

Thermocouple Psychrometers

Thermocouple hygrometers are generally accepted as the standard for measurement of plant-water potential (Oosterhuis et al., 1983; Savage et al., 1983a). They measure vapor pressure in a small chamber by using either a psychrometric (wet bulb/dry bulb) or dewpoint technique. Because both are used, the more general term thermocouple hygrometer is sometimes used rather than thermocouple psychrometer (Campbell and Campbell, 1974). However, most people call the instruments thermocouple psychrometers.

We use thermocouple psychrometers to determine water potential by measuring relative humidity. But we actually are measuring a temperature depression (either the wet-bulb or the dewpoint temperature depression). To relate the temperature depression to relative humidity, we use the psychrometric equation. Let us look at these points now in detail.

18.1 RELATION BETWEEN WATER POTENTIAL AND RELATIVE HUMIDITY

The use of thermocouple psychrometers to measure water potential is based on a sound physical–chemical foundation. A definite, quantitative relation exists between water potential of a sample and the relative vapor pressure above it (Barrs, 1968, p. 281; Rawlins, 1972; Savage and Cass, 1984), as follows:

$$\Psi = [(RT)/V_w^0] \ln (e/e^0), \quad (18.1)$$

where Ψ = water potential, R = ideal gas constant, T = absolute temperature (K), V_w^0 = molar volume of pure water, e = partial pressure of water vapor in air, e^0 = saturated vapor pressure, and e/e^0 = relative humidity. Equation (18.1) is called the Kelvin equation (Rawlins, 1972).

Except for T , which is always in K, units vary according to values used. If Ψ is expressed in bars, then $R = 83.2 \text{ cm}^3 \text{ bar/mole degree}$, $V_w^0 = 18.048 \text{ cm}^3/\text{mol}$ at 20°C , e and e^0 = bars (or millibars). Other values

of R are: 0.0821 l atm/mole degree; 0.0832 l bar/mole degree; and 82.1 cm³ atm/mole degree. We remember that $K = ^\circ C + 273.16$. Absolute zero is at -273.16 (or -459.69 $^\circ F$) and it is the temperature at which a gas would show no pressure if the general law for gases would hold for all temperatures (Weast, 1964, p. F-29). Absolute zero is the hypothetical point at which a substance would have no molecular motion and no heat (Webster's New World Dictionary of the American Language, 1959). The Kelvin scale of temperature measured is in degrees centigrade from absolute zero and is named after William Thomson, Baron Kelvin. (For a biography of William Thomson, see the Appendix, Section 18.11.) In 1967 the 13th General Conference on Weights and Measures adopted the unit *kelvin* (K) as its standard for temperature, making it one of the seven base units of Le Système International d'Unités (SI system; see Chapter 2, Section 2.2). The definition of the 1967 thermometric unit replaced degrees Celsius and degrees absolute in scientific work (Patterson, 1988). The kelvin now is defined as the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water (Haynes, 2013, pp. 1–22). (The *triple point* is defined as the point in *pressure, temperature* space where the solid, liquid, and gas phases of a substance are in thermodynamic equilibrium. The corresponding temperature and pressure are called the triple point temperature and the triple point pressure (Haynes, 2013, pp. 2–67). For water, the triple-point temperature is 0.01 $^\circ C$ and the triple-point pressure is 611.657 Pa (Haynes, 2013, pp. 6–9)).

A measurement of relative vapor pressure, or of some related property, gives the water potential of the sample directly, provided that the sample and the space in the chamber have first come to equilibrium. Suitable electrical transducers are thermocouple psychrometers (Barrs, 1968, p. 281) or, using the more general term, thermocouple hygrometers. A hygrometer is an instrument for measuring humidity or the moisture in the air. A psychrometer is a type of hygrometer in which the humidity is measured with wet and dry bulb thermometers. The initial combining form of the word is *psychro-*, which comes from the Greek word *psychros*, meaning “cold” (Webster's New World Dictionary of the American Language, 1959).

18.2 THERMOELECTRIC EFFECTS

Before discussing thermocouple psychrometers used in plant-water measurements, let us review the thermoelectric effects on which they are based. Figure 18.1 shows an electric circuit of two metals formed into two junctions. If a temperature difference exists between the two junctions, an electric current will flow between them (Barrs, 1968, p. 287). This is the Seebeck effect, named after Johann Seebeck in Berlin, who

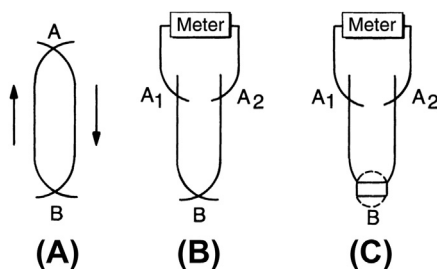


FIGURE 18.1 Thermoelectric effects used in thermocouple psychrometry. (A) The Seebeck effect; current flows due to a temperature difference between junctions A and B; (B) Measurement of temperature difference between A and B. B may initially be cooled by the Peltier effect (Spanner psychrometer); (C) Maintenance of permanently wet junction at B (Richards-and-Ogata psychrometer). From [Barrs \(1968\)](#). Reprinted by permission of Academic Press.

discovered it in 1821 ([Shortley and Williams, 1971](#), p. 578). Holding the two junctions at different temperatures causes a current when no other source of electromotive force (emf) is present. The Seebeck effect is used in solid-state physics to generate currents ([Ong, 2008](#); [Uchida et al., 2008](#)).

If both junctions are initially at the same temperature, then, by passing an electric current through them, one junction will cool and the other will heat ([Barrs, 1968](#), p. 287). This is the Peltier effect, named after Jean Charles Athanase Peltier in Paris, who described the phenomenon about 1834 ([Shortley and Williams, 1971](#), p. 577). (For a biography of Peltier, see the Appendix, Section 18.9) The rates of heat generation and absorption are proportional to the current. When the current is reversed, the roles of the two junctions are reversed. Although the Peltier current tends to heat the reference junction, while the free junction is cooled, the rise in temperature is negligible due to the rapid outflow of heat along the massive copper wires attached to junctions A₁ and A₂ ([Figure 18.1](#)) or the junctions at the top of the thermocouple psychrometer ([Figure 18.2](#), right).

The Peltier effect can give only a small degree of cooling, but it is of interest biologically. For example, if the osmotic pressure of a solution is 10 atm, depression of the dewpoint temperature is about 0.124 °C at 25 °C, which corresponds to a relative humidity of 99.3%. For a dewpoint depression of 1 °C, osmotic pressure would be 80 atm (94.3% relative humidity) ([Spanner, 1951](#)).

18.3 JOULE HEATING

The temperature changes associated with the Peltier effect appear in addition to increases in temperature resulting from the normal joule heating, which we now review. (For a biography of Joule, see the

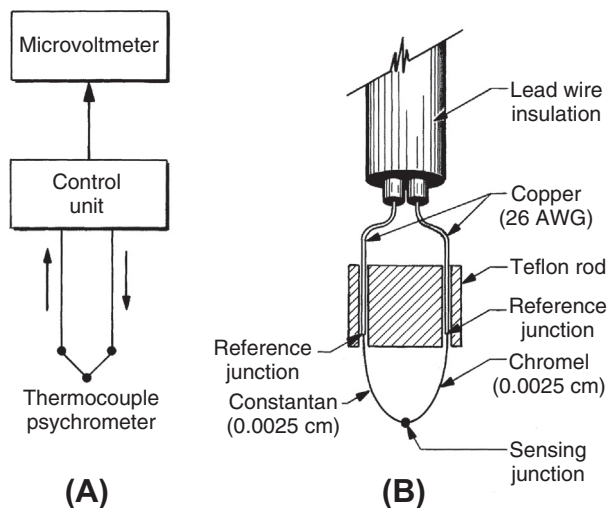


FIGURE 18.2 A Peltier thermocouple psychrometer system used to measure water potential consisting of (A) a microvoltmeter, control unit, and the thermocouple psychrometer; (B) a single-junction Peltier thermocouple psychrometer illustrated in detail. From [van Haveren and Brown, 1972](#). Reprinted by permission of the Utah Agricultural Experiment Station.

Appendix, Section 13.10.) The work W in joules done in transferring in a circuit a charge of q coulombs between two terminals having a potential difference V volts is

$$W = qV = It(V) = IVt, \quad (18.2)$$

[Remember from Chapter 12, Section 12.2 on electrolysis, that I (amperes) = q (coulombs) / t (s).] Because $V = IR$, where R is resistance, $IVt = I(IR)t = I^2Rt$. Thus the electrical energy in joules converted into heat in a conductor of resistance R ohms carrying a current I amperes is

$$W = I^2Rt, \quad (18.3)$$

which is called Joule's law of heating ([Schaum, 1961](#), p. 153). Because 1 Joule = 0.239 calories, the heat H in calories developed in the conductor is

$$H = 0.239I^2Rt. \quad (18.4)$$

By use of low-resistance pieces of metal, it is possible, in spite of Joule heating, to get one of the junctions to cool below room temperature ([Shortley and Williams, 1971](#), p. 578). The maximum degree of cooling due to the Peltier effect is limited by Joule heating.

The value of a thermocouple, when used as a thermometer (measurement of temperature difference between two junctions), depends on the fact that the net emf developed is directly related to the temperature

difference between the junctions. For small temperature differences, it is approximately proportional to the temperature difference (Shortley and Williams, 1971, p. 578).

The thermoelectric effect is not an unmixed blessing. In any electrical apparatus in which the circuits contain different metals or even different grades of the same metal, temperature differences arising from any cause will set up small “thermal emfs” and “thermal currents”, as they are called. Even when a piece of equipment is constructed of a single grade of metal, small thermal emfs exist if there are temperature differences between different portions of the equipment. These emfs appear as a result of a phenomenon known as the Thomson effect. If a copper rod is heated at one end and cooled at the other, a difference of potential is observed between the ends. This Thomson difference of potential arises from a temperature dependence of the density of free electrons in the metal (Shortley and Williams, 1971, p. 579).

18.4 THERMOELECTRIC POWER

The thermoelectric power of thermocouples varies. One of the most commonly used thermocouples in plant-water measurements is constantan–chromel, because it is commercially available. Its thermoelectric power is $60 \mu\text{V}/^\circ\text{C}$. Bismuth–bismuth + 5% tin is preferred by some workers, because its thermoelectric power ($126 \mu\text{V}/^\circ\text{C}$) is twice as high as that of constantan–chromel (Barrs, 1968, p. 289). A further point in favor of the bismuth–bismuth + 5% tin thermocouple is that the maximum Peltier cooling possible is 4.9°C as against 1.5°C for constantan–chromel. There is a maximum Peltier cooling (dewpoint temperature). If the temperature depression is greater than the dewpoint-temperature depression, it is not possible to condense dew on the wet junction. With most biological systems, this is not a limitation, because such low potentials usually are not encountered. For example, if one uses constantan–chromel, the lower useful limit is about -65 bars (Barrs, 1968, p. 291), which is below the potentials measured in most plants.

18.5 RELATIONSHIP BETWEEN VAPOR PRESSURE AND TEMPERATURE

As stated earlier, we obtain water potential by observations of vapor pressure. The changes in temperature measured are actually minute. The relation between vapor pressure and temperature is as follows:

$$e = e_w^0 - \gamma(T_A - T_W), \quad (18.5)$$

where e = partial pressure of water vapor in air; e_w^o = saturated vapor pressure at the wet-bulb temperature; T_A = dry-bulb temperature (air temperature); T_W = wet-bulb temperature; γ = psychrometric constant, taken to be $0.658/^\circ\text{C}$ at 20°C and 1000 mb pressure (Monteith, 1973, p. 221). (γ is 0.655 at 15°C ; 0.662 at 25°C ; 0.665 at 30°C ; 0.668 at 35°C ; and 0.671 at 40°C —all at 1000 mb.) The interested reader can study Monteith (1973, pp. 171–173) or Monteith and Unsworth (2013, pp. 221–224) for an explanation of the psychrometric constant and the basis for Eqn (18.5).

The Smithsonian Meteorological Tables (List, 1951) give exact values of saturation vapor pressure over water in metric and English units. In the metric units, values for saturation vapor pressure over water in millibars are given for temperatures ranging from -50.0 to 120.0°C , in tenths of degree increments (List, 1951; pp. 351–353, Table 94). Rigorous expressions for the dependence of saturation vapor pressure on temperature are obtained by integrating the Clausius–Clapeyron equation (Monteith and Unsworth, 1990, p. 8; 2013, p. 11). Many authors have proposed simpler equations for estimating the saturation vapor pressure of water at different temperatures. Perhaps the most useful form is the Tetens (1930) formula (Ham, 2005). Values of saturation vapor pressure from the Tetens formula are within 1 Pa of the exact values from -5 to 35°C (Monteith and Unsworth, 1990, p. 10; 2013, p. 13). The Tetens formula, as given by Murray (1967; see his Eqn 6), is

$$e_s = 6.1078 \exp[a(T - 273.16)/(T - b)] \quad (18.6)$$

where $a = 17.2693882$ and $b = 35.86$.

Buck (1981) also gives a form of the Tetens formula, and most microclimatologists now use the Buck formula (Jay M. Ham, Department of Agronomy, Kansas State University, personal communication, December 30, 2003). Ham (2005) compares the coefficients in the Murray (1967) and Buck (1981) formulas.

To avoid the necessity of knowing coefficients, we can use Eqn (18.5) and Table 94 from List (1951) to determine the partial pressure of water vapor in air (e), as well as relative humidity (RH), and vapor pressure deficit (VPD). van Haveren and Brown (1972, pp. 266–277) also give tables of saturated vapor pressure over water both in mb and mm Hg. Or one can get values from Monteith (1973, pp. 222–223) or Monteith and Unsworth (1990, p. 269, 2008, p. 397, and 2013, p. 377). Monteith (1973) gives values in mb, and Monteith and Unsworth (1990, 2008, and 2013) give values in kPa, for saturation vapor pressure at temperatures ranging from -5 to 45°C . Our method is simple. All we need is Eqn (18.5) and Table 94 to determine e , RH, and VPD.

18.5.1 Sample Problem

Assume that the dry-bulb temperature is 27.2 °C and the wet-bulb temperature is 23.9 °C. Find e , RH, VPD, and dewpoint temperature (T_{dewpoint}). Let $\gamma = 0.66/^{\circ}\text{C}$.

Solution: From Table 94 in [List \(1951\)](#), we find at 27.2 °C, $e^{\circ} = 36.070$ mb (e° = saturated vapor pressure at the dry-bulb temperature); at 23.9 °C, $e_w^{\circ} = 29.652$ mb (e_w° = saturated vapor pressure at wet-bulb temperature).

Putting the known values in [Eqn \(18.5\)](#), we get:

$$e = 29.652 - [(0.66/^{\circ}\text{C}) (27.2^{\circ}\text{C} - 23.9^{\circ}\text{C})] = 27.474 \text{ mb.}$$

$$\text{RH} = e/e^{\circ} = 27.474 \text{ mb}/36.070 \text{ mb} = 0.76\% \text{ or } 76\%.$$

$$\text{VPD} = e^{\circ} - e = 36.070 \text{ mb} - 27.474 \text{ mb} = 8.596 \text{ mb.}$$

$$T_{\text{dewpoint}} = 22.6^{\circ}\text{C}.$$

(Read Table 94 backwards for dewpoint temperature; temperature for saturated vapor pressure of 27.474 mb = 22.6 °C.)

18.6 CALIBRATION

Each thermocouple psychrometer is calibrated to yield an answer in units such as bars, megapascals, or atmospheres. Calibration solutions are often NaCl because water potentials of sodium-chloride solutions at different molalities have been published by [Lang \(1967\)](#) and have been reproduced (e.g., see [Barrs, 1968](#), p. 288; [Brown and van Haveren, 1972](#), pp. 304–305). A table of water potentials of potassium-chloride solutions also has been published ([Rawlins and Campbell, 1986](#)). Care must be taken that the filter paper soaked with the salt solution is exposed in the same way as subsequent samples to minimize effects of changed geometry ([Barrs, 1968](#), p. 294).

The calibrating solution is put on filter paper in the thermocouple psychrometer chamber and the sample is equilibrated. Solutions take less time for equilibration than do plant samples; a solution may take an hour or less for equilibration, depending upon the concentration. After equilibration, a cooling current (e.g., 3 mA for 15 s) is passed through the thermocouple psychrometer. A microvoltmeter is used to measure the microvolt output of the different salt solutions. Salt solutions varying from 0.05 molal NaCl (−2.3 bars at 25 °C) to 1 molal NaCl (−46.4 bars at 25 °C) cover the range of interest when measuring plant-water potential. Most plants are severely wilted well above −46.4 bars. After calibration, the plant tissue is put in the chamber, using the same geometry for the sample as was used for the filter paper. The tissue is equilibrated. This

usually takes 2–3 h. A cooling current again is passed through the thermocouple psychrometer, and the microvolt output is recorded. From the calibration curve, the water potential of the tissue is determined.

18.7 IMPORTANCE OF ISOTHERMAL CONDITIONS WHEN MAKING MEASUREMENTS

The measurements of plant-water potential made with thermocouples must be done under isothermal conditions. [Rawlins and Dalton \(1967\)](#) (summarized by [Savage and Cass \(1984\)](#)) point out four ways in which temperature affects the measurements:

1. Through the relationship between water potential and relative humidity ([Eqn \(18.1\)](#));
2. Through the temperature dependence of the relationship between wet-bulb depression and vapor pressure ([Eqn \(18.5\)](#));
3. Through differences in temperature between the sensing junction of the thermocouple and the sample (arising, for example, from respiration by the tissue);
4. Through changes of temperature within the cavity formed by the thermocouple psychrometer and sample, which will alter the relative humidity of the air in the cavity, if water vapor cannot be exchanged with the surrounding system.

In the first two cases (temperature dependence of water potential on relative humidity and temperature dependence of wet-bulb depression on relative humidity), the errors are relatively small, and are about 0.3%/°C and 2%/°C, respectively ([Rawlins and Dalton, 1967](#)). These errors can be reduced by following suitable calibration procedures ([Savage and Cass, 1984](#)). Heat-of-respiration effects are corrected by reading the psychrometer with its free junction first dry and then wet ([Barrs, 1968](#), pp. 302–303 and 311–312). By using thermocouple walls with adequate conductivity, temperature effects due to number 4 above can be minimized and will not be significant ([Rawlins and Dalton, 1967](#)). If one cannot take readings at a constant temperature, [Comstock \(2000\)](#) tells how to convert readings made under variable temperature conditions to equivalent readings expected if measured at 25 °C.

There are several other sources of error, in addition to those caused by temperature. They include resistance to diffusion of water vapor into or out of a leaf, adsorption of water on the walls of the container, effects of excision of leaves from plants, and surface contamination. Errors resulting from low tissue permeability are probably negligible, unless leaves are heavily cutinized ([Barrs, 1968](#), p. 311). Adsorption errors can be minimized by using Teflon for the sample container.

Cut-edge effects can be decreased by using samples with a small cut-edge-to-volume ratio (Barrs, 1968, p. 307–308; Nelsen et al., 1978). Extraneous dust and soil can be easily washed off. But water potential apparently cannot be measured reliably in salt-extruding species such as cotton (Barrs, 1968, p. 309).

18.8 TYPES OF THERMOCOUPLE PSYCHROMETERS

Four types of instruments with thermocouples are in use to measure water potential of plants:

1. Isopiestic thermocouple psychrometer (Boyer, 1972a,b) (Figure 3) in which solutions of varying concentrations are put manually on the wet junction of the thermocouple psychrometer. Boyer (1972a) uses sucrose solutions (p. 53, legend to his Figure 18.3). The isopiestic solution is the solution that has the same vapor pressure

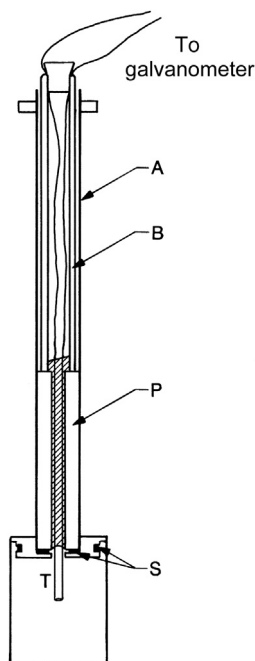


FIGURE 18.3 Thermocouple for making isopiestic determinations. The psychrometer chamber and barrel are made of brass and are submerged in a constant-temperature water bath. Key to symbols: barrel, A; Plexiglas tube, B; plunger heat sink, P; diagrammatic representation of O-ring seal (coated with stopcock grease) for chamber and seal of stopcock grease for plunger, S; thermocouple with ring junction, T. From Boyer (1972). Reprinted by permission of the Utah Agricultural Experiment Station.

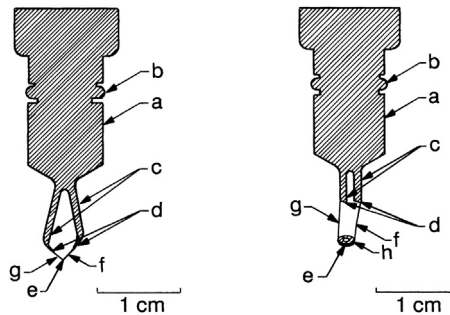


FIGURE 18.4 Left, Silhouette of Spanner-type thermocouple psychrometer; Right, silhouette of Richards-and-Ogata-type thermocouple psychrometer. Symbols: a, brass mount; b, O-ring seal; c, twin core, PVC-covered copper flex, bared in this region; d, reference junction; e, free junction; f, chromel-P 0.001 in (0.0254 mm) diameter; g, constantan 0.001 inch (0.0254 mm) diameter; h, silver cylinder. From *Barrs (1968)*. Reprinted by permission of Academic Press.

as that of the tissue and produces no thermocouple output (the “null point”).

2. The Peltier thermocouple psychrometer ([Figure 18.4](#), left) in which the wet junction is cooled, using the Peltier effect, to the dewpoint temperature. The junction then quickly rises to the wet-bulb temperature. This thermocouple psychrometer is also called the Spanner thermocouple psychrometer, named after [Spanner \(1951\)](#), who described the instrument. The degree of cooling is a function of the water potential of the tissue.
3. The thermocouple psychrometer in which a drop of water is put manually on the wet junction ([Figure 18.4](#), right; [Figure 18.1](#), right), instead of having a cooling current form the drop of water, as is done with the Peltier thermocouple psychrometer. This instrument is known as the Richards-and-Ogata thermocouple psychrometer or just the Richards thermocouple psychrometer, named after [Richards and Ogata \(1958\)](#), who developed the psychrometer. As with the Spanner thermocouple psychrometer, the degree of cooling is a function of the water potential of the tissue.

The Richards-and-Ogata thermocouple psychrometer is similar to the isopiestic one in that both require a liquid to be placed on the wet junction. The liquid is sucrose in Boyer’s isopiestic method and water in the Richards-and-Ogata thermocouple psychrometer.

4. The dewpoint hygrometer ([Neumann and Thurtell, 1972](#)) ([Figure 18.5](#)) in which the wet junction is cooled to the dewpoint and stays at the dewpoint for the measurement. This method uses the Peltier effect to cool the wet junction, but differs from the Peltier thermocouple psychrometer in that it detects the dewpoint

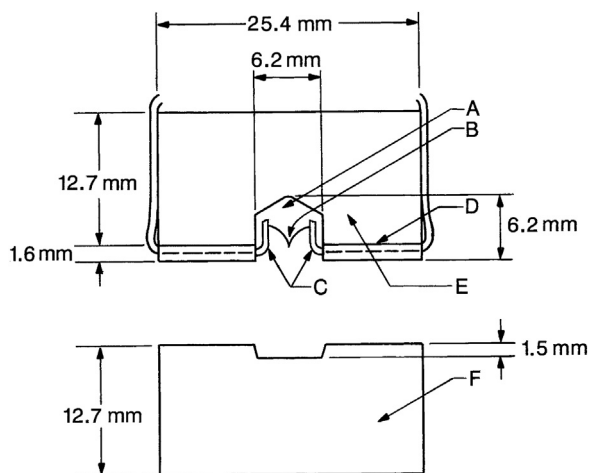


FIGURE 18.5 Cross-section view of leaf hygrometer. A, cavity; B, thermocouple; C, posts supporting thermocouple; D, faceplate; E, cavity containing section; F, base plate. From Neumann and Thurtell, 1972. Reprinted by permission of the Utah Agricultural Experiment Station.

depression rather than the wet-bulb depression (Neumann and Thurtell, 1972). Neumann and Thurtell (1972) reported that a dewpoint measurement is preferable to a wet-bulb measurement in determination of water potential, because with a dewpoint measurement, no net water exchange occurs at the wet junction, allowing the measurement to be made without disturbing the vapor equilibrium within the chamber.

The dewpoint technique is similar to the isopiestic procedure (Boyer, 1972a,b). Both methods adjust the vapor pressure of the droplet on the wet junction until it is in equilibrium with the vapor within the chamber. In the isopiestic technique, the vapor pressure of the droplet is adjusted by changing the osmotic potential. With the dewpoint hygrometer, the vapor pressure is regulated by controlling the temperature of the droplet (Neumann and Thurtell, 1972).

Dewpoint hygrometers were designed to minimize the need for temperature control (Neumann and Thurtell, 1972; Campbell and Campbell, 1974). Internal temperature gradients between the sample and the thermocouple, however, must be small (Neumann and Thurtell, 1972; Shackel, 1984). Savage et al. (1981a, 1983a) reported that dewpoint hygrometers were less sensitive to temperature than thermocouple psychrometers, but the accuracy of dewpoint hygrometers was dependent upon the correct setting of the dewpoint cooling coefficient. Measurements made with thermocouple psychrometers (isopiestic, Spanner,

Richards-and-Ogata) require careful temperature control (Rauscher and Smith, 1978; Bristow and de Jager, 1980; Slack and Riggie, 1980; Bruckler, 1984).

In situ hygrometers, which measure the water potential of intact plants, have been extensively studied (Savage et al., 1979, 1981a,b, 1982, 1983a; McBurney and Costigan, 1982; Savage and Cass, 1984). They can be used either in the psychrometric or dewpoint mode. Several designs have been described (Neumann and Thurtell, 1972; Michel, 1977, 1979; Brown and McDonough, 1977), including one that is commercially available (Campbell and Campbell, 1974) (Figures 18.6 and 18.7) and one that measures water potential of the soil (McAneney et al., 1979). The advantage of an in situ measurement is that tissue does not need to be excised to determine water potential, which avoids errors due to cutting (Campbell and Campbell, 1974; Baughn and Tanner, 1976b; Nelsen et al., 1978; Savage et al., 1984a).

Measurements obtained with in situ hygrometers have been compared to those obtained with other methods. Baughn and Tanner (1976a) found that readings of water potential of plants in a greenhouse, made with a pressure chamber, did not agree with those made with an in situ hygrometer. The pressure chamber gave a lower (drier) water potential than the hygrometer in the high potential range and a higher potential than the hygrometer in the dry potential range. Under field conditions, however,

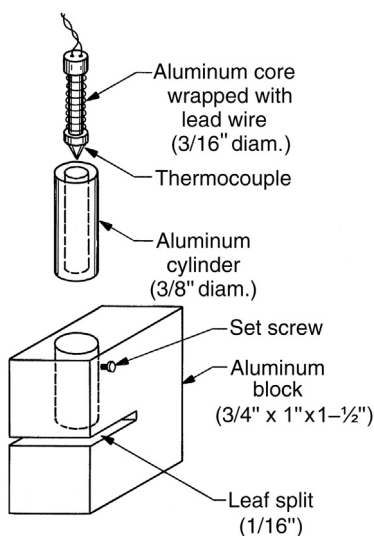


FIGURE 18.6 Expanded view of in situ leaf hygrometer. From Campbell, G.S., Campbell, M.D., 1974. *American Society of Agronomy*, Madison, Wisconsin. Reprinted by permission of the American Society of Agronomy.

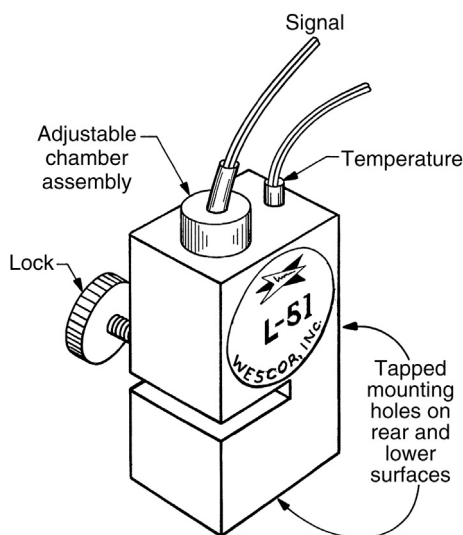


FIGURE 18.7 A commercially available in situ hygrometer. From a figure in a brochure from Wescor, Inc., Logan, Utah. Reprinted by permission of Wescor, Inc., Logan, Utah.

water potentials measured with a hygrometer were about 0.2 MPa (2 bars) greater (less negative) than those measured with a pressure chamber (Brown and Tanner, 1981). Brown and Tanner (1981) felt that the higher potential obtained with the hygrometer was caused by its covering the leaf and decreasing transpiration. In contrast, Savage et al. (1983b) found that the water potential of field-grown plants, obtained with an in situ hygrometer, agreed well with that measured by using a pressure chamber.

In all these experiments (Baughn and Tanner, 1976a; Brown and Tanner, 1981; Savage et al., 1983b), the cuticle of the leaf was abraded to obtain rapid vapor equilibrium between the leaf and the hygrometer. Savage et al. (1984b) showed that the water potential was dependent upon the amount of abrasion. Coarse abrasion resulted in deep cavities in the epidermis and large variability in readings of water potential. Turner et al. (1984) said that in situ hygrometers should not be used on plants with thick cuticles because, even after abrasion, the instruments gave inaccurate values of water potential.

Oosterhuis et al. (1983) compared measurements of water potential obtained by using three instruments: an in situ hygrometer, a pressure chamber, and screen-caged psychrometers, described by Brown and Bartos (1982) (Figure 18.8). They found that measurements made with the in situ hygrometer gave reliable, nondestructive measurements of water potential, if precautions were followed. These included thermal insulation of the aluminum housing, careful positioning of the hygrometer to

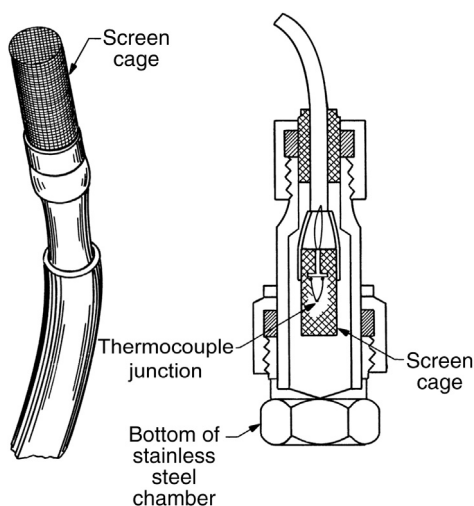


FIGURE 18.8 Screen cage psychrometer. *From a figure in a brochure from J.R.D. Merrill Specialty Equipment, Logan, Utah.*

the leaf to minimize shading, and allowing adequate time for vapor equilibrium.

The Spanner and dewpoint methods are more popular than the isopiestic and Richards-and-Ogata methods. The isopiestic technique takes more time than the other three techniques. It is not readily adaptable to automatic measurements (Boyer, 1972a). The solutions must be put quickly on the wet junction to minimize evaporation, which changes their potentials. The chamber holding the thermocouple is perturbed each time a new solution is introduced into it. With the Spanner, Richards-and-Ogata, and dewpoint methods, the chamber remains closed after the sample is placed in it. Instruments commercially available utilize the Spanner or dewpoint methods (Figures 18.9 and 18.10). Boyer's laboratory used the isopiestic procedure (Matthews et al., 1984). The laboratory of Robert E. Sharp of the University of Missouri also has used the isopiestic procedure (personal communication, December 3, 1994).

All four techniques require precise electrical measurements and expensive equipment: for example, voltmeters that can read in the microvolt range. Measurements of water potential using thermocouple psychrometers were not possible until about the early 1960s, when microvoltmeters came on the market. Microvoltmeters are not necessary to determine plant-water potential, and it can be measured, using liquid-phase or vapor-phase techniques, with simple equipment (Barrs, 1968, pp. 263–285). Zyalalov (1977) described a method to measure water potential that used only salt solutions, capillary tubes, a weighing bottle with a greased ring to hold the capillary tubes, and a ruler. Learning how to take proper measurements with thermocouple psychrometers requires much

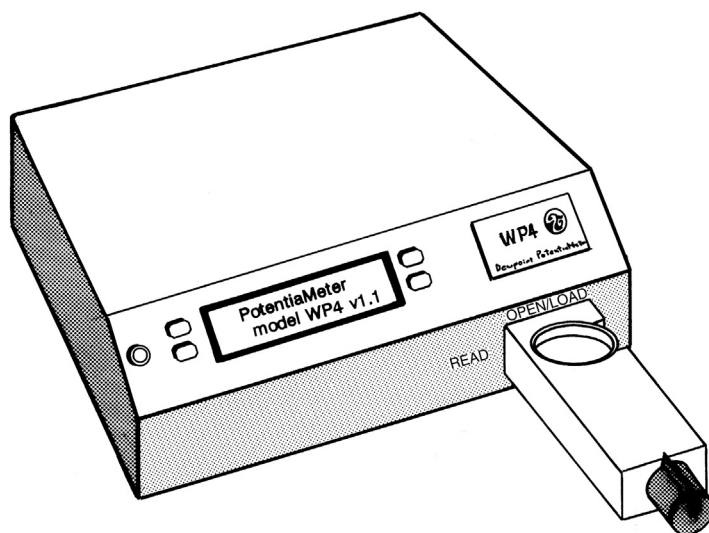


FIGURE 18.9 A dewpoint hygrometer. From a figure in a brochure from Decagon, Pullman, Washington. Reprinted by permission of Decagon Devices, Inc., Pullman, Washington.

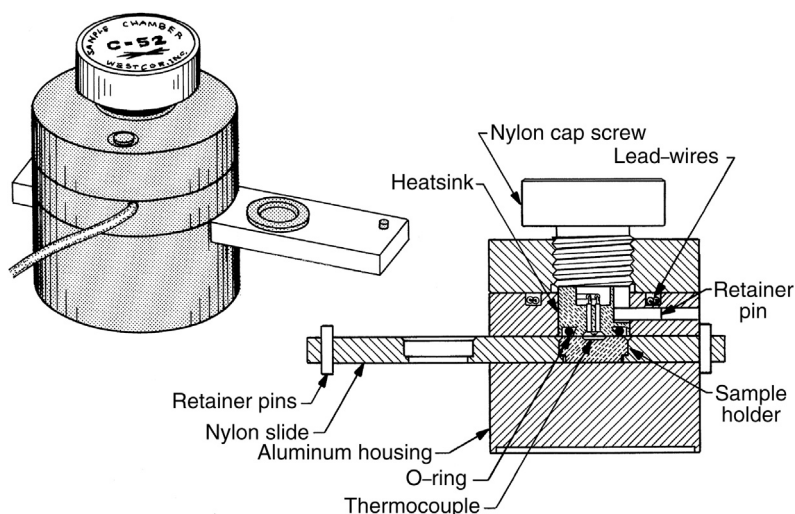


FIGURE 18.10 An instrument that operates either as a hygrometer or psychrometer. It measures water potential of small samples in the laboratory or in the field without requiring a constant temperature bath. The large aluminum casing insulates the sample from temperature changes. A thermocouple in an internal chamber functions either as a psychrometer (wet-bulb depression method) or a hygrometer (dew-point depression method), depending on the type of readout equipment employed. From a figure in a brochure from Wescor, Inc., Logan, Utah. Reprinted by permission of Wescor, Inc., Logan, Utah.

training (several months) and skill. Many precautions are required for accurate measurements ([Brown and Oosterhuis, 1992](#)). Most people do not have the time or dedication to learn how to use thermocouple psychrometers, which is why the pressure chamber is the most popular method to measure water potential (see Chapter 19).

18.9 APPENDIX: BIOGRAPHY OF J.C.A. PELTIER

Jean Charles Athanase Peltier (1785–1845), French physicist, was born at Ham (Somme), France, on February 22, 1785. He was originally a clock-maker, but retired at about the age of 30 to devote himself to experimental and scientific observations. He is best known for his discovery (1834) that an electric current produces, according to direction, either heat or cold at the junction of two dissimilar metals in a circuit. This is called the Peltier effect. Peltier is also remembered for introducing the concept of electrostatic induction. His papers, which are numerous, are devoted in great part to atmospheric electricity, waterspouts, the polarization of skylight, the temperature of water in the spheroidal state, and the boiling point at great elevations. There are also a few papers devoted to points of natural history. He died in Paris on October 27, 1845 ([McKie, 1971b](#)).

18.10 APPENDIX: BIOGRAPHY OF JAMES PRESCOTT JOULE

James Prescott Joule (1818–1889) was an English physicist who established the principle of the interconvertibility of the various forms of energy (i.e., the first law of thermodynamics), and whose name was given to an energy unit, the “joule” ([McKie, 1971a](#)). He was born at Salford, Lancashire, on Christmas Eve, 1818, into a famous brewing family and spent some of his early years working for the firm ([Hughes, 1989](#)). Eventually his scientific interests predominated. The requirements of brewing technology and the accountancy needed to run a business helped to mold his scientific attitudes. A spinal weakness at birth turned him into a hunchback, and this shy and unassertive man was always sensitive about his public appearances ([Hughes, 1989](#)). Science at the time of Joule was changing from being the affair of the gentleman devotee to being the occupation of the full-time professional, ensconced in the university laboratory. Joule was in the first category. Almost all of his research was carried out in his laboratory at home and at his own expense. His reticence often meant that his discoveries were attributed to more verbose and flamboyant researchers. Joule’s main interest lay in exact measurement and his special genius showed itself at its best in the invention of

methods for obtaining greater accuracy in quantitative experiments. He was systematic and hardworking (Hughes, 1989).

Joule found that the heat generated by the flow of electricity was proportional to the electrical resistance multiplied by the square of the current. His experimental skills firmly established the law of conservation of energy. We take this law for granted now, but in Joule's time the complete conversion of heat into work or work into heat was not conceivable (Hughes, 1989).

Except for some instruction from John Dalton (1766–1844; English chemist and physicist and originator of the atomic theory), Joule was self-taught in science. He early realized the importance of accurate measurement. In a long series of experiments, he studied the quantitative relation between electrical, mechanical, and chemical effects, and was thus led to his great discovery. Joule announced in 1843 his determination of the amount of work required to produce a unit of heat. This is called the mechanical equivalent of heat. He used several methods to show this. The best-known method produced heat from friction in water by means of paddles rotating under the action of a falling weight. His paddle-wheel experiment, which showed that any fluid could be heated merely by agitating it, is famous. Because of this simple fact, the water that has dropped 49 m over Niagara Falls is 0.11 °C higher in temperature than the water at the top of the falls (Hughes, 1989). In 1853, with W. Thomson (later Lord Kelvin; see next section), he researched the work done in compressing gases and the thermal changes gases undergo when forced under pressure through small apertures. Joule's *Scientific Papers* were collected and published in two volumes by the Physical Society of London (1885–1887). Joule died at Sale, Cheshire, on October 11, 1889 (McKie, 1971a).

18.11 APPENDIX: BIOGRAPHY OF WILLIAM THOMSON, BARON KELVIN

Baron William Thomson Kelvin (1824–1907) was a British physicist, who discovered the second law of thermodynamics and was an inventor of telegraphic and scientific instruments. He was born in Belfast, Ireland, on June 26, 1824. He was first educated by his father, but at the age of 11 he entered the University of Glasgow, Scotland, where his father was professor of mathematics. Leaving Glasgow without taking a degree, in 1841 he entered Peterhouse, Cambridge, and in 1845 took his degree as second wrangler. Wranglers were mathematically brilliant boys who competed to get the top prize in mathematics at Cambridge University.

At that time (1845) there were few facilities for the study of experimental science in Great Britain. On his father's advice (Gooding, 1990),

Thomson traveled to Paris to learn experimental methods in the laboratory of Henri Victor Regnault (1810–1878; French chemist and physicist noted for his work on the properties of gases), who was then engaged in his classical researches on the thermal properties of steam. In 1846 Thomson accepted the chair of natural philosophy at the University of Glasgow, which he filled for 53 years (Preece, 1971). Within four years of his appointment as professor at the age of 22, Thomson established the century's most successful applied physics laboratory, remembered for its compasses and precision instruments. It also was known for another innovation: using laboratory instruction to teach experimental practice and habits of accuracy and precision (Gooding, 1990). This was Britain's first teaching laboratory. It harnessed the skills of a large corps of students to produce intellectual capital, which Thomson invested in new ventures (Gooding, 1990).

In 1847 Thomson first met James Prescott Joule, whose views of the nature of heat strongly influenced Thomson's mind. In 1848 Thomson recognized -273°C as absolute zero and proposed a new scale of temperature, which is independent of the properties of any particular thermometric substance. In 1851 Thomson presented to the Royal Society of Edinburgh a paper on the dynamical theory of heat. It was in this paper that the principle of the dissipation of energy, briefly summarized in the second law of thermodynamics, was first stated.

Although his contributions to thermodynamics may properly be regarded as his most important scientific work, it is in the field of electricity, especially in its application to submarine telegraphy, that Lord Kelvin is best known (Preece, 1971). The compass went through a process of complete reconstruction in his hands, a process that enabled both the permanent and the temporary magnetism of the ship to be readily compensated, while the weight of the 10-inch (25-cm) card (the dial of a compass) was reduced to one-seventeenth of that of the standard card previously in use (Preece, 1971). Thomson also invented his sounding apparatus, whereby soundings can be taken in shallows and in deep water. Thomson's tide gauge, tidal harmonic analyzer, and tide predictor are famous. He developed tables to simplify the method for determining the position of a ship at sea. The firm of Kelvin and White, in which he was a partner, was formed to manufacture his inventions (Preece, 1971).

In 1866 Thomson was knighted for helping to engineer that year the first successful trans-Atlantic cable (Gooding, 1990). He was raised to the peerage in 1892 with the title of Baron Kelvin of Largs. Thomson took the name Kelvin from the river that flows past the University of Glasgow. In 1890 he became president of the Royal Society and in 1902 received the Order of Merit. In 1904 he was elected chancellor of the University of Glasgow. Thomson published more than 300 original papers bearing upon nearly every branch of physical science. Thomson's

extraordinary productivity shows how effectively his father taught him to expend his energy in highly efficient ways (Gooding, 1990), typical of the Scottish attitude of never wasting anything, even time. He wrote, "When you can measure what you are speaking about... you know something about it, and when you cannot measure it... your knowledge is of a meager and unsatisfactory kind..." (Gooding, 1990). Kelvin died on December 17, 1907, at his residence, Netherhall, near Largs, Scotland, and was buried in Westminster Abbey (Preece, 1971).

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