Chapter 6

Meteorological Instruments for Use in the Atomic Energy Industry

Harry Moses*

With contributions from Elmer Robinson,†
Maynard E. Smith,‡ Gerald C. Gill,§
Eugene M. Wilkins,¶ and C. Ray Dickson**

6-1 INTRODUCTION

The type of meteorological-data acquisition system required for the nuclear-energy industry varies with the nature of the process contemplated, with the geographical and meteorological features of the site considered, and with quantity and type of potential receptors. The magnitude and diversity of the operations at, for instance, the Atomic Energy Commission site at Richland, Wash., have dictated a meteorological system that has at one time or another employed every type of sensor discussed in this chapter. In contrast, the observational requirements of many small facilities have been met by one or a few commercially available systems of the simplest variety, i.e., systems providing only relatively crude records of wind, temperature, and precipitation. No attempt will be made here, and indeed no attempt can be made, to specify the types and quantities of meteorological instruments and

equipment required in particular situations. Instead a broad survey of appropriate instrumentation will be presented. In the case of wind instruments, the characteristics of the sensors will be discussed in some detail since a correct choice will depend in some measure on these features.

One of the most prominent uses of meteorological instrumentation in the atomic energy field is in the evaluation of sites for nuclear installations. Foregoing chapters have emphasized the problems involved, and here we need note only that when any substantial hazard is believed to exist it is prudent to examine the meteorology of the site. For this reason the Atomic Energy Commission requires that a meteorological site survey be made before a license to operate a reactor is granted. Meteorological information obtained in this manner provides a reliable basis for hazards evaluations by the Advisory Committee on Reactor Safeguards and by the Division of Reactor Licensing of the AEC. Thus a consideration of site meteorology is a routine feature of site evaluation, and it is not unusual for some meteorological measurements to be made in order to develop adequate detail.

The number of locations on a site at which meteorological measurements are necessary depends on the complexity of the terrain and the estimated distances to which abnormal behavior of the nuclear system would cause concern in the environs. For example, the study of a hill-valley complex that might

*Radiological Physics Division, Argonne National Laboratory, Argonne, Illinois.

†Stanford Research Institute, Menlo Park, California.

‡Instrumentation and Health Physics Division, Brookhaven National Laboratory, Upton, New York.

§Department of Meteorology and Oceanography, University of Michigan, Ann Arbor, Michigan.

¶Ling-Temco-Vought Research Center, Dallas, Texas.

**Air Resources Field Research Office, Idaho Falls, Idaho.

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materially influence wind-flow patterns would require additional wind-measuring points. The same would be true for studies near bodies of water over which sea-breeze circulations may be formed, for large forested areas, and for cities. Decisions concerning the number and locations of on-site meteorological stations must depend on the judgment of a competent meteorologist working in close association with nuclear technologists and with health safety personnel.

After a nuclear facility has become operative, there may be a continuing need for reduced meteorological surveillance. In some cases this may be necessary to conduct operations in the safest possible manner; in others, to achieve a greater measure of operating efficiency. The operational modes of the facility should be kept in mind when selecting the meteorological equipment for the initial site survey since in all probability one set of instruments can be used to fulfill both functions.

6-2 THE MEASUREMENT OF METEOROLOGICAL VARIABLES IN THE ATOMIC ENERGY INDUSTRY

Most meteorological problems relating to nuclear energy concern the diffusion of airborne materials. This, in turn, implies that the basic operational data must include measurements of wind direction and wind speed and often an estimate of the turbulent nature of the flow. This latter can be measured directly with wind instrumentation, or it can be inferred from measurements of atmospheric stability, a function of both the wind flow and the vertical thermal stratification. Thus by far the greatest emphasis in this chapter will be placed on measuring and recording wind data and the vertical temperature structure.

Diffusion experiments, such as those discussed in Chap. 4, are not usually a part of the site evaluation or subsequent meteorological program at most reactor sites. However, to give some idea of the nature of diffusion-experiment technology to those who might consider such a program, we will include a section on atmospheric tracers and tracer techniques in this chapter.

It is occasionally necessary to measure meteorological variables which may be of secondary importance in the diffusion and transport problem but which are required in a variety of other contexts. Therefore discussions of equipment for observing precipitation, solar and net radiation, atmospheric pressure, and humidity are presented in later sections of this chapter.

Since many meteorological surveys involve considerable detail and therefore extensive processing of the data, it is important to consider at the outset the form of recording that is most desirable for each individual problem. Because of the large number of measurements made routinely, especially at the larger installations, the handling of data becomes a serious problem unless automatic techniques are adopted. For this reason all the meteorological groups at the national laboratories currently employ some form of automatic data-processing system. A section dealing with this subject emphasizes the relative capabilities and processing speeds of commonly used recording systems.

6-3 PLATFORMS FOR METEOROLOGICAL MEASUREMENTS

When elevated measurements of wind, temperature, or relative humidity are made, a platform is needed for mounting the meteorological sensors. Such platforms can take many forms, e.g., poles, towers of various cross-sectional sizes and of different types of lattice construction, and even buildings, though the latter form is seldom recommended.

Two types of poles can be used for mounting instruments: wooden poles, such as the conventional utility pole, having a diameter of about 1 ft near the ground and tapering slightly and metal poles generally made in a tubular construction with aluminum for relatively short poles and cold-rolled steel for tall ones.

Wooden utility poles are quite suitable for mounting anemometers to a height as great as 25 m above the ground. Such poles are often unguyed but are sunk about 3 m into the ground. Steel step bolts can be used for climbing. Unguyed tubular steel masts as high as 60 m

are commercially available for mounting radio and television antennas but might well be used for mounting meteorological instruments. Such masts are mounted on a concrete base and taper from 0.5 m near the bottom to 0.1 m at 60 m. They can be purchased with adjustable side arms for attaching sensors. Assembly of the sections, which range from 3 to 8 m, is generally made at the ground. Unguyed masts are quite expensive, and guyed masts can be used at a considerable saving.

A wide variety of towers is commercially available. Because of the need for mounting radio and television antennas, such towers are mass-produced and are comparatively inexpensive up to heights of about 25 m. These towers can be quite adequate for conducting a survey of several years' duration. They can be hinged and lowered for servicing or have ladder rungs. Some are telescoping in design. The cost of such towers varies linearly with their height.

Towers of intermediate size, i.e., from about 25 to 60 m, can be furnished either with or without guying. An unguyed tower, however, costs approximately three times as much as one with guying. In deciding upon a tower, one must be careful to determine the stresses to which it may be subjected. For example, some towers will withstand stresses from winds of about 30 m/sec; others will withstand stresses from 70 m/sec winds. The probability of high winds must always be considered in selecting a suitable platform.

Very high towers, i.e., those exceeding 100 m, are used only rarely and for special purposes, e.g., at a large national laboratory or for very special problems, such as the 470-m tower at the Nevada Test Site. For special research purposes television towers, such as the 430-m tower at Cedar Hill, Tex. (Gerhardt, Mitcham, and Straiton, 1962), have also been used.

It is interesting to note that, as of mid-1967, 188 television or radio towers taller than 300 m (with five slightly taller than 600 m), have been built in the United States and another 80 towers taller than 300 m are in the planning stage. In addition, there are at least as many towers in the height range from 150 to 300 m. Although the expense and complication of placing meteorological sensors on these tall towers are great, there will be instances that justify such an effort. A current listing of the heights and

locations of television towers in the United States can be found in the *Television Fact Book*, an annual publication prepared by Television Digest, Inc. of Washington, D. C.

Side arms or booms extending from towers are generally about 3 m in length. The direction in which the booms extend should be selected with a knowledge of the least-frequent wind direction so as to minimize the tower wind-shadow effect (Moses and Daubek, 1961). A discussion of the errors in measurement of wind speed and direction for sensors mounted on openwork towers and on stacks is given by Gill, Olsson, and Suda (1966). At low speeds the tower effect can produce a substantial reduction in the measured wind. Anemometers are generally mounted some distance above the booms, and thermal elements are mounted below the booms. Humidity elements can be mounted on the booms.

Any high tower causes a deformation of the equipotential surfaces of the earth's electric field, especially if the tower is located in an unobstructed area. Since a high tower or even one of the order of 15 m may invite lightning strokes, it is essential to take necessary precautions to suitably ground the tower and avoid lightning damage to the meteorological instrumentation.

6-4 WIND MEASUREMENTS

6-4.1 Wind Speed

There are many types of instruments for measuring wind speed. The following classification given by Middleton and Spilhaus (1953) illustrates the different types that have been used at various times:

1. Rotation anemometers
 - a. Propeller or windmill anemometers
 - b. Cup anemometers
 - c. Special types
2. Pressure-plate anemometers
 - a. Plate allowed to swing
 - b. Plate held normal to the wind
3. Bridled cup anemometers
4. Pressure-tube anemometers
5. Anemometers dependent on cooling
 - a. The hot-wire anemometer
 - b. The Kata anemometer
 - c. The heated-thermometer anemometer

6-4.1.1 Commonly Used Wind-speed Systems. The most commonly used wind-speed measurement system is the cup anemometer revolving about a vertical shaft. High-quality instruments that meet U. S. Weather Bureau and Federal Aviation Agency specifications are durable and accurate and will give years of reliable service with little maintenance. Such instruments usually employ a cup wheel 38 to 45 cm in diameter from the center of rotation to the center of the cups and utilize conical beaded cups about 10 cm in diameter. Above speeds of 1 m/sec, the rate of rotation of the cups is essentially linear with wind speeds up to about 30 m/sec.

For accurate wind measurements at low speeds and for more sensitivity (more-rapid response to fluctuations in wind speed), small three-cup anemometers have been developed. These have an arm length, i.e., from the center of rotation to the center of the cup, of about 7.5 cm and a cup diameter of 5 cm. The cups are made of either plastic or very thin aluminum. The moment of inertia of such anemometers is appreciably smaller than that of the standard Weather Bureau or Federal Aviation Agency type. In addition, these instruments minimize friction with miniature ball bearings and frequently employ a light beam-photocell arrangement for transmitting information concerning the rotation of the cups. Several standard lightweight cup anemometers are shown in Fig. 6.1.

During steady rotation of a cup anemometer, the linear speed of the wind is about two or three times as great as the linear speed of a point on the center of a cup. When Robinson (1850) wrote about the cup anemometer, he indicated that this factor was equal to 3; later work by Brazier (1914), Patterson (1926), and others, however, indicates that this factor is neither constant over the range of speeds used nor is it a factor of 3 but that it varies between 2 and 3 depending upon such factors as the arm length, cup diameter, moment of inertia of the cups, ratio of cup diameter to arm length, and density of material of which the system is made.

Originally, four cups were used. Patterson indicated that a wheel of three cups was preferable because of the more uniform torque around the entire revolution. Furthermore, for a three-cup wheel with the same construction materials, a greater torque per unit weight is obtained, and the instrument is more sensi-

tive to changes in wind speed since the moment of inertia is smaller.

Brazier describes the relation between wind speed and speed of the cup center as $U = a + bU_c + cU_c^2$. In this equation a , b , and c are constants, U is the speed of the steady wind,* and U_c is the linear speed of the cup centers. If this equation is divided by U_c , where $U/U_c = f$, the anemometer factor, we have $f = (a/U_c) + b + cU_c$. Brazier has found that when the ratio d/D is made approximately 0.5, where d is the diameter of the cup and D is the diameter of the circle described by the cup centers, the constant c goes to zero. In other words, the condition for constancy of the ratio is maximized. Work by Spilhaus (1934) indicates that the ratio d/D is also a function of the cup size for maximum linearity.

It might be expected that the maximum torque produced by a single cup occurs when the wind blows directly into the concave side of the cup. Patterson and later Brevoort and Joyner (1935) have shown that the maximum occurs when the concave side of the cup makes an angle of about 45° with respect to the wind direction. Figure 6.2 shows the relation between angle of attack of the cup and the normal force coefficient for hemispherical and conical anemometer cups.

The second most commonly used wind-speed measuring system is that in which a propeller or windmill revolves about a pivoted horizontal shaft that is oriented into the direction from which the wind is blowing by vanes. One example of the propeller-type anemometer is the Aerovane [(a) of Fig. 6.3]. The Aerovane uses a three- or six-blade propeller that is a modified helicoid made of durable plastic and has a diameter of about 38 cm. This is a dependable instrument for climatological measurements (Conover, 1946). Above speeds of

*In practice, the "steady" wind speed referred to here is that which might be observed in a well-maintained wind tunnel where most wind-sensor calibrations are performed. This steady speed fluctuates little about the mean speed, and the mean speed itself varies little over successive time intervals. The wind-tunnel type of steady flow is that which is represented by U in this and following equations. It is important to recognize that in the atmosphere this type of steady wind is not observed since atmospheric turbulence levels are greater and a wider range of fluctuation frequencies exists. As a result, in the atmosphere instantaneous departures of the wind from its mean are larger, and the mean itself will usually vary over successive time intervals.

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 6.1—Cup anemometers. (a) Beckman & Whitley, Inc. (b) Belfort Instrument Co. (c) Climet Instruments Inc. (d) R. M. Young Company. (e) Belfort Instrument Co. (f) C. W. Thornthwaite Associates.

Fig. 6.2—The variation of normal force coefficient with angle of attack for hemispherical and conical anemometer cups at a Reynolds number of 8×10^4 . (Brevoort and Joyner, 1935.)

(a)

(b)

(c)

Fig. 6.3—Propeller wind sensors. (a) An Aerovane wind sensor (Bendix Friez Instrument Division); (b) A Gill propeller vane (R. M. Young Company); (c) A vertical velocity propeller sensor (C. W. Thornthwaite Associates).

1 m/sec, the rate of rotation of the propeller is linearly proportional to the wind speed up to about 45 m/sec. An example of a lighter, more responsive propeller-type anemometer is shown in (b) of Fig. 6.3.

A propeller-type sensor for measuring the vertical component of the wind is shown in (c) of Fig. 6.3. The transmitter consists of a three-blade sensor mounted on a vertical shaft. The output indication of the system is proportional to the magnitude of the vertical component of the wind flow and at the same time indicates whether the vertical component is directed upward or downward.

The Aerovane and many of the standard three-cup anemometers drive a small permanent-field direct-current (d-c) generator that is connected electrically by two-conductor cable to a recording meter of the D'Arsonval type. The output of the generator is linearly proportional to the turning rate of the cup wheel or propeller. These transmitters have fairly low brush and bearing friction and need routine servicing two or three times per year. Brush and commutator maintenance is usually a minor problem. However, the friction is great enough to cause the starting speed to lie in the range of 1 to 2 m/sec. By means of a D'Arsonval galvanometer recorder and the d-c generator, a continuous trace of varying wind speed can be obtained.

Some manufacturers use alternating-current (a-c) generators instead of d-c generators to avoid using brushes and a commutator. This reduces friction considerably and eliminates the maintenance of brushes and dirty commutators. Two-, four-, six-, or eight-pole permanent-magnet rotors are usually employed, the larger number giving a correspondingly larger number of a-c pulses per revolution of the cup wheel and therefore a smoother record. The a-c pulses must be rectified, or a frequency meter circuit must be utilized for suitable recording. With normal rectifiers of the silicon type, the curve relating voltage and revolutions per minute is greatly compressed at the lower end of the scale; so speeds below 2 m/sec require correction. With the low frequency of impulses at these low speeds, each a-c impulse is individually recorded; thus spurious oscillations are produced on the wind-speed trace. Alternating-current generators are quite suitable for

indicating or recording wind speed above 2 m/sec.

Another method of obtaining information from anemometers is to use the rotation of the anemometer to activate switches or relays. There are three general types of transmitters in this category: mechanical contacts similar to telephone relays, light interrupters, and magnet-actuated switches. In instruments of the mechanical-contact type, a rotating shaft is coupled through one or more gears to an eccentric cam that opens and closes a mechanical switch after the passage of a predetermined amount of wind (e.g., a fraction of a kilometer). This switch operates a suitable counter or recorder. An event recorder (Fig. 6.4) with

Fig. 6.4—An event recorder (Easterline-Angus Instrument Co.).

suitable circuitry can be used to provide contacts for each 10-, 100-, and 1000-switch closure and simplify data extraction. Several transmitters can be used with a single time-of-event recorder; thus a single recorder can be used to economically obtain vertical wind profiles.

To reduce mechanical friction (thereby permitting the measurement of low wind speeds) and also to increase the speed of response, the small three-cup anemometers often are used with the interrupted light beam—photocell technique. In this system electrical impulses are generated each time a perforation in the shaft rotates into a position that allows a light on one side of the shaft to shine on a photocell on the other side. The shaft can be drilled with one or many such holes. When only a few electrical impulses are generated for each rotation of the shaft—cup wheel assembly, counters or recorders are usually used for totaling. When many pulses originate with each revolution of the shaft, i.e., six or more, it is convenient to feed them to a frequency-measuring circuit that gives a voltage output directly proportional to the speed of rotation of the cup wheel. Recording this voltage provides a continuous record of the wind speed.

6-4.1.2 Types of Speed Systems Infrequently Used.

The speed of air moving over a fine heated wire can be measured by the cooling effects produced. The hot wire used as an anemometer may range from 0.003 to about 0.01 cm in diameter and may be from about 0.1 to 10 cm in length. Various types of materials may be used, e.g., platinum, Nichrome, or tungsten. The wire may be heated over a range of from several hundred to well over 1000°C. The basic equations describing the theory of the hot-wire anemometer stem from the work of King (1914). An approximate equation relating electric current and wind velocity is

$$i^2 = i_0^2 + K (U)^{\frac{1}{2}} \quad (6.1)$$

where U = steady wind speed

i = electric current in the wire at wind speed U

i_0 = electric current in the wire when $U = 0$

K = an experimental constant, which depends upon the units used

It is assumed in Eq. 6.1 that the hot wire is maintained at constant temperature, i.e., current is added or subtracted from the circuit as the wind speed varies to maintain a Kelvin bridge in balance. Electronic equipment has been developed which uses feedback amplifiers to automatically control the temperature of the

hot wire and keep the bridge in balance. Hot-wire anemometers capable of measuring wind fluctuations up to several tens of thousands of cycles per second are commercially available.

With a hot-wire anemometer important variables of wind speed, such as the root-mean-square velocity or the correlation coefficient between two anemometers placed at different positions, or even lag correlations can be derived. Furthermore with suitable electronic circuitry the turbulence spectra can be obtained automatically.

Another type of hot-wire anemometer allows the temperature of the hot wire to vary, and the output voltage is read on a Wheatstone or a Kelvin bridge. This kind of instrument is calibrated to relate wind speed with bridge-imbalance to give wind-speed fluctuations. This technique is not used so frequently today as the constant-temperature technique. Although this technique is referred to as the constant-current technique, the current is not really constant.

Another technique for measuring wind speed utilizes three thermocouples in a T formation, as shown in Fig. 6.5. The thermocouple junc-

Fig. 6.5—A schematic drawing of a heated-thermocouple anemometer. Thermocouple junctions are labeled A, B, and C.

tions A and B form the probe and face into the wind. Junction C acts as a temperature-compensating junction. This anemometer has been used by Cramer, Gill, and Record (1957) and is commercially available. The thermocouples are made of fine constantan-chromel P wires. Thermocouples A and B are heated by alternating current provided by a transformer; thermocouple C is unheated. The millivoltmeter, V , measures only direct current because the transformer is center tapped and the resistances of the heated thermocouples are equal.

Although hot-wire and thermocouple techniques can be extremely useful for turbulence studies both in wind tunnels and in the atmosphere, they are not usually used in operational diffusion studies because the instruments have the following disadvantages:

1. Deposits of dust and dirt necessitate frequent cleaning and frequent recalibration.
2. Zero shifts in the bridge can cause appreciable errors.
3. Rain or snow can cause very large errors.

If a rotation-type anemometer is prevented from rotating, it develops a torque proportional to the square of the wind speed. A measurement of this torque therefore provides a measure of the wind speed. An instrument based on this principle is called a bridled cup anemometer. Because of its insensitivity and inaccuracy at low speeds, as well as its distorted recording of gust speeds, it is no longer manufactured and is used rarely.

The response of the pressure-tube anemometer, a rarely used instrument, is based on the Bernoulli principle. Static and dynamic pressure holes lead to a float manometer that measures the pressure difference and transforms this difference into a linear displacement recorded on a chart wound about a clock-driven drum. Although the pressure difference is proportional to the square of the wind speed, the float manometer arrangement is designed to provide a linear relation between pen displacement and wind speed. Standard electrical transducers are also available to provide wind-speed readings based on the static and dynamic pressure difference. A disadvantage of the pressure-tube anemometer is that it must be oriented into the wind.

The force exerted upon a plate oriented perpendicularly to the wind direction is proportional to the square of the wind speed. Such pressure-plate anemometers have been used for detailed studies of the wind (Sherlock and Stout, 1931). Although such instruments offer the potential of high-frequency response and conceptual simplicity, they suffer from the difficulties of nonlinear drag coefficient and the necessity of orientation into the wind. This type instrument is not produced in the United States at the present time.

6-4.1.3 The Anemometer Distance Constant. Owing to moment of inertia and friction, a cup or propeller anemometer has appreciable lag, i.e., peaks and lulls are attenuated for frequencies greater than 1 cycle per several seconds. Schubauer and Adams (1954) have shown that the lag characteristics of this anemometer can be expressed by a length called the distance

constant. If an instantaneous change in wind speed occurs, this constant represents the length of wind that must pass the anemometer before it indicates 1-1/e or 63% of the change. For example, if the anemometer was placed in a 10 m/sec wind but its rotational rate was retarded to correspond to a 9 m/sec reading and then the retarding force was removed, the distance constant would represent the distance the wind would have to travel before the anemometer indicates a value of 9.63 m/sec, i.e., 63% of the change. For any anemometer the distance constant is independent of the wind speed. Values of the distance constant range from about 0.7 to 8.0 m for commercially available anemometers (Table 6.1).

Table 6.1—ANEMOMETER CHARACTERISTICS

Manufacturer and Instrument	Model	Distance constant, m
Beckman & Whitley, Inc.:		
3 cup	Series 50	1.22
Staggered 6	Series 50	0.98
Bendix Friez Instrument Division:		
Aerovane (3-blade prop.)	Model 120	4.6
Aerovane (6-blade prop.)		5.8
Climet Instruments Inc.:		
3 cup		1.0 to 1.5
4-blade prop.		0.45
Electric Speed Indicator Co.:		
3 cup	Type F-420C	7.9
R. M. Young Company:		
Gill anemometer, 3 cup		0.73
Belfort Instrument Co.:		
3 cup	Type M	6.4
Meteorology Research, Inc.:		
Velocity Vane	1057	1.7 to 1.8
C. W. Thornthwaite Associates:		
3 cup		1.07

Wind-speed data of sufficient accuracy for the evaluation of a reactor site, for day-to-day reactor operation, or for the rare accident can be obtained from an anemometer with a distance constant characteristic of the less sensitive but rugged instruments, such as the Aerovane. For installations where meteorological measurements are to be made over a period of many years, the economy gained from the rugged equipment is attractive.

The dynamic response characteristics of a cup or propeller anemometer, neglecting bearing friction, can be represented by the differential equation for a first-order system

$$\tau \frac{dU_i}{dt} + U_i = f(t) \quad (6.2)$$

where τ = the time constant (i.e., the time for the system to respond to $1 - 1/e$ or 63% of a step change)

U_i = the indicated wind speed

t = time

$f(t)$ = a time-dependent forcing function

For a forcing step function, assume that an anemometer is held fixed and is suddenly released in a steady wind of U m/sec. Its response can be described by

$$\tau \frac{dU_i}{dt} = U - U_i \quad (6.3)$$

The solution of Eq. 6.3 can be written

$$U_i = U \left[1 - \exp \left(-\frac{t}{\tau} \right) \right] \quad (6.4)$$

Let $L = U\tau$ and $x = Ut$, then

$$U_i = U \left[1 - \exp \left(-\frac{x}{L} \right) \right] \quad (6.5)$$

It is readily seen that L is the distance constant or the length of travel of the wind before the anemometer attains 63% of a step wind change. Experiments by Schubauer and Adams (1954) and by MacCready and Jex (1964) indicate that the distance constant is independent of wind speed for cup and propeller anemometers over the usual range of atmospheric speeds. Since $L = U\tau$, τ must be inversely proportional to wind speed. Schubauer and Adams give the relation

$$\tau = \frac{Ik^2}{\rho Uc} \quad (6.6)$$

where ρ = the density of the air

I = the moment of inertia of the anemometer

c = an effective drag coefficient appearing in the formula for the torque (T) exerted by an anemometer as shown by the relation $T = 1/2cU^2Ar$, where A is the blade or cup area and r is an effective radius

k = the anemometer factor U_c/U , where U_c is the linear speed of the center of the cup

Thus

$$L = U \left(\frac{Ik^2}{c} \right) \frac{1}{\rho} \left(\frac{1}{U} \right) = \frac{K}{\rho} \quad (6.7)$$

or

$$L\rho = K = \text{constant} \quad (6.8)$$

The distance constant is therefore inversely proportional to the air density and directly proportional to the moment of inertia of the cups.

If the forcing function is taken as

$$f(t) = U + A \sin bt \quad (6.9)$$

where U is the steady wind speed, A is the amplitude of an imposed sinusoidal variation, and b is $2\pi f$, where f is the frequency in cycles per second and b is in radians per second, then Eq. 6.2 can be transformed to

$$\tau \frac{dU_i}{dt} + U_i = U + A \sin bt \quad (6.10)$$

Neglecting transient effects, one can write a particular solution of Eq. 6.10 as

$$U_i = U + A (1 + b^2\tau^2)^{-1/2} \sin (bt - \beta) \quad (6.11)$$

where β is a phase-lag angle and is equal to $\arctan b\tau$. According to Eq. 6.11 the anemometer reading will show an amplitude reduced by a factor $(1 + b^2\tau^2)^{-1/2}$ and will lag a sinusoidally varying wind by an angle β . Although this equation indicates that the average indicated wind equals the steady wind, this is not strictly correct because the anemometer speeds up faster than it slows down and thereby gives a mean that is higher than the mean wind.

Since $b = 2\pi U/\lambda$, where λ is the gust wavelength, and $L = U\tau$, Eq. 6.11 can be written

$$U_i = U + \frac{A}{[1 + (2\pi L/\lambda)^2]^{1/2}} \sin (bt - \beta) \quad (6.12)$$

Figure 6.6 shows the percentage of attenuation for a sinusoidally varying wind as a function of λ/L .

It should be emphasized that the above analysis is only approximate since equations for both the vane and cup anemometers are much more

Fig. 6.6—Amplitude reduction of cup anemometers in a sinusoidally varying wind as a function of λ/L . The amplitude reduction factor, $r = \left[1 + \left(\frac{2\pi L}{\lambda}\right)^2\right]^{-1/2}$ (see Eq. 6.12). (Schubauer and Adams, 1954.)

complex than indicated (see MacCready, 1966, and Corcoran and Esau, 1964).

6-4.1.4 Errors in Wind-speed Measurements. There are many sources of error in wind-speed measurements. If an anemometer is mounted on top of a building, the Bernoulli effect will cause readings that are higher than the true reading. If an anemometer is mounted on a boom from a tower, the wind-shadow effect (Moses and Daubek, 1961) for certain directions will cause speeds that are lower or higher than the true speed. In addition to these errors due to poor exposure, a number of errors are inherent in the instrument itself. Errors due to lag, density variations, misalignment of the rotational axis, as well as those due to analysis technique, are discussed in the following paragraphs.

In Sec. 6-4.1.3 it was shown that the instantaneous reading lags behind the true reading for both a step function and a sinusoidally fluctuating wind. In addition, under the latter condition the amplitude is attenuated. Because the anemometer speeds up faster than it decelerates, the mean wind indicated may be slightly higher than the true speed. Schrenk (1929), Deacon (1951), and Schubauer and Adams (1954) discuss this type error. Figure 6.7 represents the errors that might be expected in a fluctuating wind. The K in this figure can be expressed as

$$K = \frac{A\rho T U a^2 r^2}{4I} \quad (6.13)$$

where A = a constant

ρ = air density

T = period of fluctuations

U = steady wind speed

a = cup radius

r = arm radius

I = moment of inertia of the cup rotor

Deacon used the value of 2.7 for the quantity A . For an air density of 1.2×10^{-3} g/cm³, Deacon finds for a Sheppard cup anemometer that $K = 0.031 UT$, where U is in meters per second and T is in seconds. The dashed line in this figure shows the curves for a Sheppard anemometer, a type frequently used in this country.

Fig. 6.7—The overestimation of the Sheppard anemometer (broken lines) compared with Schrenk's (1929) results (solid lines) for an anemometer with hemispherical cups for various values of K (see Eq. 6.13). The amplitude of the speed fluctuations as a percentage of the mean speed ($100\Delta U/U$) is indicated. (Deacon, 1951.)

Ower (1949) carried out an analysis for the errors expected from wind fluctuations of the order of 1 cycle/sec as indicated by a vane anemometer. He assumed that $U_i = U(1 + \Lambda \sin bt)$ and derived the relation

$$\bar{U}_i = U \left(1 + \frac{\Lambda^2}{2}\right) \quad (6.14)$$

where $\bar{U}_i$ is the indicated mean wind speed, U is the true steady wind speed, and Λ is an amplitude parameter. It can be seen that the percentage of error is $100 \Lambda^2/2$. This relation indicates that the errors are greater than those indicated by Shrenk. MacCready (1966) indicates that the errors due to fluctuating winds are ordinarily quite small, on the order of 1.0% or 2.0%. Additional experimental work of this nature for anemometers currently in use, especially for precision measurements, is in order.

For the usual variation of pressure and temperature, the changes in density are generally too small to materially affect the calibration of cup or propeller anemometers. Nevertheless one must remember that calibration does depend upon density and that density has a second order effect on the calibration.

MacCready (1966) made a study of the effects of turbulence on the measurement of horizontal mean wind speeds. He noted that various horizontal speed sensors respond differently to the vertical fluctuations of the real wind. Part (a) of Fig. 6.8 shows the vertical-angle effect for several representative mechanical sensors. Since the true horizontal wind speed would be $V \cos \phi$, where V is the total three-dimensional wind speed and ϕ is the angular departure of the total wind direction from the horizontal, it is seen that the conventional cup anemometer can give unrepresentative readings. MacCready indicated that the VectorVane and the VelocityVane respond to the cosine of the wind angle, and Mazzarella (1954) showed that the Aero-vane-type of instrument responds to a $\cos^2$ relation. In a private communication Gill indicated that some vanes may respond to a $\cos^3$ law. Using data collected by Swanson and Cramer (1965), MacCready calculated that the error between the true and indicated horizontal wind speeds might be on the order of 6.0% for cup anemometers and negligibly small for a cosine propeller anemometer.

MacCready further discussed the error due to the inability of the vane-mounted propeller anemometer to faithfully follow the horizontal fluctuations of the wind. Again using the Swanson and Cramer data, he found that this error amounted to about 1.0%.

A third type of error discussed by MacCready was that due to along-wind turbulent fluctuations. A brief evaluation indicated that this

Fig. 6.8—(a) The response of a number of speed sensors to various vertical wind-direction angles. (b) An illustration of the data-processing error, i.e., the error that will arise in the measurement of the net wind flow along the direction of the mean wind with a sensor that measures the total wind flow. (MacCready, 1966.)

error could become increasingly important with typical sensors as the height of measurement approached the ground level.

In addition to instrumental errors, errors arise from the manner in which the data are analyzed. For a totalizing anemometer, i.e., one in which the wind is integrated over a changing horizontal direction, as shown in (b) of Fig. 6.8, the instrument reading differs from the horizontal component of the mean wind vector, i.e., obtained by averaging the vector components. This type of error can be circumvented by recording the wind components. The magnitude of this error applied to the White Sands data (MacCready, 1966) was calculated by MacCready to be 4.5%. Thus, even with low lag, a cup anemometer in a strongly fluctuating wind can produce a 10% difference between the indicated speed and the horizontal component of the mean vector speed.

Errors from recorder malfunctions, including drift in calibration, are always of concern. Procedures should be devised to check this source of error frequently.

6-4.2 Wind Direction

6-4.2.1 Wind Vanes and Bivanes. Wind vanes can take many different forms from the very ornate, as seen on some farmhouses, to the relatively simple rectangular flat plate. Flat plates are easy to construct and provide reliable data. For increased torque at low wind speeds, some splayed vanes, i.e., two vanes joined at their forward vertical edge and spreading out at an angle up to 20° , have been used. Sanuki (1950) has shown that the overall performance of the splayed vane is not superior to that of a single vane. Some manufacturers have used an airfoil as a vane. Gill (1959) indicates that up to 15% more torque is produced by this type with the same physical dimensions for certain ranges of attack angles, but, because of the added mass and therefore the increased moment of inertia of the airfoil, the improved torque is offset by poorer dynamic performance. Various wind-vane forms are shown in Fig. 6.9.

The vertical and horizontal components of the wind direction can be determined by means of a bivane. The bivane can take either of two forms. The first arrangement consists of two plates perpendicular to each other mounted on a gimbal so that the unit can rotate both horizontally and vertically. The plates are constructed of thin aluminum or expanded polystyrene. The second type consists of an annular fin, either an airfoil or a flat sheet of metal, with a similar gimbal arrangement. Various bivanes are shown in Fig. 6.10. Both types of bivanes, as well as bivanes with a propeller mounted on the shaft, are available commercially. The output from such an instrument can be used to determine all three components of the total wind vector.

6-4.2.2 Wind-direction Transmitters and Recorders. Perhaps the most trouble-free and reliable technique for recording the angular position of a vane is one that utilizes a synchro-motor system. The vane is coupled to the shaft of a synchro-transmitter, which can be located 100 m or more away from but is connected electrically to the synchro-receiver. The shaft of the

synchro-receiver reproduces the rotation of the shaft of the synchro-transmitter and thereby locates the vane position. The shaft of the synchro-receiver can operate the pointer of a wind-direction-indicating dial or it can drive the pen of a strip-chart recorder.

Coupling to a recorder pen is frequently accomplished through a heart-shaped cam. The rotation of the vane from 0° to 180° effects a counterclockwise movement of the recorder pen from the left side of the chart to the right; a continued rotation from 180° to 360° results in a clockwise motion of the pen from the upper end to the zero position. Since each position of the pen represents two angular positions of the vane (except for the end points of the traverse) and therefore creates an ambiguity, a side marking pen is used to indicate whether the direction is east or west of north. Another scheme for recording uses a 540° -wide chart scale. When the pen reaches either the upper or lower end of the chart record, an electrical relay and mechanical system causes the pen to rotate in the appropriate clockwise or counterclockwise direction corresponding to 360° of vane rotation. Since a 540° chart is used, the pen in its new position, i.e., after the 360° change, operates about one-third of the distance from one end of the scale.

A less costly method of recording or indicating the rotation of the vane is accomplished with a potentiometer and a recording voltmeter. The potentiometer contact is coupled to the vane shaft; thus any angular position of the vane corresponds to a particular voltage that can then be applied to a suitably calibrated recording voltmeter. One drawback to this arrangement is the discontinuity that occurs when the contact moves across the gap in the potentiometer. If the wind direction oscillates about a position corresponding to this gap, the pen swings from one end of the chart to the other and causes a confusing record. This difficulty can be circumvented by using double-contact potentiometers and switching arrangements (M. E. Smith, 1959). Another disadvantage of the potentiometer system is the excessive wear produced as the contact moves along the wires. An advantage of this system is the low moment of inertia of the potentiometer system compared with that of the synchro-motor system. This is especially true if microtorque potentiometers are used.

(a)

(b)

(c)

(d)

Fig. 6.9—Various wind vane forms. (a) Climet Instruments Inc. (b) R. M. Young Company. (c) Beckman & Whitley, Inc. (d) Belfort Instrument Co.

Another type of transmitter is the commutator system in which the vane is coupled to a unit that has two electrical contactors or brushes, spaced about 22.5° apart, making contact with one or two of eight 45° conducting sectors. Each of the sectors corresponds to 45° of wind direction, i.e., one point of an eight-point compass. When both brushes make contact in one sector, the direction corresponds to one of the eight compass points, e.g., north, northeast,

east. When the brushes contact two of the sectors, the direction corresponds to an intermediate direction, such as north-northeast, east-northeast, or east-southeast. Thus direction to 16 points is obtained. This system can be used to energize light bulbs for visual reading or to operate electromagnetic relays that drive recorder pens. Similar systems can be used for dividing the compass into any other number of sectors.

(a)

(b)

(c)

(d)

Fig. 6.10—Bidirectional-vane (bivane) sensors: (a) an annular fin bivane used at the National Reactor Testing Station. (b) the Axiometer Sensor by Climet Instruments Inc. (c) the VectorVane by Meteorology Research, Inc. (d) the Gill Anemometer Bivane by R. M. Young Company.

In some installations a switch operated by an anemometer is inserted in the circuit. A recording of wind then is made only when a given amount of air, such as 1 km, has passed, and thus there is a combined recording of both wind speed and wind direction. Although the data obtained under this scheme are difficult to reduce, the system is satisfactory for obtaining climatological data under some conditions.

The standard deviation of the wind-direction distribution (σ_θ or σ_φ) over time periods approximately equal to the length of a point-source release has been used in many experiments as an index of diffusion (see Chap. 4). These quantities can be computed from high-speed analog traces from wind-direction recorders or from other analog or digital data records. A simple electronic system, popularly called a sigma meter, which presents a continuous real-time record of the standard deviations of wind direction without recourse to an intermediate collection of the raw wind-direction data has been discussed by Jones and Pasquill (1959) and has been used in diffusion research studies (e.g., MacCready, Smith, and Wolf, 1961).

Using the nomenclature and notation of Jones and Pasquill, we find

$$\sigma_{T,t}^2 = \sigma_\infty^2 \int_0^\infty F(n) \left[1 - \frac{\sin^2 \pi n T}{(\pi n T)^2} \right] \times \frac{\sin^2 \pi n t}{(\pi n t)^2} dn \quad (6.15)$$

where $F(n)$ = fraction of variance (σ_∞^2) occurring between (n) and $(n + dn)$

T = time interval of interest

t = incremental time of each sample ($t \ll T$)

$\sigma_{T,t}^2$ = the variance accounted for by the function $F(n)$ during the period T , as sampled from periods t

If the signal is a continuous one, e.g., the voltage from the wind vane, $t \rightarrow 0$ and Eq. 6.15 becomes

$$\sigma_T^2 = \sigma_\infty^2 \int_0^\infty F(n) \left[1 - \frac{\sin^2 \pi n T}{(\pi n T)^2} \right] dn \quad (6.16)$$

Equation 6.16 shows that with a filter whose characteristics approach $1 - [\sin^2 \pi n T / (\pi n T)^2]$ one could feed the wind-vane signal through it

and read the variance contained in $F(n)$ (the vane signal) directly.

The power factor (i.e., fraction of signal passed) of a two-stage resistance-capacitance network whose stages are isolated by a vacuum tube is

$$P = \frac{\omega^2 C^2 R^2}{1 + \omega^2 C^2 R^2} \quad (6.17)$$

where ω is $2\pi n$, C is capacitance in farads, and R is resistance in ohms.

The square of Eq. 6.17 is mathematically similar to the expression in brackets in Eq. 6.16. At this juncture one could either employ squaring circuits to read the variance (σ^2) or employ a few simplifying assumptions (as did Jones and Pasquill) and read out the standard deviation (σ).

Basically the sigma meter is a high pass filter permitting passage of all frequencies above a set limit and attenuating other frequencies below this limit in accordance with Eqs. 6.16 and 6.17. The alternating current (across the capacitors) is passed to a simple voltmeter and read directly or, as is more often the case, is rectified to direct current and passed to a ripple filter to smooth the output signal into a more manageable form.

The device as described is limited by the performance of the capacitors. Even capacitors of very high quality cannot hold a charge reliably for more than a few minutes, hence T is limited to about 500 sec.

Since his original publication, Jones has published descriptions of various electronic filter designs for meteorological purposes (e.g., Jones, 1966). These include band-pass designs, cathode-ray-tube readout devices, and other ingenious applications. The sigma meter itself is now commercially available from several manufacturers and can be readily adapted to most telemetered systems, as well as to direct readout on charts or digital displays. For a list of manufacturers of this equipment, consult current issues of meteorological, air-pollution, and air-monitoring publications.

6.4.2.3 Dynamics of the Wind Vane. The behavior of a wind vane can be described by the differential equation for a second-order system

$$\frac{d^2\theta}{dt^2} + 2\omega_n \zeta \frac{d\theta}{dt} + \omega_n^2 \theta = f(t) \quad (6.18)$$

where θ = angular displacement of the vane with respect to a fixed wind direction

ω_n = natural or undamped angular frequency of the system

ζ = damping ratio, the ratio of the actual damping to the critical damping (which produces no overshoot)

t = time

$f(t)$ = a time-dependent forcing function

On the basis of the results of Corcoran (1962) and Garbell (1957), this equation can be expressed as

$$\frac{d^2\theta}{dt^2} + \frac{k\rho A r^2 U}{2I} \frac{d\theta}{dt} + \frac{k\rho A r U^2}{2I} \theta = f(t) \quad (6.19)$$

where k = an aerodynamic factor that depends on the geometry of the vane

ρ = density of the air

A = area of the vane

r = distance from the vane pivot to the vane centroid, i.e., arm length

U = steady wind speed

I = moment of inertia of the vane system.

From Eqs. 6.18 and 6.19, we see that the natural frequency of the vane is

$$\omega_n = U \left(\frac{k\rho A r}{2I} \right)^{1/2} \quad (6.20)$$

and that the damping ratio is

$$\zeta = \frac{r}{2} \left(\frac{k\rho A r}{2I} \right)^{1/2} \quad (6.21)$$

The dynamic characteristics of a wind vane are ordinarily determined by observing its behavior in a wind tunnel. A method frequently used is to displace the vane an angle θ_0 from the mean wind direction and then to release it. The resulting oscillations are recorded in terms of voltage output, which is proportional to the vane displacement. This allows one to determine the parameters of Eq. 6.18, ζ and ω_n .

If we take $f(t) = 0$ in Eq. 6.18, i.e., no forcing function is present, the equation will have three characteristic solutions depending on whether it is overdamped ($\zeta > 1$), critically damped ($\zeta = 1$), or underdamped ($\zeta < 1$). The most faithful response of a vane is obtained when ζ is about 0.6.

Assuming boundary conditions of $\theta = \theta_0$ and $d\theta/dt = 0$ at $t = 0$, we have for $\zeta > 1$

$$\theta = \theta_0 e^{-\zeta\omega_n t} \left[\cosh \omega_n (\zeta^2 - 1)^{1/2} t + \frac{\zeta}{(\zeta^2 - 1)^{1/2}} \sinh \omega_n (\zeta^2 - 1)^{1/2} t \right] \quad (6.22)$$

For $\zeta = 1$ we have

$$\theta = \theta_0 e^{-\omega_n t} (1 + \omega_n t) \quad (6.23)$$

and for $\zeta < 1$ we have

$$\theta = \theta_0 \frac{1}{(1 - \zeta^2)^{1/2}} e^{-\omega_n \zeta t} \times \cos [\omega_n (1 - \zeta^2)^{1/2} t - \beta] \quad (6.24)$$

where

$$\beta = \arctan \frac{\zeta}{(1 - \zeta^2)^{1/2}} \quad (6.25)$$

It is customary to let

$$\omega = \omega_n (1 - \zeta^2)^{1/2} \quad (6.26)$$

when ω is the observed angular frequency, i.e., 2π times the actual frequency. Then by substitution we have

$$\theta = \theta_0 \frac{1}{(1 - \zeta^2)^{1/2}} \times \exp \left[\frac{-\omega \zeta}{(1 - \zeta^2)^{1/2}} t \right] \cos (\omega t - \beta) \quad (6.27)$$

Since Eq. 6.27 describes an oscillatory motion with a period of $2\pi/\omega$, the ratio of successive maximums can be expressed as

$$\begin{aligned} \frac{\theta_{n+1}}{\theta_n} &= \frac{\exp \left\{ -\frac{\omega \zeta}{(1 - \zeta^2)^{1/2}} \left[\frac{2(n+1)\pi + \beta}{\omega} \right] \right\}}{\exp \left[-\frac{\omega \zeta}{(1 - \zeta^2)^{1/2}} \left(\frac{2n\pi + \beta}{\omega} \right) \right]} \\ &= \exp \left[-\frac{2\pi \zeta}{(1 - \zeta^2)^{1/2}} \right] \end{aligned} \quad (6.28)$$

where n is an integer.

Figure 6.11 shows a typical record of a vane test. If the ratio of successive peaks is determined, ζ can be determined, and if the

Fig. 6.11—Response of a wind vane to a step-function direction change. Time markers are at 1-sec intervals. (a) Displacement, 45°; wind speed, 4.5 m/sec. (b) Displacement, 45°; wind speed, 9.0 m/sec. (Courtesy of Beckman & Whitley, Inc.)

angular frequency, ω , is measured, Eq. 6.26 can be used to calculate ω_n , the natural frequency.

When the second-order system of Eq. 6.18 has a forcing function impressed on it, i.e.,

$$\frac{d^2\theta}{\omega_n^2 dt^2} + \frac{2\zeta}{\omega_n} \frac{d\theta}{dt} + \theta = A \sin bt \quad (6.29)$$

the general solution can be expressed as the sum of the complementary and particular solutions. Thus

$$\begin{aligned} \theta = & C_1 \exp [-\omega_n \zeta - \omega_n (\zeta^2 - 1)^{1/2} t] \\ & + C_2 \exp [-\omega_n \zeta + \omega_n (\zeta^2 - 1)^{1/2} t] \\ & + \frac{A \sin (bt - \beta)}{\left[4\zeta^2 \frac{b^2}{\omega_n^2} + \left(1 - \frac{b^2}{\omega_n^2} \right)^2 \right]^{1/2}} \end{aligned} \quad (6.30)$$

where

$$\beta = \tan^{-1} \left(\frac{2\zeta\omega_n b}{\omega_n^2 - b^2} \right) \quad (6.31)$$

When $\zeta < 1$, the contribution of the first two terms will become negligibly small in a short

time, and the motion can be described by

$$\theta = \frac{A \sin (bt - \beta)}{\left[4\zeta^2 \frac{b^2}{\omega_n^2} + \left(1 - \frac{b^2}{\omega_n^2} \right)^2 \right]^{1/2}} \quad (6.32)$$

The denominator of Eq. 6.32 is equal to $1/G$, where G is referred to as the gain. Figure 6.12

Fig. 6.12—Second-order gain characteristics. (Trimmer, 1950.)

shows the relation between the gain and the ratio of the forcing angular frequency, b , to ω_n , the natural angular frequency. When $b = \omega_n$, for ζ less than 0.5, amplification will occur since $G = (2\zeta)^{-1} > 1$ as can be seen from Eq. 6.30. Figure 6.12 indicates that for $\zeta = 0.6$, and $b/\omega_n < 0.8$, faithful response is to be expected.

The angle β is the phase lag between the forcing and response. This relation as a function of b/ω_n for a range of damping factors, ζ , is shown in Fig. 6.13. Even for a damping factor of $\zeta = 0.6$, the phase lag is appreciable.

The foregoing analysis is based on a sine wave of a given single frequency. The wind,

Fig. 6.13—Second-order phase characteristics. (Trimmer, 1950.)

however, as sensed by a wind vane is composed of sine waves having a spectrum of frequencies. Thus one might expect errors because the gain G , as well as the phase angle β , will be different for each frequency. Where the wind has frequency components comparable to or higher than the natural frequency of the vane, these will be attenuated as indicated in Fig. 6.12.

Figure 4.21 in Chap. 4 indicates the dependence of $\sigma_y(x)$ (the standard deviation of the plume concentration distribution in the horizontal transverse direction at a given distance, x , from the source) on σ_θ (the standard deviation of the azimuth-direction fluctuations). If data from different sites are to be compared or, alternatively, if graphs such as Fig. 4.21 are to be used as guides for estimating diffusion at a given site, one must be able to properly interpret the wind-vane readings.

In practice σ_θ is often estimated from a recorder trace by determining the range of fluctuations over an interval, such as 20 min, and assuming that this range is approximately equal to $6.0\sigma_\theta$. Others have suggested that a few of the largest deviations on either side of the mean be omitted and that the range be represented by $4.0\sigma_\theta$. These techniques may be satisfactory if the damping ratio is greater than 0.5 as seen from Fig. 6.12.

With data from a vane or bivane having a damping factor appreciably less than 0.4, the resonant oscillations must be removed mathematically by averaging the data over a 10- or 20-sec interval and using these averages for computing σ_θ . The most appropriate interval would depend on the characteristics of the vane and can be determined by the analysis of wind-vane dynamics presented in this chapter.

6.4.2.4 The Distance Constant of a Vane. The distance constant for an anemometer was defined as the distance over which the wind travels corresponding to $(1 - 1/e)$ or 63% of a step function change. A similar concept can be used for the vane, but there is some difference in definition among different authors. MacCreedy and Jex (1964) suggest a 50% change for a step impulse from initial to final values; Gill (1959) suggests the length of wind trajectory necessary to complete an oscillation. Of course, wind vanes of less than critical damping are considered.

To show that for a given wind vane the distance concept is valid, i.e., that the fraction of the change from the initial to final position during the first oscillation is a function of wind distance rather than speed, we can rewrite Eq. 6.24

$$\frac{\theta}{\theta_0} = \frac{1}{(1 - \zeta^2)^{1/2}} e^{-\omega_n \zeta x/U} \times \cos \left[\omega_n (1 - \zeta^2)^{1/2} \frac{x}{U} - \beta \right] \quad (6.33)$$

since $t = x/U$, where x is the distance of wind travel in time t .

From Eqs. 6.20 and 6.21, we see that

$$\omega_n = U \left(\frac{k\rho A r}{2I} \right)^{1/2} = \frac{2U\zeta}{r} \quad (6.34)$$

Hence, when we substitute for ω_n in Eq. 6.33, the wind speed, U , cancels, and we have

$$\frac{\theta}{\theta_0} = \frac{1}{(1 - \zeta^2)^{1/2}} e^{-2\zeta^2 x/r} \times \cos \left[\frac{2\zeta}{r} (1 - \zeta^2)^{1/2} x - \beta \right] \quad (6.35)$$

Since x is the only variable in the right-hand side of the equation, a distance constant can be defined. Thus the distance over which the wind must travel for the wind vane to adjust to $(1 - 1/e)$ of its displacement, θ_0 , is independent of the wind speed.

From Eq. 6.20 we have

$$2\pi f_n = U \left(\frac{k\rho A r}{2I} \right)^{1/2} \quad (6.36)$$

where f_n is the natural vane frequency.

Multiplying both sides of the equation by λ_n , the natural gust wavelength, and using the relation $f_n \lambda_n = U$, we have

$$2\pi f_n \lambda_n = 2\pi U = \lambda_n U \left(\frac{k\rho A r}{2I} \right)^{1/2} \quad (6.37)$$

or

$$\lambda_n = 2\pi \left(\frac{2I}{k\rho A r} \right)^{1/2} \quad (6.38)$$

Thus we see that λ_n is also independent of the wind speed and is a useful vane parameter. Table 6.2 shows values of λ_n and ζ , the damping ratio, for some frequently used wind vanes.

since $\tan \beta = 2\zeta(b/\omega_n)/1 - (b/\omega_n)^2$. If the two phase angles are set equal to each other, then

$$bt = \frac{2\zeta b}{\omega_n} \quad (6.41)$$

or

$$t = \frac{2\zeta}{\omega_n} \quad (6.42)$$

In terms of the distance constant,

$$L = U\tau = \frac{2U\zeta}{\omega_n} = \frac{2U\zeta}{2\pi f_n} = \frac{\lambda_n \zeta}{\pi} \quad (6.43)$$

since $U = \lambda_n f_n$ and $\omega_n = 2\pi f_n$, where λ_n is the

Table 6.2—VALUES OF THE DAMPING RATIO AND GUST WAVELENGTH FOR VARIOUS WIND VANES

Manufacturer	Model	Damping ratio (ζ)	Gust wavelength (λ_n), m
Beckman & Whitley, Inc.			
Quick One	Series 50	0.69	
Quick Two	Series 50	0.43	
Bendix Friez Instrument Division			
Aerovane		0.28	14.7
Climet Instruments Inc.	014-6	0.45	3.5
	014-51	0.60	2.3
Electric Speed Indicator Co.			
Splayed vane	F-420C	0.14	17.7
R. M. Young Company			
Gill Anemometer-Bivane		0.60	4.4
Belfort Instrument Co.			
Splayed vane	Type M	0.20	9.5
Meteorology Research, Inc.			
VelocityVane	1057	0.45 to 0.65	5.3
VectorVane	1053	0.60 to 0.66	3.2

6-4.2.5 Matching of Speed and Direction Sensors. In an Aerovane or an anemometer bivane, we can minimize wind-measuring error by matching the characteristics of the speed and direction sensors. This is done by making the phase lags of the two systems equal.

Because of phase lag, the vane or anemometer provides a reading corresponding to the wind some distance downstream. For large eddies, i.e., in the low-frequency region, the relation between phase angle and frequency is approximately linear.

For an anemometer, since $\beta = \arctan bt$,

$$\beta \approx bt \quad (\text{for small } bt) \quad (6.39)$$

Similarly, for a vane for $b/\omega_n \ll 1$,

$$\beta \approx 2\zeta b/\omega_n \quad (6.40)$$

wavelength corresponding to the natural frequency.

The speed lag refers to the propeller, and the direction lag, to the vane centroid. If there is an appreciable distance between the two, an additional correction equal to the distance d between the vane and propeller should be applied, i.e.,

$$L = \frac{\lambda_n \zeta}{\pi} + d \quad (6.44)$$

MacCready and Jex (1964) indicated that this technique will provide a phase mismatch of less than 1° for eddies larger than five times the natural wavelength and 10° for eddies of the order of twice the natural wavelength.

The vane and propeller can also be matched by making the distance constants equal and cor-

recting for the separation between vane and propeller, i.e.,

$$L_{\text{propeller}} = L_{\text{vane}} + d \quad (6.45)$$

According to MacCready and Jex, this technique will provide a better match at higher frequencies, i.e., a few degrees for eddies twice the natural wavelength and 10° for eddies only 1.4 times λ_n .

The preceding discussion on the dynamics of the vane applies to a vane without a propeller. When an instrument with a forward fin or propeller is considered, such as an anemometer bivane or an Aerovane, the analysis becomes considerably more complicated. It is then necessary to consider both downwash from the forward surface and the gradient of wind along the vane. The forward surface will reduce the natural frequency and increase the damping factor. Analyses of the dynamics of the vane with a propeller are given by MacCready and Jex (1964) and by Sanuki, Kimura, and Baba (1960).

6.5 TEMPERATURE MEASUREMENTS

At meteorological installations within the atomic energy industry, three types of temperature measurements are commonly made. The first and most frequent type measures the temperature of the air at about 1.5 m above ground. This is frequently referred to as the surface air temperature. The second type measures the temperature of the air at various elevations within about the first 100 m. The purpose of these measurements is to determine the thermodynamic stability of the atmosphere, which is of importance in assessing rates of turbulent diffusion. Such measurements, of course, are also used to establish general climatologies. The final type of temperature measurement is that of the soil at various levels below the surface.

6.5.1 Exposure of Temperature-sensing Equipment

When any object used as a thermal sensor is exposed in the atmosphere, it may assume a temperature quite different from that of the surrounding air. The temperature it assumes is the result of (1) the radiation it absorbs

from the sun, sky, earth, and surrounding objects, (2) the radiation it emits (which, in turn, depends upon its own temperature and emissivity), (3) the heat transfer between it and the ambient air by convection and conduction, and (4) the heat conduction from surrounding materials, such as electrical lead wire or supporting mounts.

Usually the thermal sensor is placed in a well-ventilated enclosure to minimize unwanted radiation effects. At installations where only air temperatures are recorded, the enclosure is an instrument shelter such as shown in Fig. 6.14. Typical dimensions for this kind of

Fig. 6.14—Standard instrument shelter showing mounted minimum (upper) and maximum (lower) thermometers and a thermograph.

shelter are height, 83 cm, width, 73 cm, and depth, 52 cm. The shelter is painted white to enhance the reflectivity of impinging radiation. It is usually louvered on all four sides and has a double roof, with a 5.0- to 7.5-cm air space, and a slatted bottom. The shelter is mounted on an open framework so that the thermometer height above the ground is about 1.5 m. A door hinged at the bottom is placed on the side of the

shelter facing north so that when instruments are serviced the sun will not shine on them. This shelter is used to house not only mercury-in-glass thermometers for measuring ambient and wet-bulb temperatures but also hygrothermographs and maximum and minimum thermometers.

The shelter should be placed over a grass surface (never over hard gravel or cement) in an unobstructed area away from surrounding structures. A fan may be used to provide ventilation when taking hourly readings with a mercury-in-glass thermometer. Either a hand-driven or a motor-driven fan can be used. With the latter, precaution must be taken to assure that the heat from the motor does not influence the air passing over the sensing element.

The variation of temperature with height is a measure of the stability of the atmosphere. The thermal sensor must be placed on a platform to determine the temperature at various levels above ground. The platform may be a boom, 2 or 3 m in length, extending from a

structure, such as an open-lattice tower. The use of building tops or hills as locations for determining vertical temperature gradients is strongly discouraged since the temperature near such objects may be quite different from that at the same height some lateral distance away.

Resistance thermometers or thermocouples are the most common thermal sensors used for measuring the variation of temperature with height. These sensors are generally enclosed in a radiation-ventilation shield (see Fig. 6.15). Fuchs and Tanner (1965) have made an extensive study of the emissivity characteristics of various materials used in radiation shields. The shield is often made of thin sheet metal, such as aluminum, and is in the form of two concentric cylinders about 15.0 cm long. The outer cylinder has a diameter of about 7.5 cm, and the inner one, a diameter of about 3.0 to 5.0 cm. The outer surfaces of these cylinders are made highly reflective. This shield is mounted from the end of a boom, and an aspiration blower is mounted at the other end. The blower draws in air through both the inner cylinder and the

Fig. 6.15—Photograph of a fan-aspirated radiation shield for housing temperature and dew-point sensors (Climet Instruments Inc.).

annular space. A baffle must be placed at the bottom of the shield to prevent reflected or emitted radiation from the ground from affecting the sensor. An umbrella-like shield is sometimes provided to protect against precipitation and, to a lesser extent, against radiation. In this way the radiation-ventilation shield minimizes the radiation effects and allows the thermal element to come into equilibrium with the ambient-air temperature. Tanner (1963) discusses other types of radiation shields and materials as well as the problems related to measurement of air temperatures and temperature profiles.

Aspiration can be obtained by either individual blowers or a centralized fan. On the meteorological towers at Brookhaven National Laboratory and at Battelle-Northwest, centralized blower systems provide the necessary ventilation. At Argonne National Laboratory individual blowers are used. Individual blowers are economical, will operate for 3 or 4 years with minimum maintenance, and are readily available commercially.

The airflow over the thermal sensor should be of the order of 5 m/sec. At typical atmospheric wind speeds, dynamic heating is not a problem.

A problem of importance in the measurement of vertical temperature profiles is the error that can result from the effects of rain or snow on the element or the electrical junctions. If the thermocouple junctions become wet, galvanic action may create spurious electromotive forces that produce errors.

For a continuous recording of soil temperatures, resistance thermometers or thermocouples are most frequently used. Resistance thermometers enclosed in a metallic shield welded to a lead-covered cable (which prevents moisture from entering the system) have proven satisfactory. For visual readings various forms of mercury-in-glass, mercury-in-steel, and bimetal thermometers have been used.

The World Meteorological Organization (Blanc, 1958) recommends that soil-temperature measurements be made at the following levels below the ground surface: 10, 20, 50, 100, 150, and 300 cm. When soil-temperature sensors are installed, the soil structure is usually altered. The soil above and around the sensor itself should be disturbed as little as possible so that such thermal properties as volumetric

heat capacity, conductivity, and moisture content are not changed. Alteration of the soil profile can be minimized by the following procedure. First, with an auger dig a hole about 1 m in diameter to a depth slightly below the lowest level of soil-temperature measurement. Then drill a horizontal hole along a radius of the pit through the wall. This hole should be about 1 m in length with a diameter of about the same size as the protective shield of the soil thermometer. Drill similar horizontal holes at each level at which soil temperatures are to be measured. The soil thermometers should fit snugly into these horizontal holes. When the large pit is refilled, an effort should be made to restore each soil layer to its original position and compaction.

6-5.2 Types of Thermal Sensors

In general, any property of a substance that changes with temperature can be used for measuring temperature. In this section sensors based on the properties of thermal expansion, electrical resistance, and thermoelectricity will be discussed. Such properties as changes in the vapor pressure of liquids with temperature or dependence of the velocity of sound in air on temperature will not be discussed although thermometers based on these and other properties have been developed.

There are three commonly used types of temperature instruments that depend upon thermal expansion: the liquid-in-glass thermometer, the bimetal thermometer, and the Bourdon tube.

The liquid-in-glass thermometer consists of a bulb containing a liquid, e.g., mercury or alcohol, at one end of a capillary tube. The length to which the capillary tube is filled is a measure of the temperature of the bulb. Scale readings can be etched on the stem itself or on the mounting plate although the former procedure is to be preferred. Although the volumetric expansion of such organic liquids as ethyl alcohol is several times greater than that of mercury, the use of mercury is preferred because of its greater accuracy. Organic liquids must be used for very low temperatures since mercury freezes at -38.9°C but organic liquids, such as ethyl alcohol, do not freeze until temperatures well below -100°C .

Although liquid-in-glass thermometers are simple to use and require little maintenance, they are subject to a number of problems, e.g., separation of the liquid in the capillary, distillation of the liquid, hysteresis, and secular changes. When the thermometer is exposed to high temperatures and then quickly placed in a cold environment, a calibration shift may occur, i.e., the 0°C point may change. After a few days, however, the readings will return to normal. Over a period of a year, a calibration change of the order of 0.1°C is not uncommon. Therefore annual calibration checks are desirable. A calibration check can be made by immersing the thermometer in a mixture of distilled water and ice made from distilled water.

Some liquid-in-glass thermometers are calibrated as partial-immersion thermometers, i.e., they read correctly only when the bulb and a few centimeters of the stem are immersed. Only total-immersion thermometers are suitable for meteorological measurements.

One special type of liquid-in-glass thermometer is the maximum thermometer (Fig. 6.16). For many purposes it is important to know the highest temperature that occurred over a selected time interval, such as 24 hrs. A maximum thermometer can be used to accomplish this.

Fig. 6.16—Details of a maximum thermometer showing the bulb and the constriction in the capillary tube. A mounted maximum thermometer is shown in Fig. 6.14.

This sensor is similar to the ordinary mercury-in-glass thermometer except for a constriction near the bulb. When the temperature rises, the liquid column remains intact; when the temperature falls, the column breaks at the constriction, the liquid above the constriction in the tube cannot return to the bulb, and thus the highest reading is retained. The ordinary fever thermometer used in medicine is an example of a maximum thermometer.

It is also possible to obtain minimum temperatures with a liquid-in-glass thermometer. In this case, the capillary tube contains a clear organic liquid and movable index (Fig. 6.17).

Fig. 6.17—A section of the capillary tube of a minimum thermometer showing the sliding index that marks the lowest temperature reached by the meniscus of the fluid in the tube. A mounted minimum thermometer is shown in Fig. 6.14.

When the temperature falls, the surface tension of the liquid at the end of the capillary tube causes the index to move toward the bulb. When the temperature rises, however, the liquid flows around the index. Thus the position of the end of the index farther from the bulb provides a reading of the lowest temperature. For reliable results the minimum thermometer must be mounted at an angle of about 5° from the horizontal with the bulb end lower. Minimum and maximum thermometers mounted in a weather shelter are shown in Fig. 6.14.

The liquid-in-glass thermometer is essentially an indicating instrument. It can be used as a recording instrument but as such is uneconomical and cumbersome. The bimetallic sensor can be used in a recording system.

When two metallic strips of materials having different thermal-expansion coefficients, e.g., invar and brass or invar and steel, are welded together, the unit will bend with a change in temperature. If one end is fixed in position, the other end can be used for recording ambient temperature.

The welded strips can take the form of a simple strip several centimeters long and less than 2.0 cm wide or of a coil or helix. Its thickness is usually about 0.08 cm. Such an

instrument is insensitive to rough handling. A simple strip has greater sensitivity than does the coil or helix. Also, sensitivity varies inversely as the thickness but directly as the square of the total length and directly as the difference in the coefficients of expansion of the two metals. The greater the stiffness, the higher the torque available for driving the recorder pen.

The bimetallic sensor is frequently used in thermographs. With a suitable linkage, position changes of the free end of the bimetal sensor are recorded by a pen making an ink trace on a recorder chart wound on a clock-driven rotating drum.

The Bourdon tube is a thermal sensor consisting of a metallic enclosure filled with an organic liquid. The tube may be 5 cm or more in length and usually is of elliptical cross section. In its operation the Bourdon tube is similar to the bimetal thermometer. One edge of the tube is clamped, and the other is free to move. The movable edge is attached to a pen that provides a temperature-time record on a clock-driven rotating drum. The Bourdon tube is commonly used as the thermal sensor in commercial thermographs (Fig. 6.18). Although this type of equipment is subject to some sources of error, such as a calibration change due to polymerization of the organic liquid, inability to withstand rough handling, or temperature rises above design range, it nevertheless can be classed as a successful instrument. Such equipment in thermographs can operate for many years with only routine maintenance.

For remote recording, electrical thermometers are most suitable. They most frequently take either of two forms: resistance thermometers or thermal elements, depending on the thermoelectric effect.

The resistance of such metals as platinum, nickel, copper, silver, or iron increases with a rise in temperature. This property can be used to determine the temperature of the element and, in turn, the temperature of the medium in which it is immersed. This type thermal sensor can take several different physical forms. Frequently the element is a coil with enough wire to have a resistance of about 100 ohms at room temperature. If copper is used in a 100-ohm element, a 1.0°C change in temperature will provide an approximately 0.4-ohm change in resistance.

Fig. 6.18 — A thermograph. As the fluid-filled Bourdon tube (right) flexes with changes in temperature, the movement is transmitted through a series of linkages to the pen, visible in the window, which records the temperature on a calibrated chart wrapped around the clock-driven drum (Belfort Instrument Co.).

The relation between resistivity and temperature can be expressed as

$$R = R_0 [1 + a (T - T_0) + b (T - T_0)^2] \quad (6.46)$$

where R is the resistance at temperature T , R_0 is the resistance at the reference temperature T_0 , and a and b are calibration constants. Both copper and platinum show a fairly linear relation between temperature and resistance. Therefore the coefficient b is quite small. Copper is frequently used for soil thermometers that are completely enclosed in a metallic shield soldered to a lead-covered cable. Resistance thermometers of various physical sizes and resistance values are commercially available.

The output of a resistance thermometer is generally used with a self-balancing Wheatstone bridge and a strip-chart recorder.

A number of precautions must be observed in using resistance thermometers. Since the resistance change per degree is relatively small, contact resistances between electrical connections must be quite low. Changes in the temperature of the lead wire can cause problems, but these are usually compensated by making the lead wire part of the bridge. In addition, the current passing through the wires must be kept small so that the self-heating effects are kept to a minimum. With ordinary precautions these instruments will give years

of reliable service although calibration checks every 6 months to a year are necessary.

A second type of resistance thermometer is the thermistor, which is made from a mixture of metallic oxides compressed together and heat-treated. These sensors show a change of resistance with temperature that is one or two orders of magnitude higher than that of metallic resistance thermometers. Thermistors are available as rods, flakes, beads, or wafers of various sizes. The relation between resistance and temperature for the thermistor can be expressed as

$$R = a \exp \left(\frac{b}{T} \right) \quad (6.47)$$

or in differential form

$$\frac{1}{R} \frac{dR}{dT} = -\frac{b}{T^2} \quad (6.48)$$

Unlike metals, the metallic oxides exhibit the characteristic of decreasing resistance with increasing temperature. Recently metallic oxides have been developed with a positive temperature coefficient. In spite of the advantage of large resistance change with temperature, these elements have a number of deficiencies. First, the relation is extremely nonlinear, as can be observed from Eqs. 6.47 and 6.48. Second, the reliability is not so great as that of metallic resistors. These sensors may be satisfactory for short-term specialized studies where calibrations are frequently checked; however, attempts to use them for long-term climatological measurements have led to measurement errors.

Fig. 6.19—A thermocouple. In operation the junctions A and B are at different temperatures, one of which is usually a known reference temperature. If neither metal is copper, the junctions C should be at the same temperature.

Another important class of temperature sensors includes thermocouples and thermopiles. When two dissimilar metals, such as copper and constantan (approximately 60% copper and 40% nickel with small amounts of manganese, iron, and carbon), are brought together as shown schematically in Fig. 6.19 and junction A is at a higher temperature than junction B, a current will be established. The relation between the potential difference ΔE between the two junctions and the temperature difference between junctions A and B can be expressed

$$\Delta E = c_1 (T_A - T_B) + c_2 (T_A - T_B)^2 \quad (6.49)$$

where T is temperature, c_1 and c_2 are coefficients, and the subscripts A and B refer to the thermocouples A and B. The electromotive force developed depends on the metal used. For copper-constantan at room temperature, about $40 \mu\text{V}/^\circ\text{C}$ is generated. Thermopiles (several thermocouples in series) are often used to increase the signal per degree of temperature difference. The size of wires used in constructing thermocouples depends upon the degree of thermal lag desired in the measurements.

The output of a thermocouple is most frequently recorded by a self-balancing potentiometer. Except for precision work, a cold junction such as B is not necessary, but a compensating cold-junction spool in the potentiometer recorder is used. This consists of a thermocouple embedded in a resistance coil designed to compensate for the changes in the ambient temperature.

Thermocouples can be calibrated by immersion in a liquid bath of a low-volatility and preferably nonflammable liquid that can be cooled to low temperatures with dry ice and heated to temperatures of about 45°C with an electrical immersion heater. Ordinarily this is satisfactory for the range of meteorological conditions encountered.

The installation of a temperature-measuring system using thermocouples has many pitfalls, and consultation should be sought from those who have had previous experience in this area. For example, it is important to guard against induction currents from nearby a-c sources. Thermocouples can act as rectifiers and provide d-c potentials that are added to those generated from the temperature difference between the warm and cold junctions and thereby produce

an error that may be as much as 2°C. Proper electrical shielding can eliminate this type of error. It is also important to minimize the number of connecting junctions to avoid spurious contact potentials. During damp weather or rain, it is extremely difficult to eliminate all sources of the error even when extreme care is taken.

6-5.3 Thermometer Lag

Thermal sensors that must assume the temperature of the surrounding medium in their operation can be generally classed as first-order systems. Their behavior can be characterized by the first-order differential equation

$$\tau \frac{dT}{dt} + T = f(t) \quad (6.50)$$

where τ is the time constant or lag coefficient, T is temperature, t is time, and $f(t)$ is a time-dependent forcing function. The dynamic response of such thermal sensors to changing conditions is analogous to that of the cup or propeller anemometer.

When a thermal element at a temperature T_0 is suddenly placed in an environment of temperature T_e , the response is described by the differential equation

$$\tau \frac{dT}{dt} + T = T_e \quad (6.51)$$

whose solution is

$$\frac{T - T_e}{T_0 - T_e} = \exp\left(-\frac{t}{\tau}\right) \quad (6.52)$$

At time $t = \tau$, 63% of the change has already taken place.

The time constant, τ , is a function of the product of air density and wind speed raised to a power n . This relation can be expressed as

$$\tau = \frac{K}{(\rho U)^n} \quad (6.53)$$

where ρ is the air density and U is the wind speed. The exponent n has a value of about $1/2$. The lag coefficient for a mercury-in-glass

thermometer having a spherical bulb of 1.12-cm diameter is 56 sec for a ventilation rate of 5 m/sec (Great Britain, Meteorological Office, 1956).

Middleton and Spilhaus (1953) point out that for still air the lag coefficient for rising temperatures is slightly larger than for falling temperatures, but, even with a little ventilation, this difference becomes small. Peterson and Womack (1937) point out that at very high wind speeds, the exponent may approach the value of 1.

In addition to wind speed, the lag coefficient depends on other factors, e.g., the conductivity of the glass and mercury or organic material used, the specific heat and mass of the bulb and the liquid, and the geometric shape and roughness of the bulb. The latter two factors influence the turbulence and consequently the heat transfer from the sensor to the surrounding atmosphere.

When the temperature changes at a constant rate, a thermal sensor will lag behind the actual temperature. If we assume that the temperature of the environment is changing at a rate of α degrees per second, i.e.,

$$T_e = T_1 + \alpha t \quad (6.54)$$

where T_1 is the initial temperature of the environment and α is the rate of change with time in degrees per second, then the differential equation describing this condition could be expressed as

$$\tau \frac{dT}{dt} + T = T_1 + \alpha t \quad (6.55)$$

The solution of this equation is

$$T - T_e = -\alpha\tau + (\alpha\tau) e^{-t/\tau} \quad (6.56)$$

Thus we see that for a period of time that is large compared to τ , the lag coefficient, the thermometer will lag the actual temperature by a difference equal to $-\alpha\tau$ degrees.

If the environment undergoes a sinusoidal fluctuation described by

$$f(t) = T_1 + A \sin \frac{2\pi}{P} t \quad (6.57)$$

the differential equation can be given as

$$\tau \frac{dT}{dt} + T = T_1 + A \sin \frac{2\pi}{P} t \quad (6.58)$$

and its solution is

$$T = T_1 + C_1 e^{-T/\tau} + \frac{A}{[1 + (2\pi\tau/P)^2]^{1/2}} \sin \left(\frac{2\pi}{P} t - \beta \right) \quad (6.59)$$

where T_1 is the initial temperature, C_1 is a constant, A is the amplitude of the sinusoidal fluctuation, P is the period of the sinusoidal fluctuation, and β is the phase angle, which is given by

$$\beta = \tan^{-1} \frac{2\pi\tau}{P} \quad (6.60)$$

Table 6.3 shows the relative attenuation of sinusoidal temperature fluctuations for various

thermometer calibrated by the National Bureau of Standards for use as a secondary standard is essential for carrying out thermometer calibrations.

The calibration procedure ordinarily consists in immersing the thermometer beside the reference thermometer in a large vessel (4 to 5 gal in volume is desirable) filled with a suitable liquid, such as one of the silicone oils, and comparing their readings at various temperatures. A sparkless stirring motor is used to provide uniform temperatures throughout the vessel. Its stirrer is enclosed in a metal case with suitable openings to allow liquid flow. Water can be used as the bath liquid for temperatures above freezing. A thermostatically controlled electric immersion heater is quite suitable for raising the bath temperature, and either cooling coils with circulating brine or dry ice can be used for lowering the temperature. Care must be taken to assure that equilibrium is reached during the comparison of the ref-

Table 6.3—RESPONSE OF THERMOMETERS TO FLUCTUATING TEMPERATURES*

Ratio of fluctuation period to lag coefficient (P/τ)	0.2	0.4	0.6	0.8	1.0	2.0	4.0	6.0	10.0
Ratio of response to time amplitude	0.04	0.06	0.09	0.13	0.16	0.31	0.54	0.69	0.85
Phase lag (β), deg	88	86	85	83	81	72	58	46	30

*Great Britain, Meteorological Office, Instruments for Surface Observations, in *Handbook of Meteorological Instruments, Part I*, p.92, Her Majesty's Stationery Office, London, England, 1956.

ratios of fluctuation period to lag coefficient. The phase shift β is also given. Middleton and Spilhaus (1953) recommended that for ordinary uses the thermal sensing element have a lag greater than 30 sec.

For ordinary needs at a reactor site, the 30-sec lag is quite acceptable, but, for special studies, such as those involving heat-flux determinations, where the quantity $w'T'$ [i.e., the covariance of vertical wind (w') and temperature (T') fluctuation] must be determined, very low lags (≈ 1.0 sec or less) are required. In addition, the wind and thermal-sensor response times must be matched.

6-5.4 Calibration and Testing of Thermometers

Equipment for the immersion testing and calibration of liquid-in-glass and electrical thermometers is available commercially. A

reference and test thermometers. If temperature comparisons are made for temperatures about 20°C above or below room temperature, the vessel should be insulated thermally to reduce heat transfer through the walls.

There are a number of pitfalls in the calibration of thermocouples or resistance thermometers. For example, when the temperature of the bath differs from that of the room, a sufficient length of the wire attached to the thermal element should be immersed in the bath or heat will be conducted through the wire and cause an error in the reading. If a thermopile that is not enclosed in a protective cover is used, the electrical conductivity of the liquid should be checked. If a liquid such as ethyl alcohol or water is used, dirt from the dry ice, as well as condensed water on the dry ice itself, will dissolve, raise the conductivity, and thus cause a serious calibration error. During cali-

bration the lead wire of the thermocouple should be shielded to avoid inductive pickup of alternating current. If a metallic vessel is used to hold the calibrating bath, it must be well grounded to minimize this source of error. The extent of the inductive a-c pickup can be determined by means of an oscilloscope connected to one of the input terminals of the recorder and the ground.

Thermographs using bimetals or Bourdon tubes are best calibrated in an air chamber. The reference thermometer must be placed as close as possible to the thermal element.

6-6 SOLAR AND TERRESTRIAL RADIATION MEASUREMENTS

In many instances the intensity of solar radiation or net radiation flux is closely correlated with the stability of the atmosphere and thus provides a measure of its diffusive capacity. Radiation measurements are also useful to indicate cloudiness at stations that are not manned on a 24-hr basis. This is especially true of the net-radiation-flux measurements, which are of value at night as well as during the day. Recent work on atmospheric chemistry has indicated that photochemical reactions in the atmosphere, producing ozone or other substances, are related to the production of smog. A measurement of the intensity of solar radiation is thus of value in air-pollution studies.

Two types of radiation instruments are most frequently used at atomic energy installations: the Eppley pyranometer (pyrheliometer) (Fig. 6.20) and the Beckman & Whitley net radiometer based on the design by Gier and Dunkel (Fig. 6.21).

The measurement of solar and sky radiation on a horizontal surface by an instrument such as the Eppley pyranometer is based on the temperature difference between two concentric rings, one coated with lamp black and the other with magnesium oxide. The temperature is measured by either a 10- or a 50-junction thermopile in thermal contact with the rings but electrically insulated from them. The entire assembly, consisting of the two rings and thermopile, is enclosed in a 7.5-cm-diameter soda-lime glass bulb filled with dry air. The thermopile output can be recorded by a self-balancing

Fig. 6.20—A pyranometer (pyrheliometer) (The Eppley Laboratory, Inc.).

Fig. 6.21—A net radiometer (Beckman & Whitley, Inc.).

electronic potentiometer located 100 m or more from the recorder.

The net radiation flux as measured by a net radiometer is determined from the output of a differential thermopile measuring the vertical temperature gradient across a horizontal Bakelite sheet. A schematic diagram of this type of net radiometer is shown in Fig. 6.22. The entire unit is mounted in front of a housing containing a blower that provides an airflow distributed equally across the top and bottom of the flux plate. This airflow equalizes convective heat losses and minimizes dust and dew accumulation. The net radiometer, however, cannot be used during rainfall since wetting of the top surface causes appreciable cooling and thus produces a spurious indication of radiation flux.

Fig. 6.22—A schematic drawing of a net radiometer. In this instance the thermopiles are cemented between aluminum faceplates (Beckman & Whitley, Inc.).

Radiation instruments should be located so that the sun is unobstructed during all times of the year. The pyranometer can be mounted on top of a building if a suitable ground location is unavailable. The mounting of the net radiometer, however, is more critical since the radiation received by both the bottom plate and the top plate is of concern. For this reason building roofs are not suitable as platforms for net radiometers. Both types of instruments must be mounted on a firm base and leveled.

6-7 PRECIPITATION MEASUREMENTS

Systems for measuring precipitation are of two general types. The first type is the simple nonrecording collector, usually a cylinder. Total precipitation amounts are determined by measuring the amount of accumulated precipitation with a graduated dipstick. The second type of system furnishes a continuous record of the amount of precipitation by utilizing mechanical and electrical devices. The major cause of inaccuracy in precipitation gauges is the aerodynamic flow in the vicinity of the gauge mouth. Warnick (1956) established that any moderate to strong flow of air past a gauge standing vertically above the ground will create eddy patterns that will divert a significant portion of the

precipitation away from the intake of the gauge. In strong winds then the gauge itself and the pattern of upwind obstacles can produce deficiencies of 10% to 30% of the true precipitation fall. There are methods of minimizing this effect to some extent (as shown by Kurtyka, 1953), but it is not possible to eliminate the problem completely with any standard gauge.

One solution to the problem is to introduce an instrument as a simulated section of the ground surface in very uniform terrain, but the increased accuracy is seldom necessary in the atomic energy industry.

A second type of error results from the various forms that precipitation takes. Drops of rain are more readily recorded accurately, particularly as a function of time, than are similar amounts of snow, sleet, hail, and other frozen precipitation forms. It is possible to obtain gauges on special order that will melt the precipitation as it arrives on the gauge.

In a comprehensive review of rain gauges, Kurtyka (1953) shows that almost 200 types of gauges have been constructed and used. His report describes, illustrates, and gives excellent references to the various types found.

The most common type of rain gauge is a cylinder with a diameter of 20.32 cm (8 in.). At the top of the cylinder is a funnel-shaped intake below which there is a cylinder of much smaller diameter (Fig. 6.23). Rainfall collected at the mouth is then funneled into a smaller diameter cylinder so that, with the linear height of the precipitation magnified, even quite small amounts can be measured with a graduated rule. Within the limitations previously mentioned, this gauge is perfectly suitable for those purposes requiring only an integrated measure over a long period of time, i.e., 12 to 24 hr or more.

A modification of the standard rain gauge uses a spring-scale assembly that records essentially the weight of the water collected in a bucket system (Fig. 6.24). As the amount of catch increases, the bucket and its mounting platform are depressed, and the pen indicates the current weight of the bucket translated into amount of precipitation on a drum chart assembly. Depending upon the time scale of the clock mechanism used, such a gauge permits a reasonably accurate interpretation not only of the rate of rainfall but of the total amount

Fig. 6.23—A standard rain gauge. The precipitation is collected in the widemouthed funnel, which fits into the top of the large cylinder, and then passes into the narrow cylinder, which is mounted below the funnel. Precipitation depth is measured by a suitably graduated rule (Belfort Instrument Co.).

deposited within any given time period. The main disadvantage of this type of gauge is the loss of precipitation by evaporation. Calibration is relatively simple with weights corresponding to equivalent amounts of liquid water.

Another precipitation-measuring system with time resolution is the tipping-bucket rain gauge (Fig. 6.25) in which the collection of some very small amount of precipitation causes a bucket assembly to become overbalanced and flip to the opposite side. As it does so, a magnetic switch or other type of switch produces an appropriate electrical pulse indicating the event. Recording of such information is relatively simple. An event pen (a pen that changes position by a fixed amount when energized and returns to its original position when deenergized) provides a continuous chart record of

Fig. 6.24—A weighing rain gauge. Precipitation enters the top of the gauge and passes into a bucket (not shown) that rests on the bucket platform (foreground). A cumulative record of the depth of precipitation is recorded on the clock-driven drum (Belfort Instrument Co.).

the occurrence of each unit of precipitation. Thus it is possible to define with rather high precision not only the total amount of precipitation in a given time period but variations of the short-term rate if the chart speed is fast enough. An event counter would indicate the total rainfall for a given period.

Precipitation itself may be of interest in certain atomic energy studies, such as evaluating fallout or, in isolated cases, determining the presence of radioactivity or other atmospheric pollutants. Generally speaking, such evaluation requires considerably larger volumes of water than are provided by the smaller standard gauges. For this reason several labora-

Fig. 6.25—A tipping-bucket rain gauge. The precipitation enters the top of the gauge and is funneled into one cell of the pivoting bucket. After being filled, the cell tips, the impulse of the tipping is counted, and the empty cell is positioned under the funnel (Belfort Instrument Co.).

tories and Atomic Energy Commission contractors have designed and constructed collectors with very large diameters and complex bucket-switching systems so that precipitation can be separated into short-term samples, each having a volume of the order of liters.

6-8 PRESSURE MEASUREMENTS

At atomic energy installations the need for atmospheric-pressure information arises when values of atmospheric density are required. Should a reactor mishap occur and radioactive gases be contained in a reactor shell or reactor building, information on 24-hr pressure variations would be useful in determining the breathing rate from the building to the external atmosphere.

The two most frequently used pressure-measuring instruments at atomic energy installations in the United States are the Fortin mercurial barometer (Fig. 6.26) and the aneroid microbarograph (Fig. 6.27).

Fig. 6.26—Schematic drawing of a Fortin mercurial barometer: (center) the entire barometer, (right) the barometer cistern, and (left) the vernier scale. The level of the mercury in the cistern is adjusted by a screw (a) pressing on a leather bag (b) so that the top of the mercury meniscus just touches the index pointer (c). The sliding vernier (d) is adjusted by a thumbscrew (e) until the slide bottom is at the same level as the top of the mercury meniscus (f). The reading from a thermometer (g) is used to correct the height of the mercury column.

In the mercurial barometer the pressure of the atmosphere exerted on a cistern of mercury is balanced against the weight of a liquid-mercury column contained in a vertical glass tube that is sealed at the top but open at the bottom where the tube is submerged in the

cistern. In the Fortin barometer the mercury level in the cistern is raised and lowered by a screw until brought to a position just contacting a fixed ivory point. The height of the mercury column is read on a metal scale to the nearest 0.0025 cm. Readings must be corrected for variations in the gravitational constant associated with altitude and adjusted to a ref-

Fig. 6.27—An aneroid microbarograph.

erence value of 980.665 cm²/sec. The largest correction involves that of adjusting the mercury-column height to a standard of 0°C. In barometers of lower precision, an instrumental correction is frequently necessary.

The pressure-sensing element of a microbarograph consists of one or more partially evacuated flexible metal bellows enclosing a spring. One end of the bellows is fixed; the motion of the other end responds to variations in atmospheric pressure. A mechanical linkage system, including springs for zero setting, is used to move a pen making a trace on a rotating spring-driven drum. In this country a frequently used instrument exaggerates the height change of a mercury column by a factor of 2.5.

The microbarograph also contains one or several dashpots of oil to damp rapid pressure oscillations due to gustiness (called pumping) of the wind or sudden indoor pressure changes due to opening and shutting of doors. Readings accurate to about 0.025 cm Hg can be obtained with commercially available microbarographs.

6-9 ATMOSPHERIC-MOISTURE MEASUREMENTS

In day-to-day operations at the national laboratories and other large atomic installations, a variety of uses can be found for information on atmospheric moisture. For example, measurements of wet-bulb temperatures are important in the design of cooling towers, and data on relative humidity are of concern to physicists working with high-voltage machines or biologists working with experimental animals. Relatively complete summaries of the underlying theory of and techniques for measuring atmospheric moisture are given by Middleton and Spilhaus (1953) and Spencer-Gregory and Rourke (1957), and in the *Handbook of Meteorological Instruments* (Great Britain, Meteorological Office, 1956). At Atomic Energy Commission installations, the most frequently used moisture-measuring systems are the wet- and dry-bulb psychrometer, the hair hygrometer, and the hygroscopic hygrometer.

The reduction in temperature of a wetted surface owing to evaporational cooling can be used to determine the amount of moisture in the atmosphere. The ambient-air temperature and pressure must also be known. This principle is used in the operation of the wet- and dry-bulb psychrometer, which commonly consists of two mercury-in-glass thermometers, the bulb of one being wrapped in clean muslin. The muslin is wet with distilled water, and the instrument is placed in an airstream of the order of 3 to 5 m/sec. Other forms of psychrometers in which the glass thermometers have been replaced by resistance thermometers, thermocouples, or thermistors have been used. These types lend themselves to remote and continuous recording through the use of self-balancing potentiometers or Wheatstone bridges.

Conversion of the wet- and dry-bulb readings to relative humidity or dew point is easily accomplished by using psychrometric tables or humidity slide rules.

Many schemes are used for providing an airstream past the wet-bulb thermometer. In the sling psychrometer the two thermometers are mounted side by side on a metal plate or in a metal frame and whirled by hand. Often the two thermometers mounted in this way are placed in the instrument shelter in front of a fan driven

by a hand crank. Spring-driven or electric motors have been used to create the airstream in the Assmann psychrometer.

For the last 150 years, the hair hygrometer has been widely used for both industrial and meteorological purposes although its defects have been loudly criticized from time to time. Its continued use is no doubt due to the fact that the instrument is simple in construction, lends itself easily to recording, and provides measurements that are of sufficient accuracy (about 5%) for ordinary usage, at least in air temperatures above freezing. When human or animal hairs have been carefully cleaned and the grease and oil have been removed by treatment in ethyl ether, they elongate about 2.5% as the relative humidity changes from 0 to 100%. The relation between elongation and relative humidity is logarithmic in the relative humidity range 20 to 100%, i.e., $L = a + b \log RH$, where RH is the relative humidity, L is the length of the hairs, and a and b are constants. The loss in speed of response with low temperatures, i.e., below freezing, may be a distinct shortcoming for some applications.

In the conventional hygrograph the humidity element consists of a harp of human hairs held under slight tension and connected through a logarithmic compensating linkage to a pen making an ink trace on a clock-driven drum. Frequently a single drum is used to record the pen traces of both a humidity and a thermal sensor. This kind of instrument is called a hygrothermograph. Daily or weekly calibration checks are required. Human hairs can function well for several years in areas free from dust and salt.

Salts, such as calcium chloride or lithium chloride, are hygroscopic and therefore absorb water vapor when placed in a moist atmosphere. Various types of hygrometers making use of this phenomenon have been devised. In these instruments the salt may be coated on a flat surface, such as a glass or plastic slide, or may be impregnated on a fabric or a single strand of fiber glass. The gravimetric hygrometer and the electrolytic hygrometer are examples of moisture-measuring instruments using hygroscopic salts.

In the gravimetric hygrometer the actual amount of water vapor absorbed is weighed by a sensitive balance. From this measurement the relative humidity can be determined if the tem-

perature is known. In the electrolytic hygrometer the electrical resistance, either between two electrodes placed on a coated slide or between two points on an impregnated fiber, is measured by a bridge, an ohmmeter, or some other electronic device. Such resistance measurements can be related to the ambient relative humidity if the temperature is known. The radiosonde humidity element makes use of this principle.

The Foxboro Dewcel is a commonly used modified form of the electrolytic hygrometer. Its operation depends on the fact that for each value of water-vapor pressure of the surrounding air there is one temperature of the saturated solution at which equilibrium exists, i.e., the vapor pressure surrounding the lithium chloride salt surface equals that of the ambient vapor pressure. The instrument consists of a cylindrical tube about 10 cm long and 0.6 cm in diameter, covered by a wick of woven glass tape upon which gold or silver wires are wound in bifilar fashion. The tape is impregnated with lithium chloride, and the wires are connected to a 25-volt a-c power source. The conductivity between the parallel wires depends upon the amount of moisture absorbed by the hygroscopic lithium chloride. If the vapor pressure of the ambient atmosphere is greater than that in the immediate vicinity of the lithium chloride film, the vapor will be absorbed, and the conductivity between the wires will increase and allow more current to flow. The increase in current flow raises the temperature of the Dewcel element until the equilibrium vapor-pressure point is reached. If the vapor pressure of the ambient atmosphere is less than that surrounding the lithium chloride film, the reverse process takes place. Thus the Dewcel acts as an automatic self-regulating control mechanism in which the current flow between the heating wires is varied to maintain an equilibrium temperature from which the ambient vapor pressure can be determined. The thermal element can be a resistance thermometer or a liquid-expansion tube.

6-10 METEOROLOGICAL DATA-PROCESSING EQUIPMENT

The steady increase in the availability and the capability of data-processing and computing

equipment makes it advisable that the final recorded form of data from each meteorological installation be considered very carefully. Particularly when several instruments are to be involved, it is legitimate to question whether the data should be hand abstracted from simple chart recorders or whether the additional cost of a more-sophisticated recording mechanism is justified. Inasmuch as it may help the reader in his decision, several types of recording and auxiliary data-handling equipment are discussed.

Virtually all data from meteorological sensors recorded electrically are in the form of electrical voltage or current. In the initial design of a meteorological system, one must consider simultaneously the selection of the sensors, the recording technique, and the data-processing form.

In general, electrical voltages and currents are easily converted to a shaft-position change that lends itself readily to chart recording. Reliable shaft-position encoders are readily available to convert this type of analog information to digital form. Information from sensors having a digital output, such as the tipping-bucket rain gauge or an anemometer giving pulses for each unit of air passage, is readily recorded directly on magnetic tape or (with some processing) on paper punch tape. Ink-trace recordings utilizing time-of-event (chronograph) pens are often used for a pen-and-ink record, but the analysis is tedious.

6-10.1 Chart Recorders

One of the most common forms of recording in use today is the strip or circular chart on which one or more pens record the variables of interest usually as a function of time (Fig. 6.28). Although these recorders have various internal mechanisms for converting voltages and currents, shaft positions, or counts into the final pen movement, they share a number of common features:

1. All provide good resolution of the variable with time and permit easy inspection not only of existing conditions but also of conditions over previous hours or days. This advantage is not one to be overlooked in installations where it may frequently be necessary to evaluate recent meteorological changes and to utilize the infor-

Fig. 6.28 — A pair of strip-chart recorders displaying simultaneous records of two variables (Esterline-Angus Instrument Co.).

mation quickly. Figures 2.30 and 2.31 (Chap. 2) are illustrations of typical chart records.

2. Considerable effort is required to extract information from the chart records. Equipment available to simplify this task is described in a later section, but for the most part one would consider such equipment an analysis aid rather than a basic data-processing system.

3. The chart recorder, having been in use for many years, is a highly developed device, and the better equipment of this type has very high reliability. Many recorders have run without major maintenance for periods as long as 10 or even 15 years.

A partial solution to the data-abstraction problem is found in the addition of an integrating device, which can operate in conjunction with the recorders or be supplementary to them. The simplest form of such an integration device can be used with the tipping-bucket rain gauge or with the anemometer providing a pip for the same fixed unit of wind passage. For example, a counter can be added which will automatically summarize events over a period of time while the recorder provides the detail. In some recorders an event pen can count directly on the record. In others counting is accomplished externally.

Similar in principle to the counter system are more sophisticated integrators, such as the ball and disk integrator used by the Argonne National Laboratory (Moses and Kulhanek, 1962).

A somewhat different solution to the data-abstraction problem involves alteration of either

the input data or the recording mechanism to provide either integration or lagged response of the pen. The simplest form is the familiar resistance-capacitance network. Sensors with large thermal lag (such as resistance thermometers of large mass) are often used to make further integration unnecessary.

Lagging can also be accomplished mechanically or electromechanically, as is done in the Brookhaven system (Brown, 1959). Here, servomotors operating through 1000:1 gear ratios greatly slow the response of the recording system.

Implicit in the reduction of detail thus accomplished is the idea that the detail may not have been necessary. Here again, the decision regarding the recording form should precede and dictate the input wherever possible.

Hand abstraction of chart data can be accelerated considerably by the use of chart readers of one type or another. All these include mechanisms for the orderly advancing and inspection of the chart by the operator as well as simplified means of following the pen trace as a function of time. In typical systems the operator follows the pen trace with a stylus or with wheel-driven vertical and horizontal line markers, and at selected intervals the ink-trace reading is converted into digital form and recorded automatically on punch cards or tape.

Other chart readers actually follow the trace themselves photoelectrically and record either manually or automatically at set intervals of time or chart spacing.

6-10.2 Automatic Data-recording Systems

At the present time there are a number of automatic data-recording systems described in the literature. Some of these have been discussed by Brown (1959), Fritschen and van Bavel (1963), Gerhardt, Mitcham, and Straiton (1962), Moses and Kulhanek (1962), and Newstein (1963). Few systems can be adapted to general meteorological use, however, and none are offered commercially as shelf items.

Since most of the existing meteorological sensors are analog devices, the analog output must be converted to digital form prior to introduction into the programming and recording portions of the system. The digital output can

be in the form of paper or plastic punched tape, magnetic tape, or cards.

There are many devices for converting analog information into digital form. Such devices have been used for many years, and reliable units are readily available commercially.

The choice of the final output form, as well as the intermediate conversion equipment, is always a difficult one and usually represents a compromise between cost, adaptability, and anticipated needs. In principle, however, each has advantages and disadvantages, but an automatic system will ordinarily represent a saving in time and money and will provide improved accuracy in the data-reduction process.

Experience has shown that the pen-and-ink recorder trace should be retained even though an automatic data-processing system is adopted. The visual record thus provided is extremely valuable both for providing information concerning the operation of the sensors and for avoiding the loss of data in the event the automatic data system malfunctions.

Magnetic tape is an increasingly popular method of recording data; information can be in either analog or digital form although usually the latter. Probably the most important advantages of magnetic tape recordings are an extremely high speed capability (which is generally needed only in research installations) and ease of storage. One reel of tape can store the data contained on about 125,000 cards. Magnetic tape can be used in any one of many computers, assuming appropriate programs exist, and therefore presents a minimum of problems in the final utilization.

Magnetic tape, however, has at least two disadvantages, the most important of which is the cost of the tape-handling units. A good system of this type is necessary to provide reliable operation and is likely to cost as much as or more than the rest of the automatic system. Also, direct readout is ordinarily difficult. The tape usually cannot be inspected and checked except by the computer with which it is utilized.

Midway between magnetic tape and punched cards is the paper-tape system, which has some of the advantages and some of the disadvantages of each. Moderately high-speed operation is possible with paper tape, and, with the latest punch drives available, as many as

150 digits can be recorded per second. Punch tape can be stored for years without deterioration. Also it has the advantage of providing a visual check of the information for errors, often with considerable ease (some tapes have the information printed on them at the same time the punches are made). A disadvantage is that punched tape is usually converted to cards or magnetic tape before computer analysis is performed. Although this additional step, together with diligent maintenance of the tape punch, is costly, punched tape often represents the least expensive way of automatically processing and storing data.

At the risk of making this section obsolete, the authors suggest that for general meteorological use in the atomic energy field the punched card is the most versatile and suitable system of all. It is by far the most-common data-storage form, and every computer has some provision for utilizing punched cards either directly or following simple conversion to magnetic tape. In addition, the punched card automatically segregates the data into time sections and provides for easy inspection and repair of inaccurate information. Most computer facilities have card-to-tape and tape-to-card equipment.

It is not possible to record at extremely great speeds directly on punch cards, but such speed is seldom necessary. The card is not without its flaws, however, the main one being the card structure itself. The standard punched card deteriorates fairly readily with or without use, and in short order a given deck will not pass through the handling machines. In some areas this problem requires special plasticized cards. Nevertheless card reproducers can ordinarily process a deck of standard cards that have been stored under room temperature and humidity conditions for 10 years or more even though they are not suitable for passage through the computer.

6-11 EQUIPMENT FOR DIFFUSION MEASUREMENTS

Although the direct measurement of atmospheric diffusion has played a central role in our understanding of this phenomenon, those persons involved in planning a nuclear installation are not likely to become involved in

performing diffusion experiments. There are two reasons for this: first, the problems at most sites are not usually critical enough to warrant the great expense of a diffusion experiment and, second, should it be thought necessary to conduct such experiments, meteorological consultants will usually be employed for the operation and its evaluation. However, to present some background information on this subject, we will include a sketch of some of the techniques.

The diffusion characteristics of the atmosphere can be determined by measurements of purposely generated tracer materials. The experimenter, since he is dealing with the atmosphere, must be continually aware that he is working with a unique situation that will never recur in just the same way and that, if tracer tests are to have some general applicability, the results of the program must be amenable to both statistical and theoretical analysis. Otherwise the program is only an illustration of what the atmosphere did at a particular time and over a particular area. Tracer programs can be used either to illustrate individual situations or to accumulate data describing the expected variations of meteorological conditions in a particular area.

Chemical warfare groups were among the first to become interested in tracer techniques. Since the introduction of atomic energy and the development of the atomic industry, tracer techniques have been used extensively to explore atmospheric diffusion patterns in the areas around atomic operations. Both the chemical warfare and the atomic plant uses of tracers are examples of situations in which a tracer is used to approximate the diffusion of toxic materials.

A quantitative tracer-analysis program depends upon the controlled emission of relatively small amounts of a distinctive material to the atmosphere, its collection, and the careful analysis of the collected samples for minute amounts of the tracer.

Because of the usually minute amounts of tracer material in the samples, extreme care must be taken to guard against excessive background concentrations. A thorough analysis for background effects should be part of any comprehensive tracer program, and, if at all possible, techniques should be selected so that there is little or no background correction. Back-

ground effects can be caused by a number of factors. Some of the more important seem to be (1) contamination of equipment, clothes, and personnel with tracer material and its subsequent transfer to the sample, (2) mistaking natural materials for the tracer, (3) the redistribution of tracer that had been dispersed in a previous operation, (4) mistaking industrial effluents for the tracer, and (5) analysis errors caused by extraneous materials in reagents or equipment. From this list it can be seen that the background may depend upon the volume of air sampled and thus be related to the tracer concentration or it may be introduced as a single amount, such as might come from handling.

Aerosols rather than gases have been used most often in tracer studies. Since the purpose of most tracer programs is the determination of diffusion patterns applicable to the diffusion of gases, the question is often asked whether or not the diffusion of the particulate aerosol actually represents that of a gas. It is recognized that, if the gas and the particles were mixed and enclosed in still air, there would be a gradual settling out of the particles from the gas. In the open atmosphere, however, turbulence will cause gravitational settling to be an insignificant feature of the effluent distribution. Available data on these turbulent currents indicate that they are at least 100 times larger than the gravitational forces acting on the particles. Gravitational settling is thus an insignificant influence within the time scale of most tracer experiments. Several experimental programs substantiate this use of aerosols for gas tracing.

The results of particle-size determinations on a zinc sulfide tracer aerosol before and after dissemination are shown in Table 6.4. The field samples used in this check were collected at distances of 30 to 40 km from the source. These data show that there was no significant change in the particle-size distribution of the pigment between that which had not been dispersed and that which had been carried by the wind. If settling were a significant factor in the distribution of the aerosol, a difference would be expected. Webster and Duckworth (1959) and Leighton, Perkins, Grinnell, and Webster (1965) have presented studies on the relative transport of gases and aerosols.

Table 6.4—COMPARATIVE PARTICLE-SIZE DISTRIBUTIONS BEFORE AND AFTER DISSEMINATION*

Particle size, μ	Pigment sample, %	Field-collected sample,† %
0.5	8	‡
1.0	31	35
2.0	35	33
3.0	15	22
4.0	7	8
5.0	3	2
6.0	1	0

*From E. Robinson, Atmospheric Tracer Techniques Using Aerosols, presented at the Instrument Society of America Conference and Exhibit, San Francisco, 1960, Paper 11-SF60.

†Collected from 30 to 40 km from the source.

‡On the filter samples it was not possible to measure particles less than 1 μ in diameter, and thus all particles less than 1 μ are included in the 1- μ range.

6-11.1 Oil Fog Tracer Techniques

Smoke plumes from oil fog generators have been used in atmospheric diffusion studies for many years (Church, 1949, and Lowry, Mazarrella, and Smith, 1951). Most of these studies have utilized military oil fog generators, such as the M2 and M3A2, or copies of them. Such generators can conveniently produce large volumes of smoke for extended periods of time. The M2 generator produces smoke by forcing a mixture of oil and water into a coil located in a combustion chamber in which heat vaporizes the two liquids. The vapor escapes through a manifold into the air where rapid chilling condenses it into a fog of submicron droplets (War Department, 1944). In the M3A2 generator, smoke is produced when oil is injected into the engine tube of a pulse-jet engine where it is vaporized (Department of the Army, 1955). The most desirable drop size for these condensed smoke particles ranges from 0.5 to 1.0 μ . The average size of the condensing droplet is controlled by the concentration of condensing vapor and the rate of cooling. If the cooling is not rapid enough, large drops will form, and the smoke will be unsatisfactory. A properly generated smoke cloud is stable, and the life of the cloud is determined almost solely by meteorological conditions.

Three methods of analysis have been used for oil fog studies. The first was a photometric

method in which the concentration of smoke in small volumes of air was determined by the amount of light scattered by the aerosol particles (Church, 1949, and Lowry, 1951). The photometer was carried in a truck and moved around the downwind area. Samples from plumes aloft were obtained by lifting the photometer into the smoke with a captive balloon. These samplers could be used to record smoke density continuously, but equipment costs did not permit observations at a large number of points. Two more-economical methods were developed in which the amount of oil collected by a filter could be determined (Smith, Bartlett, and Potts, 1956, and Smith, Singer, Bartlett, and Marcus, 1957). In these methods the amounts of oil are determined either gravimetrically or fluorometrically. The fluorometric technique is based upon the fluorescent character of the oil used to produce the fog. When the oil collected by a filter sampler is dissolved in benzol, the amount of oil can be determined from the resulting fluorescence of the benzol solution.

6-11.2 Fluorescent Tracer Techniques

The Chemical Corps has developed techniques for using insoluble fluorescent pigments (FP) as tracer materials for diffusion studies. The materials selected were pigments of zinc sulfide or zinc cadmium sulfide from 1 to 5 μ in diameter. These particles can be detected by the green and yellow fluorescence, respectively, of the particles under ultraviolet illumination. The techniques developed included methods for quantitative dispersion of the dry pigment, the preparation of filter and impactor samplers, and optimum microscopic sample-analysis procedures. The FP technique has been described by Leighton, Perkins, Grinnell, and Webster (1965).

Other groups have used a modified fluorescent-pigment tracer. A number of tests were run in which the pigment was mixed with the oil and fed to an oil fog generator (Braham, Seely, and Crozier, 1952). Braham et al. used an airplane to sample the plumes and measured tracer concentrations as far as 160 km and as high as 3.0 km from the source. A moving-stage impactor permitted the tracer catch to be identified with certain parts of the flight path.

The fluorescent-pigment technique has also been used in diffusion tests at Hanford, Wash.

(see Sec. 4-4.2.2, Chap. 4). A dispersion method was developed in which a water slurry of the pigment is dispersed by a high-volume insecticide fog generator, the TIFA (Todd Insecticidal Fog Applicator). This method of operation overcame some feed difficulties encountered with the dry dispersers. An even more significant development of the Hanford group has been the development of an instrumental technique for the analysis of fluorescent-pigment filter samples (Barad and Fuquay, 1962). This technique photometrically measures the scintillations of the pigment particles that are excited by alpha particles. The limit of sensitivity of this technique is about 10 to 20 particles on a 2.5-cm filter. Other Hanford developments include methods for handling filters where natural dust loadings are large enough to interfere with particle resolution. Without some instrumental technique the tracer samples can be evaluated only by rather tedious manual microscopic counting.

Satisfactory results require complete dispersion of discrete pigment particles. Since dispersion is at a given mass rate of emission and sample evaluation is in terms of numbers of particles, the sample catch can be equated to the emission only by assuming some predetermined size distribution to apply to the emitted tracer. Large errors can occur if there is inefficient dispersion or agglomeration of particles because the particle-size distribution would be unknown.

In 1957 a tracer technique was developed in which water-soluble fluorescent uranin dye was used as the tracer material (Robinson, MacLeod, and Lapple, 1959). The use of other fluorescent dyes has also been described (Dumbauld, 1962). Dispersion of these liquids is by a high-pressure air-aspirated spray nozzle with the concentrated liquid spray drying to form an aerosol of dye particles from 1 to 10 μ in diameter. Filter samplers are used, and analysis is made by dissolving the dye particles of the filters in distilled water and then measuring the fluorescence of the solution in a fluorometer. The fluorescence is proportional to the concentration of dye in the solution, and thus the amount of tracer material collected can be determined. An analytical sensitivity of 10^{-10} g, which is equivalent to a single 5- μ dye particle, has been achieved.

Dispersion of the uranin dye as a concentrated water solution permits close control to be maintained over the final aerosol-particle size distribution since it depends upon readily controlled conditions of nozzle geometry, air pressure, liquid flow rate, and solution concentration. The emission and analysis of the uranin are both in units of mass; so a particle-size-distribution step such as that needed in the pigment sample is unnecessary.

In the uranin-tracer developmental tests, natural dusts were present in the samples. No correlation was noted, however, between the dust in a sample and sample fluorescence. The experimental area did not have any urban pollution concentrations, however. Wholers, Lapple, Kass, and Johnson (1959) have reported on a fluorescent-dye tracer program and the problems encountered in an area around a phosphate-fertilizer operation, where a fluorescent background of apparent industrial origin did interfere with the use of uranin dye. The interference was overcome by using another fluorescent dye, Rhodamine B, as the tracer aerosol. Difficulties were also encountered in leaching the dye from the filters and with variations of pH that affected fluorescence. These difficulties emphasize the importance of adequate checks for background concentrations and environmental effects.

6-11.3 Other Aerosol Tracer Techniques

The usual absence of freezing nuclei effective at temperatures of -15 to -20°C and the ease with which large numbers of effective nuclei can be produced with silver iodide cloud-seeding techniques led Schaefer (1958) to use silver iodide as an atmospheric tracer material. The tracer plume was measured with a portable cloud chamber in which the concentration of ice crystals was visually estimated. Schaefer states that, because of temperature effects and the appearance of the crystals, little trouble may be expected in separating natural ice nuclei from the silver iodide nuclei. The rather cumbersome sampling procedure is a major limitation to its use in a large-scale program.

A tracer method using some aspects of nuclear technology has been used in a limited pilot-plant program (Haines, Cember, and Hemeon, 1956). In this method antimony oxide

is dispersed, and the airborne material is collected on filters. The samples are exposed in an atomic pile and are analyzed for the induced radioactivity of the metallic antimony. In the tests run difficulties were encountered owing to low disperser efficiency and to relatively high background concentrations. Chemical-analysis steps were proposed to reduce background values. Even without these extra steps, the technique for handling the samples was more complex than the methods using pigment dye or oil aerosol and had the additional problem of requiring exposure in an atomic pile.

In England, Hay and Pasquill (1959) have used Lycopodium spores in diffusion tracer studies. The spores were released from a point source and collected downwind by natural impaction on exposed cylinders. Sample catches were evaluated by microscopically identifying the distinctive spore particles.

6-11.4 Gaseous Tracer Techniques

There have been a number of attempts to develop a tracer technique in which a gas could be used as the tracer material. Most have been unsuccessful, largely because of the limitation in the sensitivity of available analytical procedures. Although the aerosol tracer materials, such as the fluorescent pigments and dyes, can be detected in amounts of 10^{-10} g, the limit of sensitivity for most gaseous materials is about 10^{-7} g. However, two gases, Freon and sulfur dioxide, have been successfully used as tracers. A third material, tritiated ethane, was studied (Shapiro, Gibbs, Field, and Dillon, 1955), but a solution could not be found for high background interferences encountered. Mercury vapor has also been considered, but sufficiently sensitive analytical methods could not be found (Haines, Cember, and Hemeon, 1956).

Argonne National Laboratory developed techniques to use Freon 12 (dichlorodifluoromethane) as a tracer gas (Schultz, 1957), and further improvements have been reported by Collins, Bartlett, Turk, Edmonds, and Mark (1965). The gas was released from a cylinder through proper flowmeters and control valves. Evacuated flasks were used to collect the samples. The samples were analyzed for Freon by special techniques using a modified version of a com-

mercial halogen leak detector or gas-chromatograph techniques. Concentrations of 0.1 ppm can be measured with the leak detector and of 0.05 ppm in a 5-ml air sample with the gas chromatograph. Field tests have been successful, but further development is necessary. Collins et al. also mention that sulfur hexafluoride can be used when the analysis is carried out by gas chromatography.

Sulfur dioxide is a common air pollutant, and there are good methods for measuring it in the atmosphere, either instrumentally or chemically (Giever and Cook, 1960, and West and Gaeke, 1956). Sulfur dioxide has been used in extensive tracer diffusion studies conducted as part of Project Prairie Grass (see Sec. 4-4.2.1, Chap. 4). In this program liquid-filled bubbler samplers were used, and the results were obtained by conductivity analysis of the bubbler solution. Emission systems for compressed gases, such as sulfur dioxide or Freon, must be carefully designed to prevent large variations in the emission rate due to adiabatic cooling.

The advent and rapid growth of gas chromatography as an analytical technique has made available to the research meteorologist means for carrying out diffusion experiments on a scale and with a sensitivity and precision not previously attainable.

Gas chromatography is a technique for separating complex mixtures of volatile materials into their individual components. A carrier gas (usually nitrogen, argon, or helium) sweeps the mixture, injected as a pulse, through a long tubular column packed with an inert porous solid. A nonvolatile liquid coated on the porous packing material functions as a solvent for the several components of the mixture being separated. A component that is completely volatile and totally insoluble in this liquid will be swept through the column in the same time that it takes an element of the carrier gas to pass. Another component that is totally nonvolatile and completely soluble in this liquid will be dissolved in the liquid coating immediately upon entering the column and will never move from this point. Still other components will behave in intermediate fashions, depending on their volatilities and solubilities. In any mixture each component will possess its own combination of these properties of volatility and solubility, and the several components will there-

fore emerge from the column one by one in orderly procession. Selection of the best liquid phase and of column operating parameters, such as temperature, column length, and carrier-gas flow rate, ensures that degree of separation required for a specific problem with a minimum of effort.

A detector located at the end of the chromatographic column generates a minute electrical signal whenever the emerging carrier gas contains any other material. An amplifier and recorder convert this signal into a visual record. In such a record each component of a mixture is represented by a peak, and the quantity of each component present is proportional to the area under its peak.

An outstanding feature of gas chromatography is the sensitivity with which it can detect and measure a compound in the presence of an overwhelming quantity of one or many others. Present-day ionization detectors can measure parts-per-million concentrations of nearly any compound that may be encountered. This capability has often been extended to the parts-per-billion range. Parts-per-trillion sensitivity is far from unknown, and even this has been exceeded in a few special cases.

For further information regarding gas chromatography, the reader is referred to Burchfield and Storrs (1962). A review article by Altshuller (1963) bears closely on the present aspect and provides good bibliographic coverage.

An example of the direct application of gas chromatography to a meteorological problem is described in papers by Saltzman, Coleman, and Clemons (1966) and by Turk, Edmonds, Mark, Collins, and Bartlett (1965). These workers have demonstrated that certain selected materials, such as sulfur hexafluoride, can be used in atmospheric tracer tests. The sensitivity demonstrated is such that detailed mapping of trajectories extending over several hundreds of miles is considered feasible.

6-11.5 Tracer Techniques Based on Visible Plumes

In addition to the detailed studies possible with aerosol and gaseous tracers, diffusion information can be obtained from observations of visible plumes. This information can be either qualitative plume trajectory and behavioral data or detailed diffusion estimates

based on careful measurement of the visible plume.

Measuring the density of a photograph of visible smoke offers the possibility of directly estimating atmospheric diffusion (see Sec. 3-3.4.2, Chap. 3; Record, 1952; Ronne, 1959; and Högström, 1964). Stereoscopic techniques can be used to size individual smoke parcels in space (Clark, 1956). For visual studies smoke can be generated for short periods of time by smoke pots, flares, or other pyrotechnic devices and for extended periods by an oil aerosol generator, such as the Chemical Corps M2 model.

Visual tracer studies have involved both surface and elevated release points from either tethered balloons or a tower. Several smoke sources ignited simultaneously at different heights can be used to estimate the variations in diffusion conditions with altitude.

In one study program small black-powder charges carried aloft by a balloon were ignited, and the resultant smoke clouds were followed downwind (Sartor, Katz, and Katz, 1952). A radio-commanded smoke puffer for remote or balloon work has also been described (Randall and Clark, 1955).

Most smoke generators used in meteorological studies have been military types. The Army manual, *Military Chemistry and Chemical Agents* (Departments of the Army and Air Force, 1956), describes the several types of smoke that have been developed: titanium tetrachloride (FM), sulfur trioxide-chlorosulfonic acid solution (FS), aluminum-zinc oxide-hexachloroethane (HC), and white phosphorus (WP). The most satisfactory mixture is the HC. Disadvantages of the others are (1) that the high rate of hydrolysis of FM mixtures causes orifice clogging, etc., and corrosion is a definite problem, (2) that the FS mixture produces a sulfuric acid aerosol by absorption of moisture from the atmosphere and thus requires careful handling, and (3) that white phosphorus burns rapidly, is dangerous to handle, and is toxic.

The HC mixture burns with intense heat and smoke. By far the greater portion of the smoke is zinc chloride, which rapidly absorbs moisture from the air to form particles of effective screening size.

Colored smokes may be produced by volatilizing and condensing a mixture containing organic dyes. Standard military colors are red, green,

and yellow. Smoke candles and smoke pots can be obtained from a number of commercial firms since they are used in various air-conditioning tasks and as emergency signals. Marine supply houses are also a possible source.

Tracer sampling techniques fall into two classes: those in which the air sample is drawn directly into the detecting instrument and those in which the tracer is removed from the air sample and held for analysis at a later time. The oil aerosol photometer is an example of the former; filters used with pigment tracers are examples of the latter.

Portable field analyzers, such as the photometer, do not need further explanation because their form is fixed once the tracer method is decided upon.

Filter or bubbler sampling units, on the other hand, offer a wide choice of units. It is likely that the developments to date in this field can supply a wide variety of situations. Numerous different sampling units are described in the literature in such publications as the *Journal of the Air Pollution Control Association*, *Archives of Environmental Health*, and the *American Industrial Hygiene Association Quarterly*. A useful but incomplete compilation of air-sampling units is found in the *Encyclopedia of Instrumentation for Industrial Hygiene* (Yaffe, Byers, and Hosey, 1956). Most references describing tracer techniques also include descriptions of the field samplers used in the program, and, since many tracer studies have used similar sampling techniques, designs can be adapted from one program to another.

6-12 ATMOSPHERIC MEASUREMENTS WITH BALLOONS

Most meteorological observations necessary for the nuclear-energy industry have been made from sensors mounted on short or tall masts or towers. Occasionally, when measurements above tower heights are necessary, balloons have been used either as the sensor or as a platform for sensors. Since balloon techniques require the services of at least one observer and frequently more than one, their use in a long-term observation program results in a considerable cost.

Three primary types of balloon systems are used for obtaining meteorological information.

The first of these systems is the buoyant free balloon. In this system the horizontal motion of the rising balloon is used to infer the wind-speed profile. The rising balloon can carry pressure, temperature, and humidity sensors that transmit readings by radio to a ground station. A complete outline of these various techniques as practiced by the U. S. Weather Bureau and most other national meteorological services can be found in the Weather Bureau publications *Manual of Winds-Aloft Observations*, Circular O, and *Manual of Radiosonde Observations*, Circular P, both of which are available through the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C.

In the second type of balloon system, the balloon is tethered to a ground station, and the tether carries signals from sensors carried by the balloon. This system is sometimes called a wiresonde.

A multiconductor nylon-coated wire with braided fiber glass covering is often used both as the tether and the means for transmitting the signals. The data can be recorded automatically by a self-balancing bridge recorder or manually by an observer using a balancing bridge or reading the dials of other suitable electronic equipment. Atmospheric soundings using tethered systems have been made in the past at the Oak Ridge National Laboratory (Myers, 1952), at the National Reactor Testing Station (Humphrey, 1951), and more recently in England by Thompson (1962).

With the wiresonde a balloon or blimp with a volume of several tens of cubic meters is usually used. Commercially available blimps with a volume of 17.0 m^3 have been found very satisfactory. In this country helium is generally used as the inflating gas although hydrogen is also suitable. Measurements from tethered blimps at heights of 1500 m have been reported (F. B. Smith, 1961). Specially designed balloons with fins have desirable aerodynamic properties that provide greater stability and permit observations to somewhat greater heights than do conventional blimps.

The tethered-balloon technique is cumbersome and sometimes hazardous. During high winds the blimp is extremely hard to handle. Special precautions must be taken if there is danger of lightning or the buildup of static electricity. For this reason soundings are

avoided beneath or near convective clouds. Ordinarily the equipment must be well grounded, and the blimp upon its return to the surface must be grounded before it is touched.

The third type of balloon used in meteorological investigations has been designed to float at a constant density level. The constant-density-level balloon, with which the data in Sec. 4-11 of Chap. 4 was obtained, is constructed by filling a balloon made of an inelastic film with a lighter-than-air gas mixture at a pressure considerably above that at the computed flight altitude. Changes in the temperature of the superpressured gas within the balloon will not result in an appreciable balloon-volume change. Thus the buoyancy force will remain relatively constant, and the balloon will respond only to ambient density changes and to the forces exerted by the three-dimensional wind field. Constant-density-level balloons used to date have not been capable of maintaining their height in precipitation.

Balloons can take a variety of shapes, but the tetrahedron shape has been most commonly used. The balloon in Fig. 6.29 has a nominal volume of about 1 m^3 and is made of Du Pont

Fig. 6.29—A superpressured constant-level tetrahedron balloon (tetraon).

Mylar, with a thickness of 2 mils (0.002 in.). Such balloons are called tetrooms—a combination of the words tetrahedron and balloon. The tetrooms are inflated to a superpressure of several tens of millibars above ambient pressure and at the floating level may have a superpressure of slightly under 100 mb. Mylar has a high stress-to-strain ratio; thus its volume changes little during its rise, i.e., a few percent for 100 mb superpressure (Fig. 6.30). From information concerning tetroom volume as a function of superpressure, the total weight of the system, and the variation of atmospheric density as a function of height, the tetroom floating level can be predicted. This level can be varied by adding or subtracting weights carried by the system. As with the wiresonde blimps, helium is ordinarily used as the inflating gas in the United States, but hydrogen is also suitable.

These balloons can be tracked by three different methods. The first consists of the double-theodolite technique with a base line exceeding 1 km. This, of course, suffers from the usual difficulties inherent in visual tracking, such as loss of the target in clouds and limitations in the length of the run. The second method involves tracking with radar. The balloon material can be metalized to serve as a passive reflector, or auxiliary reflectors can be used. The latter has been more satisfactory. A difficulty associated with tracking by reflection is the interference due to ground clutter at large

Fig. 6.30—Volume vs. superpressure curves for three different tetrooms.

distances when the elevation angle is low. The third and most successful technique uses a 403 MHz transponder attached to the tetroom. The difficulties experienced with the other two techniques are thereby eliminated. Both the X-band (3 cm) M33 and the S-band (10 cm) WSR-57 radars can be used in these measurements. The radar signal triggers the transponder to transmit its 403 MHz signal, which is received by the radar. The circuitry of the radar is modified to use this signal in providing data on the range and azimuth and elevation angles. The radar-transponder system can be used to track constant-level balloons to distances of well over 100 km even when the balloon floats at 1000 m or less.