.96	13.86	14.77	15.67	16.57	17.46	18.36	19.26
)..............	20.16	21.05	21.95	22.84	23.74	24.63	25.52	26.41	27.30	28.19
)..............	29.08	29.97	30.86	31.75	32.64	33.53	34.42	35.31	36.20	37.09
)..............	37.98	38.87	39.76	40.64	41.53	42.41	43.30	44.19	45.07	45.96
)..............	46.84	47.73	48.62	49.50	50.38	51.27	52.16	53.04	53.93	54.81
....	55.70	56.59	57.47	58.36	59.24	60.13	61.02	61.91	62.79	63.68
....	64.56	65.45	66.34	67.22	68.11	68.99	69.88	70.76	71.65	72.54
....	73.42	74.31	75.19	76.08	76.97	77.85	78.74	79.62	80.50	81.39
....	82.27	83.16	84.04	84.93	85.81	86.70	87.58	88.46	89.35	90.24
....	91.13	92.01	92.90	93.78	94.67	95.55	96.44	97.32	98.21	99.09
....	99.98	100.9	101.8	102.6	103.5	104.4	105.3	106.2	107.1	107.9
....	108.8	109.7	110.6	111.5	112.4	113.3	114.1	115.0	115.9	116.8
....	117.7	118.6	119.5	120.3	121.2	122.1	123.0	123.9	124.8	125.6
....	126.5	127.4	128.3	129.2	130.1	131.0	131.8	132.7	133.6	134.5
....	135.4	136.3	137.2	138.0	138.9	139.8	140.7	141.6	142.5	143.3
....	144.2	145.1	146.0	146.9	147.8	148.7	149.5	150.4	151.3	152.2
....	153.1	154.0	154.9	155.7	156.6	157.5	158.4	159.3	160.2	161.0
....	161.9	162.8	163.7	164.6	165.5	166.4	167.2	168.1	169.0	169.9
....	170.8	171.7	172.6	173.4	174.3	175.2	176.1	177.0	177.9	178.7
....	179.6	....	....	....	....	....	....	....	....	....

ABLE 4.—*Correct or true velocities, in miles an hour, corresponding to velocities indicated by the 4-cup anemometer.* (*C. F. Marvin, 1931.*)

Indicated velocity	0	1	2	3	4	5	6	7	8	9
....	.67	2.27	3.38	4.33	5.22	6.07	6.90	7.71	8.58	9.30
....	10.08	10.85	11.62	12.39	13.15	13.91	14.66	15.41	16.16	16.91
....	17.66	18.40	19.15	19.89	20.64	21.38	22.12	22.86	23.60	24.34
....	25.08	25.82	26.56	27.29	28.03	28.77	29.50	30.24	30.97	31.71
....	32.44	33.18	33.91	34.65	35.38	36.12	36.85	37.59	38.32	39.06
....	39.79	40.52	41.25	41.99	42.72	43.45	44.18	44.91	45.64	46.37
....	47.10	47.83	48.56	49.30	50.03	50.76	51.49	52.22	52.95	53.68
....	54.41	55.14	55.87	56.61	57.34	58.07	58.80	59.53	60.26	60.99
....	61.72	62.45	63.18	63.91	64.64	65.37	66.10	66.83	67.56	68.29
....	69.02	69.75	70.48	71.21	71.94	72.67	73.40	74.13	74.86	75.59
....	76.32	77.05	77.78	78.51	79.24	79.97	80.70	81.43	82.16	82.89
....	83.62	84.35	85.08	85.80	86.53	87.26	87.99	88.72	89.44	90.17
....	90.90	91.63	92.36	93.09	93.82	94.55	95.28	96.01	96.74	97.47
....	98.20	98.93	99.66	100.4	101.1	101.8	102.6	103.3	104.0	104.8
....	105.5	106.2	106.9	107.7	108.4	109.1	109.9	110.6	111.3	112.1
....	112.8	113.5	114.2	115.0	115.7	116.4	117.2	117.9	118.6	119.3
....	120.1	120.8	121.5	122.3	123.0	123.7	124.4	125.2	125.9	126.6
....	127.4	128.1	128.8	129.5	130.3	131.0	131.7	132.5	133.2	133.9
....	134.6	135.4	136.1	136.8	137.6	138.3	139.0	139.8	140.5	141.2
....	141.9	142.7	143.4	144.1	144.9	145.6	146.3	147.0	147.8	148.5
....	149.2	150.0	150.7	151.4	152.1	152.9	153.6	154.3	155.1	155.8

SUPPLEMENTARY TABLE 5.—*Corrections for indicated velocities, derived from Tables 3 and 4.*

Velocities indicated: By 3-cup anemometer m. p. h.	Velocities indicated: By 4-cup anemometer m. p. h.	Correction in whole miles per hour
0 to 16*	0 to 8	+1
17 to 26	9 to 12	0
27 to 35	13 to 16	−1
36 to 44	17 to 20	−2
45 to 52	21 to 24	−3
53 to 61	25 to 28	−4
62 to 70	29 to 32	−5
71 to 79	33 to 36	−6
80 to 87	37 to 39	−7
88 to 96	40 to 43	−8
97 to 105	44 to 47	−9
106 to 114	48 to 51	−10
115 to 122	52 to 54	−11
123 to 132	55 to 58	−12
133 to 139	59 to 62	−13
140 to 149	63 to 65	−14
150 to 157	66 to 69	−15
158 to 166	70 to 73	−16
167 to 174	74 to 77	−17
175 to 184	78 to 80	−18
185 to 192	81 to 84	−19
193 to 200	85 to 88	−20
	89 to 91	−21
	92 to 95	−22
	96 to 99	−23
	100 to 103	−24
	104 to 106	−25
	107 to 110	−26
	111 to 114	−27
	115 to 117	−28
	118 to 121	−29
	122 to 125	−30
	126 to 128	−31
	129 to 132	−32
	133 to 136	−33
	137 to 140	−34
	141 to 143	−35

* Inconsequential variation from the rule for disposal of decimals disregarded at 3 and 4 m. p. h.

APPENDIX II-A

HOURLY WIND VELOCITIES

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ourly wind-velocity data recorded prior to January 1, 1932, may be corrected to the 932 standard (true velocities) by using the correction published in Instructions No. 1‹ , 931.

U. S. DEPARTMENT OF AGRICULTURE

INSTRUCTIONS No. 1. WEATHER BUREAU

Washington, D. C., January 2, 1935.

1. The following corrections will be made in INSTRUCTIONS No. 14, 1931, together with marginal reference to this authorization:

Table 3, page 4: For indicated velocity, 1 mile, change true velocity from 2.43 to 2.33.

Table 4, page 4: For indicated velocity, 1 mile, change true velocity from 2.27 to 2.32.

Table 4, page 4: For indicated velocity, 8 miles, change true velocity from 8.58 to 8.50.

2. Additional tables for use in correcting indicated or recorded values of wind velocity published herewith are authorized for use as follows:

Table 3a: This is an expansion to tenths of miles of values up to 25 miles of Table 3, INTRUCTIONS No. 14, 1931. It will be found useful in treating mean values.

Table 4a: This is an expansion to tenths of miles of values up to 25 miles of Table 4, INSTRUCTIONS No. 14, 1931. It will, likewise, be useful in treating mean values.

Table 6: This table gives corrections for 4-cup anemometers, with beaded, or rolled-edge, light, copper cups, 4 inches in diameter. Such cups have been issued to a limited number of stations at various times since July 1, 1932. The use of table 6 for corrections will begin upon receipt of these instructions. Revision of corrections of records heretofore made with such cups need be made only in the event that winds of unusual interest at the station have occurred. When, in the discretion of the official in charge, such revised corrections are made the Central Office should be advised so that corresponding corrections may be made in Central Office copy of records.

Table 6a: This is simply an expansion of part of table 6 to tenths of miles.

For information, no beaded-edge cups have been procured for 3-cup anemometers.

For discussion of tests, reference is made to article by Charles F. Marvin, "Recent Advances in Anemometry," Monthly Weather Review, April 1934, vol. 62, pp. 118–119.

Supplementary table 5a: This is an extension of Table 5, of INSTRUCTIONS No. 14, 1931, to include an additional column for anemometers fitted with 4-beaded (or rolled-edge) cups. It will be printed in card form for distribution to stations.

3. The abbreviation "4-cup B" will be used on record sheets to identify the 4-cup anemometer with beaded cups.

Table 3a.—*Correct, or true, velocities (in miles an hour), corresponding to velocities indicated by the 3-cup anemometer.*

Ind. Vel.	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.....	0.67	0.95	1.16	1.34	1.50	1.66	1.80	1.94	2.08	2.21
1.....	2.33	2.45	2.58	2.69	2.81	2.93	3.04	3.15	3.26	3.37
2.....	3.48	3.59	3.69	3.80	3.90	4.01	4.11	4.22	4.32	4.42
3.....	4.52	4.63	4.73	4.83	4.93	5.03	5.13	5.23	5.32	5.42
4.....	5.52	5.62	5.72	5.81	5.91	6.01	6.10	6.20	6.30	6.39
5.....	6.49	6.58	6.68	6.78	6.87	6.97	7.06	7.16	7.25	7.34
6.....	7.44	7.53	7.63	7.72	7.82	7.91	8.00	8.10	8.19	8.28
7.....	8.38	8.47	8.56	8.66	8.75	8.84	8.93	9.03	9.12	9.21
8.....	9.30	9.40	9.49	9.58	9.67	9.77	9.86	9.95	10.04	10.13
9.....	10.23	10.31	10.41	10.50	10.59	10.68	10.78	10.87	10.96	11.05
10.....	11.14	11.23	11.32	11.42	11.51	11.60	11.69	11.78	11.87	11.96
11.....	12.05	12.15	12.24	12.33	12.42	12.51	12.60	12.69	12.78	12.87
12.....	12.96	13.05	13.14	13.24	13.33	13.42	13.51	13.60	13.69	13.78
13.....	13.86	13.96	14.05	14.14	14.23	14.32	14.41	14.50	14.59	14.68
14.....	14.77	14.86	14.95	15.04	15.13	15.22	15.31	15.40	15.49	15.58
15.....	15.67	15.76	15.85	15.94	16.03	16.12	16.21	16.30	16.39	16.48
16.....	16.57	16.66	16.75	16.84	16.93	17.02	17.11	17.20	17.29	17.38
17.....	17.46	17.56	17.65	17.74	17.83	17.92	18.01	18.10	18.19	18.28
18.....	18.36	18.46	18.55	18.64	18.73	18.82	18.91	18.99	19.08	19.17
19.....	19.26	19.35	19.44	19.53	19.62	19.71	19.80	19.89	19.98	20.07
20.....	20.16	20.25	20.34	20.43	20.52	20.61	20.69	20.78	20.87	20.96
21.....	21.05	21.14	21.23	21.32	21.41	21.50	21.59	21.68	21.77	21.86
22.....	21.95	22.04	22.13	22.22	22.31	22.40	22.48	22.57	22.66	22.75
23.....	22.84	22.93	23.02	23.11	23.20	23.29	23.38	23.47	23.56	23.65
24.....	23.74	23.83	23.92	24.01	24.10	24.19	24.27	24.36	24.45	24.54

Table 4a.—*Correct or true velocities (in miles an hour), corresponding to velocities indicated by the 4-cup anemometer*

Ind. Vel.	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.....	0.67	0.96	1.18	1.36	1.52	1.67	1.81	1.95	2.07	2.20
1.....	2.32	2.43	2.55	2.66	2.77	2.87	2.98	3.08	3.18	3.29
2.....	3.38	3.48	3.58	3.68	3.77	3.87	3.96	4.05	4.15	4.24
3.....	4.33	4.42	4.51	4.60	4.69	4.78	4.87	4.95	5.04	5.13
4.....	5.22	5.30	5.39	5.47	5.56	5.64	5.73	5.81	5.90	5.98
5.....	6.07	6.15	6.23	6.32	6.40	6.48	6.57	6.65	6.73	6.81
6.....	6.90	6.98	7.06	7.14	7.22	7.30	7.38	7.46	7.54	7.62
7.....	7.71	7.78	7.86	7.94	8.02	8.10	8.18	8.26	8.34	8.42
8.....	8.50	8.58	8.66	8.74	8.82	8.90	8.98	9.06	9.14	9.21
9.....	9.30	9.37	9.45	9.52	9.60	9.68	9.76	9.84	9.92	10.00
10.....	10.08	10.15	10.22	10.30	10.38	10.46	10.54	10.61	10.69	10.77
11.....	10.85	10.92	11.00	11.08	11.15	11.23	11.31	11.38	11.46	11.54
12.....	11.62	11.69	11.77	11.84	11.92	12.00	12.07	12.15	12.23	12.31
13.....	12.39	12.46	12.53	12.61	12.68	12.76	12.83	12.91	12.99	13.07
14.....	13.15	13.22	13.29	13.37	13.44	13.52	13.60	13.67	13.75	13.83
15.....	13.91	13.98	14.05	14.12	14.20	14.28	14.35	14.43	14.50	14.58
16.....	14.66	14.73	14.80	14.88	14.96	15.03	15.11	15.18	15.26	15.33
17.....	15.41	15.48	15.56	15.63	15.71	15.78	15.86	15.93	16.01	16.08
18.....	16.16	16.23	16.31	16.38	16.46	16.53	16.61	16.68	16.76	16.83
19.....	16.91	16.98	17.06	17.13	17.20	17.28	17.36	17.43	17.50	17.58
20.....	17.66	17.73	17.80	17.88	17.95	18.03	18.10	18.18	18.25	18.33
21.....	18.40	18.48	18.55	18.62	18.70	18.77	18.85	18.92	19.00	19.07
22.....	19.15	19.22	19.30	19.37	19.44	19.52	19.59	19.67	19.74	19.82
23.....	19.89	19.97	20.04	20.11	20.19	20.26	20.34	20.41	20.49	20.56
24.....	20.64	20.71	20.78	20.86	20.93	21.00	21.08	21.15	21.23	21.30

Table 6.—*Correct or true velocities (in miles an hour), corresponding to velocities indicated by anemometer equipped with 4-hemispherical cups with beaded edges. (Put into service at some stations beginning July 1, 1932.)*

Ind. Vel.	0	1	2	3	4	5	6	7	8	9
0.....	0.40	1.80	2.81	3.75	4.66	5.56	6.44	7.32	8.20	9.07
10.....	9.94	10.80	11.67	12.53	13.39	14.26	15.12	15.98	16.84	17.70
20.....	18.55	19.41	20.27	21.13	21.99	22.84	23.70	24.56	25.41	26.27
30.....	27.13	27.99	28.84	29.70	30.56	31.41	32.27	33.12	33.98	34.83
40.....	35.69	36.55	37.40	38.26	39.11	39.97	40.82	41.68	42.53	43.39
50.....	44.25	45.10	45.96	46.81	47.67	48.52	49.38	50.23	51.09	51.95
60.....	52.80	53.65	54.51	55.36	56.22	57.08	57.93	58.79	59.64	60.50
70.....	61.35	62.21	63.06	63.92	64.77	65.63	66.48	67.34	68.19	69.05
80.....	69.90	70.76	71.61	72.47	73.32	74.18	75.03	75.89	76.74	77.60
90.....	78.45	79.31	80.16	81.02	81.87	82.73	83.58	84.44	85.29	86.15
100....	87.00	87.86	88.71	89.57	90.42	91.28	92.13	92.98	93.84	94.69
110....	95.55	96.40	97.26	98.11	98.97	99.82	100.7	101.5	102.4	103.2
120....	104.1	105.0	105.8	106.7	107.5	108.4	109.2	110.1	110.9	111.8
130....	112.6	113.5	114.4	115.2	116.1	116.9	117.8	118.6	119.5	120.3
140....	121.2	122.0	122.9	123.8	124.6	125.5	126.3	127.2	128.0	128.9
150....	129.7	130.6	131.5	132.3	133.2	134.0	134.9	135.7	136.6	137.4
160....	138.3	139.1	140.0	140.9	141.7	142.6	143.4	144.3	145.1	146.0
170....	146.8	147.7	148.5	149.4	150.3	151.1	152.0	152.8	153.7	154.5
180....	155.4	156.2	157.1	158.0	158.8	159.7	160.5	161.4	162.2	163.1
190....	163.9	164.8	165.6	166.5	167.4	168.2	169.1	169.9	170.8	171.6
200....	172.5	....	....	....	....	....	....	....	....	....

Table 6a.—*Correct or true velocities (in miles an hour), corresponding to velocities indicated by anemometer equipped with 4-hemispherical cups with beaded edges. (Put into service at some stations beginning July 1, 1932)*

Ind. Vel.	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.....	0.40	0.64	0.81	0.96	1.10	1.23	1.35	1.47	1.58	1.69
1.....	1.80	1.91	2.01	2.12	2.22	2.32	2.42	2.52	2.62	2.71
2.....	2.81	2.91	3.00	3.10	3.19	3.29	3.38	3.47	3.57	3.66
3.....	3.75	3.84	3.94	4.03	4.12	4.21	4.30	4.39	4.48	4.57
4.....	4.66	4.75	4.84	4.93	5.02	5.11	5.20	5.29	5.38	5.47
5.....	5.56	5.65	5.74	5.82	5.91	6.00	6.09	6.18	6.27	6.36
6.....	6.44	6.53	6.62	6.71	6.80	6.88	6.97	7.06	7.15	7.24
7.....	7.32	7.41	7.50	7.59	7.67	7.76	7.85	7.94	8.02	8.11
8.....	8.20	8.28	8.37	8.46	8.55	8.63	8.72	8.81	8.89	8.98
9.....	9.07	9.16	9.24	9.33	9.42	9.50	9.59	9.68	9.76	9.85
10.....	9.94	10.02	10.11	10.20	10.28	10.37	10.46	10.54	10.63	10.72
11.....	10.80	10.89	10.98	11.06	11.15	11.24	11.32	11.41	11.49	11.58
12.....	11.67	11.75	11.84	11.93	12.01	12.10	12.19	12.27	12.36	12.45
13.....	12.53	12.62	12.70	12.79	12.88	12.96	13.05	13.13	13.22	13.31
14.....	13.39	13.48	13.57	13.65	13.74	13.82	13.91	14.00	14.08	14.17
15.....	14.26	14.34	14.43	14.51	14.60	14.69	14.77	14.86	14.94	15.03
16.....	15.12	15.20	15.29	15.37	15.46	15.55	15.63	15.72	15.80	15.89
17.....	15.98	16.06	16.15	16.23	16.32	16.41	16.49	16.58	16.66	16.75
18.....	16.84	16.92	17.01	17.09	17.18	17.27	17.35	17.44	17.52	17.61
19.....	17.70	17.78	17.87	17.95	18.01	18.12	18.21	18.30	18.38	18.47
20.....	18.55	18.64	18.73	18.81	18.90	18.98	19.07	19.15	19.24	19.33
21.....	19.41	19.50	19.58	19.67	19.76	19.84	19.93	20.01	20.10	20.18
22.....	20.27	20.36	20.44	20.53	20.61	20.70	20.79	20.87	20.96	21.04
23.....	21.13	21.21	21.30	21.39	21.47	21.56	21.64	21.73	21.81	21.90
24.....	21.99	22.07	22.16	22.24	22 33	22.42	22.50	22.59	22.67	22.76

Supplementary Table 5a (Revised)—*Corrections for indicated velocities derived from Tables 3, 4, and 6.*

Velocities Indicated			Correction in whole miles per hour
By 3-cup anemometer, m. p. h.	By 4-cup anemometer, m. p. h.	By 4-cup anemometer with beaded cups, m. p. h.	
0 to 16*...........	0 to 8	0 to 5	+1
17 to 26...........	9 to 12	6 to 13	0
27 to 35...........	13 to 16	14 to 20	−1
36 to 44...........	17 to 20	21 to 27	−2
45 to 52...........	21 to 24	28 to 34	−3
53 to 61...........	25 to 28	35 to 41	−4
62 to 70...........	29 to 32	42 to 48	−5
71 to 79...........	33 to 36	49 to 55	−6
80 to 87...........	37 to 39	56 to 62	−7
88 to 96...........	40 to 43	63 to 69	−8
97 to 105...........	44 to 47	70 to 75	−9
106 to 114...........	48 to 51	76 to 82	−10
115 to 122...........	52 to 54	83 to 89	−11
123 to 132...........	55 to 58	90 to 96	−12
133 to 139...........	59 to 62	97 to 103	−13
140 to 149...........	63 to 65	104 to 110	−14
150 to 157...........	66 to 69	111 to 117	−15
158 to 166...........	70 to 73	118 to 124	−16
167 to 174...........	74 to 77	125 to 131	−17
175 to 184...........	78 to 80	132 to 138	−18
185 to 192...........	81 to 84	139 to 145	−19
193 to 200...........	85 to 88	146 to 152	−20
	89 to 91	153 to 158	−21
	92 to 95	159 to 165	−22
	96 to 99	166 to 171	−23
	100 to 103	172 to 178	−24
	104 to 106	179 to 185	−25
	107 to 110	186 to 192	−26
	111 to 114	193 to 200	−27
	115 to 117		−28
	118 to 121		−29
	122 to 125		−30
	126 to 128		−31
	129 to 132		−32
	133 to 136		−33
	137 to 140		−34
	141 to 143		−35

* Inconsequential variation from the rule for disposal of decimals disregarded at 3 and 4 m. p. h.

APPENDIX IV

Weather Bureau Instructions No. 2 - Feb. 12, 1936

The use for official records of any of the three forms of rotating cup anemometers heretofore issued to stations is authorized.

The applicable table as published in Instructions No. 1, 1935, shall be employed to make the corrections required by Instructions No. 14, 1931, paragraph 1. It is not essential that station and extra anemometers be of the same form.

For information, the three forms of anemometer, now in use in the Bureau are: Four-cup anemometer, fitted with old-style straight-edged cups; four-cup anemometer, fitted with beaded-edged cups; three-cup anemometer, fitted with straight-edged cups. With few exceptions, only the last-named is equipped with both 1 mile and 1/60 mile contacts.

APPENDIX V

TABLE 8-6. *Corrections to indicated wind speeds*

(1/60- or 1-mile anemometers)

Speed indicated: By 3-cup anemometer ML-80 m.p.h.	By 3-cup "S" type anemometer, m. p. h.	By 4-cup[1] anemometer, m. p. h.	By 4-cup anemometer with beaded cups, m. p. h.	By small airway "SA" type anemometer, m. p. h.	Corrections in whole miles per hour
11- 60	[2] 0- 16	[2] 0- 8	[2] 0- 5	[2] 0-35	+1
[2] 0- 10 and 61- 70	17- 26	9- 12	6- 13	35-57	0
71- 80	27- 35	13- 16	14- 20	(Corrections for higher velocities not determined; use zero.)	−1
81- 90	36- 44	17- 20	21- 27		−2
91-100	45- 52	21- 24	28- 34		−3
101-110	53- 61	25- 28	35- 41		−4
111-120	62- 70	29- 32	42- 48		−5
121-130	71- 79	33- 36	49- 55		−6
131-140	80- 87	37- 39	56- 62		−7
141-150	88- 96	40- 43	63- 69		−8
	97-105	44- 47	70- 75		−9
	106-114	48- 51	76- 82		−10
	115-122	52- 54	83- 89		−11
	123-132	55- 58	90- 96		−12
	133-139	59- 62	97-103		−13
	140-149	63- 65	104-110		−14
	150-157	66- 69	111-117		−15
	158-166	70- 73	118-124		−16
	167-174	74- 77	125-131		−17
	175-184	78- 80	132-138		−18
	185-192	81- 84	139-145		−19
	193-200	85- 88	146-152		−20
		89- 91	153-158		−21
		92- 95	159-165		−22
		96- 99	166-171		−23
		100-103	172-178		−24
		104-106	179-185		−25
		107-110	186-192		−26
		111-114	193-200		−27
		115-117			−28
		118-121			−29
		122-125			−30
		126-128			−31
		129-132			−32
		133-136			−33
		137-140			−34
		141-143			−35

[1] Except 4 cup S-EX type, for which correction is +2 at all speeds.
[2] Movement of anemometer cups observed.

APPENDIX V

Cont.

Note Regarding Appendix V, Concerning Corrections for 3-Cup Anemometer ML-80

A supply of 3-cup anemometers designated as ML-80 was received by the Weather Bureau from the U. S. Army Signal Corps as surplus stock. After examination it appeared that these instruments are identical mechanically to the anemometer designed as the 3-cup "S" type which has been widely used by the Weather Bureau. On these grounds the plate containing the designation No. ML-80 was removed from the anemometers thus obtained, and the Bureau replaced it with a plate giving the Weather Bureau designation "S" type.

Referring to Appendix V, it will be observed that the corrections listed under the first two columns which pertain to the ML-80 and "S" types are not in agreement. The cause of this inconsistency is unknown to the author.

In an effort to find published data relevant to this matter, the following sources were consulted:

(1) U. S. War Department Technical Manual No. 1-235, entitled "The Weather Observer", Washington, D. C., June 29, 1942. (See page 110)
(2) U. S. War Department Technical Manual TM 1-235, entitled "Weather Station Handbook for the Observer", Washington, D. C., 1945. (See pages 1-80)

If one considers the range of indicated wind speeds from 0-105 miles per hour, both of these sources give the same corrections as shown for the "S" type Weather Bureau anemometer in Appendix V (See the second column). On these grounds it would appear that the data shown in the first column of Appendix V regarding the corrections for the ML-80 type are not valid.

Table 8–5. ***Corrections to indicated wind speeds***
(Condenser-discharge and direct-reading types)

Indicator or wind system	Anemometer	Uncorrected speed (m. p. h. or knots)[2]	Correction (m. p. h. or knots)[2]
[1] F420		2.5 to 75	0
		5.0 to 150 (double range).	−3
[1] F420A or F420B		2.0 to 75	0
		4.0 to 150 (double range).	−2
[1] F430		3 to 75	0
		6 to 150 (double range).	−3
F210 or F222	F102	From pointer-swing value to 59.	0
		60 to 69	−1
		70 to 79	−2
		80 to 100	−3
F210 or F222	F103	From pointer-swing value to 87.	0
		88 to 94	+1
		95 to 100	+2
[1] F431		0 to 10	+3
		11 to 20	+2
		21 to 25	+1
		26 to 60	0
		61 to 65	+1
		66 and above	+2
Aerovane		0 to 8	+1
		9 to 95	0

[1] Corrections are based on adjustment of the pointer, under calm conditions, to the lowest indicated speed given in this table for the type of indicator in use.
[2] As appropriate to calibration of instrument used.

According to information supplied by the Instrumental Engineering Division of the Weather Bureau about May 1, 1958, the following revised data are pertinent to the instruments designated as F420, F420A, F420B, and F420C:

Uncorrected Speed (knots)	Correction (knots)
2 to 75 or 100	0
4 to 150 or 200 (double range)	-2

APPENDIX VII

DISCUSSION ON MATTERS OF HISTORICAL INTEREST REGARDING ANEMOMETERS

The first anemometer to measure the strength of the wind was a pressure plate, of pendulum type which is generally attributed to a design by Dr. Hooke (1667, see Ref. 40). It was intended for use primarily by seamen; and consisted of a plate suspended by a bar from a pivot. Pressure due to the wind acting on the plate caused it to swing upwards along a graduated quadrant, enabling one to make readings. The device was free to turn with the wind about a vertical axis so that the plane of the quadrant acted as a wind vane. Since the plate could swing about the pivot, it behaved like a pendulum in an unsteady wind, oscillating while inclined in the leeward direction.

In 1667 there was also published an account of an instrument conceived by Dr. Croune to measure wind speed, which was a sort of paddle-wheel mounted on a vertical shaft and encased in a drum. (Ref. 14). Narrow vertical slits in the drum permitted the wind to enter its interior and drive the paddle-wheel; but this device yielded erratic indications. Hooke proposed about this time (Ref. 39) that concentration of the blast from the wind on the blades would result in better performance; however, the instrument based on this design does not seem to have been successful enough to have had a long life.

A bridled anemometer was invented about 1708 by Wolf (Ref. 98). This device had a set of small windmill-sails on a horizontal axis, which carried a worm gear. The latter engaged a toothed wheel from whose axle there projected a rod. A weight made of lead was fastened to some suitable point on the rod, and the torque thus acting on the toothed wheel limited the rotation of the windmill-sails about their axis. By observing the angle through which the wheel turned as shown by an index-hand on a dial, it was possible to estimate the force of the wind.

Another form of bridled anemometer was described by Leupold in 1724 and Leutmann in 1725 (Refs. 48 and 49). This consisted of a paddle-wheel having six curved sails, capable of revolving about a vertical spindle. A cam fixed on the spindle had fastened to it a cord which passed over a pulley and carried a weight suspended on its free end. A series of about eight fixed vanes or louvers were arranged vertically around the periphery of the curved sails at an oblique angle to the radii in order to conduct the wind to the sails. When the spindle turned with the force of the wind acting on the sails, the leverage of the cam-and-weight system increased, thereby governing the angle through which the wheel rotated as equilibrium was established between the torque due to the wind force on the sails and that due to the leverage.

Many other forms of bridled anemometers were devised, but we shall not describe them, since the interested reader can find accounts of them in articles giving historical surveys on the subject of anemometry (Laughton, 1882, Ref. 46; Abbe, 1888, Ref. 1; Kleinschmidt, 1935, Ref. 45; Fergusson, 1939, Ref. 24; Sheppard, 1941, Ref. 82).

The rotation anemometer, being of especial interest, merits more attention at this point. In this form of anemometer the speed of the wind is measured by the actual continuous rotation of some type of wheel having windmill-sails, cups, or other surfaces on which the force of the moving stream of air can act. The earliest mention in the literature to to one of this type is contained in an article by Leupold (Ref. 45), who briefly mentions

Dinglinger in connection with a rotating anemometer which the latter devised about 1720. In 1734, d'Ons-en-Bray (Ref. 17) described such an instrument which consisted basically of a small windmill with vertical axis. This rotated under the action of the wind, and by means of an attached mechanism a hammer was allowed to fall for every 400 revolutions of the windmill. With each fall a perforation was made in a recording sheet, the motion of which was controlled by clockwork. The mechanism required gearing, whose effect must have adversely influenced the accuracy and sensitivity of the device.

Lomonosov (Ref. 50) in 1751 presented an account of an interesting form of rotation anemometer which was essentially a paddle-wheel and acted in a capacity similar to that of an overshot water-wheel with respect to the horizontal wind stream. The plane of the wheel was maintained parallel to the wind direction by virtue of its attachment to a wind vane. The latter, which had the form of a narrow box, covered the lower half of the wheel; hence when the wind acted on the upper, exposed half of the wheel, a rotation of the wheel about its axis occurred. A train of gears was connected to the axle and a pulley was fastened concentrically to the axle of the last member of the train. A continuous wire ran over this pulley and passed down the hollow spindle of the vane, then passed over another pulley. Thus, it was possible to observe the rate of rotation of the latter pulley, thereby estimating the speed of the wind. (See Refs. 1 and 31). No further developments took place with this instrument.

Numerous efforts were made to adapt the idea of windmill sails or fan blades for the purpose of measuring wind speed. In most of these the axis is maintained in a horizontal direction parallel to the wind with the aid of a wind vane. Perhaps the earliest windmill type anemometer was described by Schober (Ref. 76) in 1752. It had four thin brass sails, rectangular in shape, 1.25 by 2.5 inches in size. They were fastened at the ends of two cross arms, light in weight, and 4 inches from the axis to the center of the sails. The longer dimension of each sail was perpendicular to the arm on which it was fastened, and the sail was set at an angle of 52° with its axis of rotation. When this arrangement was employed, the middle points of the sails would rotate with approximately the same speed as the wind. In order to obtain a record of the speed of the sails, a bell was attached to the axle of the anemometer in such a manner as to cause it to be struck once for every rotation, thereby permitting the observer to count the number of rotations in any given time.

With the intention of improving the method of recording, Edgeworth in 1783 (see Ref. 46), modified the design by cutting a worm screw in the arbor of the horizontal axis of the anemometer which was similar in general structure to that of Schober and connected a cotton counter mechanism to the screw. This device permitted an observer to ascertain the number of rotations between the times at which readings were made.

Woltmann in 1790 (Ref. 99) published the results of his work in developing and testing a windmill-type anemometer patterned more or less after the design of Schober. In his instrument the sails were made of polished hard wood, 2.5 by 5 inches in size. The radial arms constructed of polished steel, were 19.1 inches in length from the axis to the center of the sails, the latter being set at an angle of 48.5° with respect to their axis of rotation. A worm screw on the end of the anemometer axle was engaged with a gear having 100 teeth. By means of observations of the number of rotations per unit time of the gear one could determine the number of rotations per unit of time of the windmill. On the basis of certain theoretical considerations and experimental investigations, Woltmann calibrated his anemometer in accord with an equation of the following form:

$$V^2 = a^2 n^2 + V_o^2 (d_o/d)$$

where V = wind speed;

V_o = wind speed at which the anemometer just begins to turn; when the air density is d_o

d = existing air density;

d_o = standard air density

n = number of rotations of the windmill per unit of time; and

a = constant factor to be determined empirically for each instrument.

Various modifications were made in the windmill anemometer by a number of investigators especially with a view to making it yield a continuous record. Among these, mention may be made of the work of Whewell (Refs. 33, 63, 96) who in 1837 developed a windmill anemometer having eight brass planes for the sails. By use of a gear train connected to the worm gear a rotation was imparted to a long vertical screw arranged parallel to the axis of a clock-driven drum which carried a recording sheet wrapped around it. The rotation of the screw, being governed by the rotation of the anemometer axle, controlled the motion of a pencil over the recording sheet, and thus a continuous record was obtained. Unfortunately, friction introduced serious errors in the results yielded by Whewell's instrument.

Turning now to the cup anemometer, which has been so widely used by meteorological services for the determination of wind speed, the first published announcement of its development by Robinson (Ref. 66) of Armagh Observatory, Ireland, appeared in 1846. His original objective was to calibrate Whelwell's anemometer by comparisons with some other device which had the capability of yielding more accurate and consistent values. In this connection the following statement appears in the report which was published regarding Robinson's work:

> He was enabled to do this by application of a fact which he learned from the late Richard Lovell Edgeworth, Esq.: if hemispherical cups be carried by horizontal arms attached to a vertical axis, with their diametral planes vertical, they constitute an effective windmill, which Robinson has found revolves with one-third of the wind's velocity. To the bottom of the axis is attached wheelwork actuating a revolving disc, which rotates through a degree for every mile traversed by the wind. (Ref. 66).

In order to secure a continuous record Robinson employed the following arrangement: "A pencil moved in the direction of the radius by clockwork, at the rate of half an inch per hour, traces on paper fixed on this disc the curve of space and time."

Four-cup anemometers based on Robinson's design have been extensively used over the entire world. They were introduced in the United States in 1870 when the U. S. Army Signal Corps began to establish meteorological stations under the general direction of the Chief Signal Officer. Early investigations pertaining to the calibration of the Robinson anemometer have been described by Abbe (Ref. 1). A valuable bibliography on the subject has been published by Fergusson (Ref. 24).

Calibrations of anemometers have been carried out in various ways, principally by comparisons between the readings of different types of wind-speed measuring devices; (a) under natural wind conditions; (b) with the aid of a whirling machine; and (c) in the wind tunnel. The most common method employed for rating cup anemometers was to determine the so-called "cup factor" which represents the ratio of the true wind speed to the speed at which the centers of the cups move in a circle under the given wind conditions. Robinson had been of the opinion that the cup factor was a constant (viz. 3), but investigations by Stow (1872, Ref. 88) involving comparisons under natural wind conditions revealed that the cup factor varied with the size of the anemometer, especially the length of the arms.

Most of the early investigations made in an effort to determine the characteristics of anemometers were carried out with the whirling machine. This consists of an arm rotating in a horizontal plane about a vertical axis, with a provision for mounting the anemometer on the outer end of the arm. Since the arm length and the rate of rotation of the arm are known, the speed at which the spindle of the anemometer moves in its circular orbit can be readily calculated. Generally, this speed was compared with the speed of the center of the cups, and the cup factor determined. However, certain corrections were found to be necessary, including those for the relative wind speed and for the effects of friction. Thus, if the experiment is conducted in a place where the equipment is exposed to a natural wind, it is essential to make a correction for both the added component due to this wind and for a component owing to the so-called "mitwind". The "mitwind" represents the velocity of the induced air stream caused by the whirling of the anemometer and the arm of the machine. Experiments indicate that the "mitwind" has a direction at some angle (such as 45°) to the tangent to the circular orbit in which the anemometer travels, on the whirling arm. (Refs. 1 and 24). In addition, centrifugal and gyroscopic forces act upon the anemometer while it is being whirled. These create frictional influences and other forces not present under ordinary conditions of operation. Therefore, if these additional forces or frictional torques are significant when compared with those involved under normal operating conditions, suitable allowances must be made for them when evaluating the calibration data.

In modern times calibrations of anemometers are conducted in wind tunnels, for which the Pitot-static tube serves as the standard wind-speed measuring device. Turbulent fluctuations in the wind tunnel are determined with the aid of the hot-wire anemometer.

The period from about 1920-1940 was very important for the history of anemometry in view of the developments which took place with the aid of wind-tunnel investigations. By way of illustration we may single out certain high-lights. First, mention will be made of the studies of Brazier (Refs. 4, 5, 6, 7). He compared readings of 4-cup Robinson anemometers with those of a Richard windmill type anemometer; and found that the inclination of natural wind currents with respect to the plane of rotation of the cups caused the Robinson anemometer to overread. For example, when the angle of inclination was 30°, the instrument rotated about 10 percent faster than it did at the same wind speed under zero angle of inclination. It appears, then, that anemometers mounted over the roofs of buildings will be subject to a systematic error since the disturbance of the air flow by the building produces vertical components. Brazier compared results yielded by Robinson 4-cup anemometers having different sizes of cups and arm lengths. He concluded that the ratio of the diameter of the cups to the distance between the centers of opposite cups is an important parameter governing the accuracy of the instrument; e.g., when the ratio was 5/8, the data given by the anemometer were more accurate than with smaller values of the ratio. In an installation where there are frequent eddies due to pronounced vertical components of air movement, the indications of the Robinson anemometer are too high whereas those of the Richard windmill type are too low, according to the findings of Brazier. He indicated that the differences between the conditions prevailing in natural winds and those in the wind tunnel where the equipment was calibrated would give rise to an uncertainty in the results obtained with natural winds, unless the conditions happened to be the same as those which existed in the wind tunnel during the calibration.

Secondly, we may call attention to the valuable investigations conducted by Patterson (Ref. 62) of the Canadian Meteorological Office at the wind tunnel of the University of Toronto in 1921 and 1924. He compared the torques due to the wind acting on anemometers having 2, 3, 4, 5, and 6 cups. Furthermore, he studied the effects of varying the cup diameters and arm lengths, measured the torques at various angles of the cups with respect to the wind, and also measured the torques of the cylindrical rods used as the arms on which the cups were mounted.

Patterson's conclusions may be summarized briefly as follows (Ref. 62):

(a) When one investigates the torques on anemometer systems having 2, 3, 4, 5, and 6 cups, it is found that the torque on the 3-cup system is more uniform than on the others; and that the cup factor is slightly more constant in this system than in the others.

(b) The mean torque on the 3-cup system is slightly greater than for the 4-cup.

(c) Comparison of results obtained with anemometers having a given cup diameter but various arm lengths, shows that the instrument with the shortest arm length yields the least variation of the cup factor with wind speed. The cup factor pertaining to a given wind speed varies with the ratio of the cup radius to the arm length; and for a given ratio, the cup factor decreases with increase of wind speed. For example, if R = cup radius, in cm.; L = arm length, in cm.; f = cup factor; and V = wind speed, in m.p.s.; the following typical results were obtained:

4-cup anemometers

R/L	Value of f when: V = 6.26	14.97
10.15/14.6	2.47	2.44
10.15/35.6	2.34	2.16
3.8/6.0	2.64	2.56
3.8/35.6	3.17	2.74

3-cup anemometers

R/L	Value of f when: V = 5	25
7.62/16	2.58	2.34
7.62/40	2.67	2.21
2.86/16	3.40	2.74
2.86/40	6.69	3.35

While it may appear that short arm lengths yield the best results for f with any given cup radius, there are limitations to this conclusion as Patterson pointed out in the following quotation:

Constancy of factor (f) is a most desirable feature in an anemometer, but it has been demonstrated that this can only be obtained by making the arms very short. Short arms, however, are objectionable in that the turning moment is small and the angular velocity high, so that the bearings would wear rapidly, oiling would be a difficult problem, and the centrifugal effects so great that frequent replacement would be necessary. On the other hand, long arms give a greater turning moment and a lower angular velocity, but they would require stronger bracing and a heavier instrument; the factor would be more variable. It is thus necessary to adopt as a compromise arms of medium length.

As the factor is variable with velocity, it is necessary to select the factor that most nearly represents average conditions and then correct for other velocities. (Ref. 62).

Referring to the anemometer investigations by Fergusson of the U. S. Weather Bureau which were conducted simultaneously with those in Canada, Patterson stated: "Both investigations have shown that the three cup anemometer is decidedly superior to the four cup, and it was decided to construct the new instrument with three cups." In closing his valuable report, Patterson gave the dimensions agreed upon: "After careful consideration of all the various factors involved, it was decided to construct the new standard with cups 6.35 cm. radius (5" diameter) on arms 16 cm. (6.3") long and to give it a factor 2.50."

In the United States, Professor C. F. Marvin, formerly Chief of the U. S. Weather Bureau, undertook or sponsored many investigations in the field of anemometry, mainly during the periods 1888-1900 and 1921-1934. A bibliography covering both periods is contained in Reference 24. (See also Refs. 55 and 56 concerning Marvin's later work.)

The first period involved calibrations of the 4-cup anemometer by means of the whirling arm and open air comparisons with other wind indicating devices such as flat pressure plates. The second period related to the study of results based on wind tunnel tests of various 4- and 3-cup anemometers (Refs. 55 and 56). The tests were first undertaken in the wind tunnels of the National Bureau of Standards, beginning in 1921, by Fergusson and Covert of the Weather Bureau, their preliminary results being published in 1924 (Ref. 27).

By virtue of the conclusions of Patterson (Ref. 62) and Fergusson (Ref. 27) that the 3-cup anemometer was superior to the 4-cup instrument, both the Meteorological Office of Canada and the U. S. Weather Bureau decided to adopt the 3-cup anemometer as the standard, with the expectation that it would eventually replace the 4-cup instrument. The Weather Bureau began using the 3-cup anemometer for official wind speed measurements at regular stations on January 1, 1928 (see Appendix I). No corrections were applied to its readings on the assumption that this anemometer "runs so close to the true velocity of the wind that errors in the anemometer itself are smaller than errors from other sources, such as those due to exposure, variability in wind velocity during the time period chosen, the mechanical condition of the anemometer, and limitations in making and interpreting the record" (Appendix I). Table 2 of Appendix I permits conversion from indicated wind speed to true wind speed, on the basis of the corrections considered valid in December 1927.

A reversion to the use of the 4-cup anemometer was begun on January 1, 1932 (see Appendix II), but after a period of several years the 3-cup instrument came back into favor again. However, corrections were applied to the readings of both anemometers from the first of 1932, and they have been required ever since for all types of anemometers where necessary. Significant revisions were found to be essential in the corrections for the 3-cup anemometer between the times that Appendices I and II went into effect.

In 1932 Marvin published his paper entitled "A Rational Theory of the Cup Anemometer" (Ref. 55). This paper offered an empirical equation intended to represent the relationship between wind speed as indicated by cup anemometers in steady winds and the true wind speed. It involved three constants which had to be determined experimentally over a wide range of wind speed. An additional constant (A) was included to take account of the gear train of the instrument in relation to the scale of indicated wind speed.

Marvin's equation may be written as follows:

$$V = (W - W_o)\ (b/A)/(1 + a/W)$$

where V = indicated wind speed by some scale;

W = true wind speed;

W_o = a small wind speed just adequate to keep a cup wheel turning against friction (determined experimentally);

A = the so-called "anemometer index", which represents the constant number of cup wheel turns per mile mark, that is, of each registered or otherwise indicated mile of wind travel;

and a and b are constants for a given anemometer, to be determined empirically.

Denoting L for the length of arm (in inches) from axis of the anemometer to the center of the open face of the cup, Marvin found on the basis of all the data available to him that the value of b for any cup wheel with arms ranging from 2.3 to 8.6 inches, and with 3 or 4 cups from 4 to 6 inches in diameter, could be quite accurately computed by the equation:

$$b = (5247.8 - 17.78\ L)/(L + 0.7976)$$

It is important to observe that Marvin's equation for cup anemometers does not take into account various aerodynamic considerations; for example, the variation of V/W with appropriate dimensionless parameters such as: Reynolds number; ratio of cup radius to arm length (L); ratio of arm cross-section to arm length; geometry of the cup form; size of turbulent eddies in relation to cup radius and arm length; frequency of turbulent eddies in relation to the ratio nV/L or nW/L, where n is the number of cups in the cup wheel; ratio of W_o to W; and the ratio of W to the speed of sound at high wind speeds. As is well known, the Reynolds number is defined as the product of the air density, the speed involved (W), the characteristic dimension (such as the cup diameter) divided by the dynamic viscosity of the medium (air in this case).

During the period from about 1930-1935, wind-tunnel tests on various designs of cup anemometers were made at various laboratories; and in this regard especial mention is due to the aerodynamic laboratories of the National Bureau of Standards and of the National Advisory Committee for Aeronautics (NACA).

In 1930, Pinkerton (Ref. 64) published the results of an investigation of a 3-cup magneto-type anemometer in the Variable Density Wind Tunnel of the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics. This instrument was calibrated against a Pitot-static tube placed directly above the anemometer at air densities corresponding to sea level, and to an altitude of approximately 6000 feet. According to the results of these tests, when the anemometer was exposed to air having a density 2/3 of that corresponding to the normal sea-level value, the indicated wind speed given by the instrument was about 6 percent lower than it was under normal sea-level density at the same true wind speed. This showed clearly the need to take proper account of the effect of air density. In another experiment, Pinkerton observed that when the axis of the anemometer was inclined forward 30°, the indicated wind speed was approximately 6 percent higher than it was with the axis vertical at the same true wind speed. (In this connection see also the results found by Brazier; (Refs. 5, 6, 7). It thus appears that the neglect of the variation of the cup factor with Reynolds number, or with parameters which depend upon air density and viscosity, etc., introduces a significant error in wind speed measurements at high level stations.

In 1933, wind-tunnel trials were conducted at the National Bureau of Standards with anemometers having very light cups whose edges were stiffened to prevent deformation during high winds (Ref. 24). To this end the cups were "beaded", where the "bead" is produced by rolling the edge of the cup outward to form a ring (e.g., in two cases under consideration the ring had a diameter of 1/16th inch and 1/8th inch, respectively). Tests were also made on anemometers whose cups were in the form of 90° cones with the apex bluntly rounded over (Ref. 9, 56).

As a result of the studies conducted by Dryden at the Aerodynamic Laboratories of the National Bureau of Standards it was discovered that micro-turbulence (or "fine-grained turbulence") has a profound effect on the performance of anemometers constructed of smooth (unbeaded) cups, such as the old standard 4-cup anemometer (see fig. 1), but much less on the response of those constructed of beaded cups. (Refs. 18, 20, 56). It is of interest to quote Dryden (Ref. 18) who provided a discussion of the matter in connection with Marvin's paper of 1934 (Ref. 56):

> In brief, the question involved is this --- if you test the old smooth-cup anemometer in different wind tunnels at the same average wind speed, you will find the anemometer runs at a different rate. These discrepancies are found also in measurements of the maximum lift of an airplane wing and in a great many other aerodynamic measurements. By a process of elimination and by direct measurement we find that these discrepancies are tied up in some way with the very fast fluctuations of speed. What we are really dealing with are the eddies formed by the walls of the honeycomb cells of the wind tunnel. These eddies produce very small ripples with frequencies from 30 to 40 per second to 100 or more per second. There is a fairly accurate correlation of the magnitude of the fluctuations, paying no attention to the frequencies, with the aerodynamic effects. To measure the magnitude of the fluctuations we transform the speed variation into a variation of electrical current, which is measured like any alternating current.
>
> I think the development of the anemometer with a bead, which in a sense we must consider accidental, is one of the most important that has ever been made. It not only reduces to a small amount the effects of fine grained turbulence, but it also makes the rate much less variable with the Reynolds number.

Dryden (Ref. 19) has given a qualitative account of the effects of fine-grained turbulence on the aerodynamic characteristics of objects exposed to an air current, and he has summarized the results for anemometers in the following words:

> The rate of rotation of Robinson cup anemometers has been observed to to be a function of the turbulence of the air stream. A bead around the rim of the cups decreases greatly both the variation of the rate with turbulence and with Reynolds number.

Although the discovery of the effects of a bead around the rim of the cups was large-y accidental, it must be regarded as an important landmark in the history of anemometry. ɪarvin, in his paper of 1934 (Ref. 56), presented a graphic illustration of the signifi-ɪnt contrast between the errors of unbeaded cup anemometers and those of beaded cup in-ɪtruments, depending upon the intensity of the turbulence, rated on a percentage basis. ɪn the case of a comparison involving several 4-cup anemometers constructed with cups in ɪhe form of 90° cones, with the apex bluntly rounded over, the following data were obtained ɪor a true wind speed (W) of 65 miles per hour, and indicated speed V:

	V - W	
ANEMOMETER CUP DESCRIPTION	5.7% TURBULENCE	0.7% TURBULENCE
Smooth without beads	9.7	7.4
External beaded edges, 1/16 in. diameter	1.7	0.6
External beaded edges, 1/8 in. diameter	0.9	0.3

Some understanding of the method of measuring the intensity of the turbulence in the wind tunnel on the basis of the amplitude of the speed fluctuations will be gained from the following statement of Dryden (Ref. 19):

> The equipment consists of a special form of hot-wire anemometer, with a wire of small diameter, an amplifier, an electrical network to compensate for the lag of the wire, and an alternating-current milliammeter. The speed fluctuation is converted into an alternating electric current whose intensity is measured by a thermal type milliameter. Thus, the square root of the mean square of the departures from the mean value is determined. The turbulence is defined as the ratio of the average fluctuation to the mean speed. If the wave form were sinusoidal, a turbulence of 1 percent would mean fluctuation of $\pm$ 1.4 percent from the mean speed. Actually no account is taken of the wave form. The equipment is usually designed to pass only frequencies of fluctuation between 10 and 1000 per second, thus excluding comparatively slow changes of speed.

Although it is probable that the intensity and wave form of fine-grained turbulence in the open air are not identical to those which exist during the wind tunnel tests, nevertheless the calibrations are likely to be more representative when the cups are provided with beads than when they are smooth (as in fig. 1), since the beads reduce the effects of the turbulence.

While the employment of beaded cups was thus found to be advantageous, it is not clear why beads were not generally adopted for the standard 3-cup anemometer ("S" type), as indicated in Appendix III. However, conical beaded cups were embodied in the small airway 3-cup anemometer ("SA" type, see fig. 3A); and some 4-cup anemometers having hemispherical cups with beaded edges were supplied to a limited number of stations (see Appendix III).

Tests were made by Dryden at the National Bureau of Standards on a 4-cup anemometer constructed of hemispherical cups having a bead of a little less than one-sixteenth inch ɪn diameter, and a slender brace wire securely attached to the extremities of the arms was stretched around the periphery of the cup wheel to strengthen it in high winds, as stated by Marvin (Ref. 56). When this instrument was exposed to superhurricane wind speeds, its cup wheel made 584 turns per mile of wind movement; whereas the standard 4-cup anemometer having smooth hemispherical cups would have yielded 686 turns per mile under the same conditions, according to the calibrations conducted by Fergusson and Covert in 1922 (Refs 27 and 56). To illustrate the benefit derived by the use of the beaded cups in such anemometers, Marvin has pointed out that if the beaded cup instrument were provided with a gear system of 570 cup turns to the indicated mile, the scale errors of the device would fall within 1 m.p.h. for speeds within the range between 0 and 100 m.p.h. (Ref. 56).

After considering the relative merits of the 3-cup and 4-cup anemometers, Marvin took the view finally that both were capable of yielding results of about the same degree of accuracy, provided that the best choice were made for the gear system in each case and that appropriate corrections are applied to the indicated readings of each instrument (Refs. 54, 55, 56).

Fergusson, however, presented evidence which led to the conclusion that the 3-cup anemometer is slightly more sensitive to changes in wind speed from a given mean than the 4-cup instrument of the same dimensions, weight, and proportions. Also, in agreement with Patterson (Ref. 62), he concluded that instruments of the 3-cup type have more uniform scales at different wind speeds than the 4-cup anemometers of the same dimensions and proportions. (Refs. 24 and 26). Spilhaus (Refs. 86 and 87), using a more rigorous mathematical method of analysis, reanalyzed the data and verified Fergusson's conclusions concerning the comparative sensitiveness of the 3- and 4-cup anemometers.

In the light of their value for historical reasons we shall quote in full the conclusions reached by Marvin (Ref. 56) in his paper of 1934:

> (1) That cup forms seem to run faster in a turbulent than in a non-turbulent wind stream.
>
> (2) The overrun is much greater for cups with smooth external surfaces. This is especially true of smooth hemispherical cups such as all the old 3- and 4-cup standard wheels.
>
> (3) Cone-shaped cups, especially when provided with external beads, seem to run more slowly than the hemispherical forms.
>
> (4) The overrun caused by increased turbulence is much less with beaded cups than with smooth cups.
>
> (5) Small variations in size of beads seem to be of secondary importance in cup performance.
>
> While the body of data now available is as yet insufficient to provide final quantitative relationships, nevertheless on the basis of data we have the percentage relationships may be stated about as follows:
>
> (6) The percentage overrun effects due to increased turbulence is higher for high velocities than for moderate and low velocities.
>
> (7) The percentage overrun on a 4-cone cup wheel without beads, at velocity of about 20 miles per hour, was about 3 percent when the rapid changes of wind speed were about 8 percent of the mean speed.

(8) The overrun was only 1 percent for these same cups with beads a little over one-sixteenth inch diameter.

(9) The run of old standard non-beaded cups was more than 17 percent greater than that of the same cups with a comparatively small bead.

(10) Dr. Dryden, of the Bureau of Standards, made the crucial tests on an old standard hemispherical 4-cup rotor which indicated unequivocally that the marked change in rate that had been noticed in beaded cone and hemispherical cups was due to the bead rather than to the cup form.

(11) Con-shaped cups seem to possess advantages for standard anemometers over hemispherical cups, but additional tests are needed to evaluate important secondary effects.

Not many years elapsed after Marvin's final paper (1934), before an answer was obtained with regard to the relative merits of the cone-shaped cup anemometer in contrast to those of the hemispherical-shaped cup anemometer. About 1933-1934, Brevoort and Joyner (Refs. 8 and 9) of the National Advisory Committee for Aeronautics conducted an investigation on the Robinson-type cup anemometer. By means of wind-tunnel equipment they made force measurements on individual cups, as well as static and dynamic torque measurements on complete cup wheels. Five different cup forms were tested in measurements on individual cups, involving both hemispherical and conical cups of different diameters, with and without beads. The complete cup wheels all had four cups, while observations were made with three arm lengths for each cup wheel tested. The investigation included measurements of the lift coefficient (C_L), drag coefficient (C_D), and normal-force coefficient (C_N) on individual cups through a range of Reynolds numbers, and covering angles of attach from 0° to 180°. In the case of the hemispherical cups, the drag coefficient and the normal-force coefficient both showed a discontinuity at angle of attack 45°; and the 90° conical beaded cup with a ratio of cone height to cup face diameter 0.525 also displayed a similar characteristic; however, the 90° conical unbeaded cup with a ratio of cone height to cup face diameter 0.595 did not manifest such a discontinuity. This fact suggests that some conical cups may have greater uniformity and stability than hemispherical cups in respect to the aerodynamic forces acting on them at various angles of attack, which possibly implies smoother performance in the former case than the latter, especially when the winds are variable.

According to the measurements of Brevoort and Joyner (Refs. 8 and 9) the coefficients C_L, C_D, and C_N for any angle of attack are functions of the Reynolds number, which implies that for a given cup wheel they vary with the ratio of wind speed to kinematic viscosity of the air, the latter being the ratio of dynamic viscosity to the air density. These facts indicate that corrections for cup anemometers should take account of the Reynolds number.

Mention might also be made of the investigation of Hubbard and Brescoll (Ref. 41), using the wind tunnel at the University of Detroit during May 1933. They measured the values of C_D and C_N for hemispherical cups 15.5 cm in diameter. Observations were made to determine these coefficients for (1) a single cup with no interference, (2) a single cup with 3-cup interference, and (3) 4-cup Robinson anemometer. Their data reveal that the coefficients vary with the Reynolds number, and that the effect of interference upon a single cup is to increase the coefficients.

Some indication of advances in regard to the theory of cup anemometers is necessary at this point. Theories on this subject had been proposed many years ago by various authorities, among whom may be listed Chree (Ref. 10), Robinson (Ref. 65), and Thiesen (Ref. 90), whose considerations are summarized in Abbe's work (Ref. 1). Hunt (Ref. 42) and others have given an outline of the elementary theory of the steady state of a cup anemometer based on the equating of the driving couple to the resisting couple. This theory suffers from serious limitations, since it does not take into account the effects of change in direction of the air stream impinging on individual cups owing to the deflection of the stream on passing through the cup wheel. This influence of the cup wheel on the aerodynamic flow conditions was pointed out by Patterson (Ref. 62), and Brevoort and Joyner (Refs. 8 and 9). Since the flow conditions will depend upon the Reynolds number and other non-dimensional parameters, such as the ratio of cup diameter to arm length, it may be expected that the mean effective values of the pertinent coefficients previously discussed (C_L, C_D, and C_N) will vary with these parameters (see Ref. 87). Thus, the elementary theory fails to allow for these effects.

Grimminger (Ref. 32) endeavored to take account of the variations of the aerodynamic factors, such as C_L and C_D, with the pertinent non-dimensional parameters such as the Reynolds number. Dryden, Mock, and Schubauer (Ref. 20) indicated the effect of turbulence on the rating of cup anemometers.

Spilhaus (Ref. 87) advanced the theory by giving due consideration to the relevant non-dimensional parameters, conducted some wind-tunnel tests with anemometers at the Massachusetts Institute of Technology, and made use of the available wind-tunnel test data on anemometer cups to draw useful conclusions. One of the most valuable of his results was that by a suitable choice of the ratio of cup radius to arm length it was possible to construct a cup anemometer characterized by a substantially constant error over a considerable range of wind speed.

With further regard to the relative merits of the 3-cup versus the 4-cup anemometer, Sheppard (Ref. 81) in 1940 published a description of an improved design of cup anemometer which he had developed. It was a beaded 3-cup instrument, whose cups were semi-conical, having the same relative dimensions as the beaded cups tested by Brevoort and Joyner (Ref. 9). The cups had an internal diameter of 5.16 cm. and were spun from thin aluminum sheet, while the arm length from center of spindle to center of cups was about 7 cm. Constructed of light-weight material so that the moment of inertia was low, and employing ball bearings to minimize friction, the Sheppard anemometer had a very low starting speed, viz., 0.19 m.p.s., and it was very sensitive in gusty winds. Its tendency to yield overestimates of speed under such wind conditions was relatively insignificant as compared with that of the conventional anemometers having a relatively large moment of inertia, a large ratio of arm length to cup radius, and a large ratio of mass to area of the cup. The first ratio was so chosen that the instrument yielded practically a linear relationship between the true wind speed and the rate of rotation of the cups.

Schrenk (Ref. 78), in Germany (1929), investigated the theory of the errors of cup anemometers due to the inertia of the equipment, when exposed to winds having a fluctuating speed. He gave special consideration to the case where the wind speed is assumed to vary sinusoidally, and developed a parameter by which one might assess the tendency of a hemispherical cup anemometer to yield over-estimates of the wind speed under such a condition. Schmidt (Ref. 75), also in Germany, conducted experimental studies (1934) concerning the response of such anemometers subject to rapid fluctuations of wind speed. In the United States about 1933-1934, experiments were made by Dryden, Mock, and Schubauer (Ref. 20) relating to the effects of air speed fluctuations in the wind tunnel on the calibration of cup anemometers (see also Refs. 54 and 56).

It was recognized by many investigators that there remained a question regarding the rits of the conical cup anemometer as contrasted with those of the hemispherical cup emometer. Scrase and Sheppard (Ref. 80) gave consideration to this problem (1944), king account of the theoretical developments of Schrenk concerning the errors of anemom-ers exposed to a fluctuating wind speed. Their conclusion relative to this matter may best summarized in their words: "that conical cup anemometers over-estimate the mean eed of a gusty wind to a much less extent than do hemispherical cup instruments". rase and Sheppard also found that Schrenk's theory gives reasonably good values for the er-estimation errors of hemispherical cup anemometers, but it gives excessive values re-rding these errors in the case of conical cup instruments. Scrase and Sheppard reached e conclusion that the extent of over-estimation by a cup anemometer depends mainly on e mass of cup material per unit area of cup, and that the smaller this parameter is the sser the extent of over-estimation by the instrument when exposed to a fluctuating wind.

Deacon (Ref. 15) and Sanuki (Ref. 68) have also investigated the over-estimation er-or of cup anemometers exposed to fluctuating winds.

Studies concerning the problem of the response of cup anemometers and wind vanes in a luctuating wind together with the matter of determining the wind speeds at which cup ane-ometers start and stop have been undertaken by various investigators in Japan (Refs. 69 nd 71).

With regard to the making of wind observations on board ship these Japanese investi-ators have also carried out valuable studies pertaining to the behavior of a cup anemom-ter and a wind vane subject to a pitching and rolling motion (Refs. 69 and 71).

This historical account may be closed by pointing out a few other high-lights of levelopments in anemometry during recent times. Due to the need for a wind-speed measuring levice which could operate under conditions existing on mountain summits where icing and rong winds are fairly common, a heated bridled anemometer capable of yielding readings or speeds of over 200 miles per hour was developed by Mann (Ref. 52), together with some nembers of the staff of the Blue Hill and Mount Washington, N. H., Observatories (Ref. 61). Various types of electrical generator (or magneto) anemometers were developed, e.g., Corwin (Ref.13) has described an instrument which involves the measurement of the frequency of alternating current depending upon the rate of rotation of the cup wheel; and a report by Pinkerton (Ref. 64) indicates the results of the calibration in the wind tunnel of an early design of magneto-type anemometer. Other electrical recording anemometers have been de-scribed by various investigators among whom may be mentioned Wood, 1945 (Ref. 100: propel-ler type); Hartley, 1951 (Ref. 34); and Kesavamurthy and Venhiteshwaran (Ref. 44). Some manufacturers have placed on the market cup anemometers having a very low starting speed for micrometeorological studies; for example, in one case the device employs a light chopper frequency meter to measure the rate of rotation of the cup wheel, thereby permit-ting friction to be kept small. Fergusson (Refs. 24, 25, 26) has constructed a lightweight windmill-type anemometer constructed of balsa wood, which showed itself to be extremely sensitive, and he has compared the sensitiveness of various anemometers. He reached the conclusion that the order of sensitiveness is as follows (commencing with the most sensi-tive): balsa wood windmill, Richard cinemometre (windmill), 3-cup anemometer, and 4-cup anemometer (see also Spilhaus, Ref. 86, Scrase and Sheppard, Ref. 80; Sanuki, Ref. 68).

A very sensitive pressure plate anemometer, having a very short response time, was developed by Sherlock, Stout, et al. (Refs. 83 and 84).

Anemometers which operate on the basis of a measurement of the transit time of an ion in an electric field of known intensity have been developed by several workers, e.g., Love-lock and Wasilewska, 1949 (Ref. 51); Cooley and Stever, 1952 (Ref. 11); and Welman, 1955 Ref. 95).

Sonic anemometers which involve the measurement of the speed of sound have been devised, e.g., Schotland, 1955 (Ref. 77); Suomi, 1957 (Ref. 89).

A multiple pressure tube anemometer whose indications yield both wind speed and direction was described by Goudy and Colvin, 1949 (Ref. 30). An anemometer which integrates the wind according to direction, vectorially, has been described by Whitaker, 1949 (Ref. 97).

The use of hot-wire anemometers (e.g., see Ref. 16), especially to measure turbulent wind fluctuations, has been covered in a literature which by now has grown to voluminous proportions, and it is not practical to present extensive references here. Works which provide bibliographies and summaries regarding the subject are References 2, 29, 35, 36, 38, 43, 58, 59, 60, 85, 91.

Finally, it seems appropriate to cite a few references dealing with investigations regarding the problem of the effects of obstacles on anemometer readings (Refs. 12, 21, 28, 37, 47, 72, 74, 79).

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