Temperature and Its Measurement

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Glossary

absolute zero The lowest temperature on the Kelvin temperature scale.

blackbody A perfect emitter and absorber of thermal radiation.

Celsius temperature scale A temperature scale based on 0 and 100°C for the ice and steam points of water, respectively; named for Swedish astronomer Anders Celsius.

emissivity The ratio of power radiated by a substance to the power radiated by a blackbody at the same temperature.

Fahrenheit temperature scale A temperature scale based on 32 and 212°F for the ice and steam points of water, respectively; named for German scientist Gabriel Daniel Fahrenheit.

infrared thermometer A device using Planck's law and measurements of thermal power in the range 0.7 to 80 μm to deduce the temperature of the source.

International Temperature Scale of 1990 (**ITS-90**) An internationally recognized standard adopted on January 1, 1990. Between 0.65 and 5 K, temperatures on the ITS-90 are defined in terms of the vapor–pressure temperature relations of helium-3 and helium-4. Above 5 K, the ITS-90 assigns temperatures to sixteen fixed points (Table I). Between the fixed points, temperatures on the ITS-90 are obtained by interpolation using a helium gas thermometer in the range 3 K to 24.5561 K, a platinum resistance thermometer in the range 13.8033 K to 1234.93 K, and an optical thermometer above 1234.93 K.

kelvin A unit of temperature defined as $\frac{1}{273.16}$ of the triple point temperature of water.

Kelvin temperature scale A temperature scale based on a temperature of 273.16 K for the triple point of water; named for physicist and mathematician Lord Kelvin, born William Thomson and knighted by Queen Victoria as the first Baron of Largs (1824-1907).

manometer A device for measuring pressure differences, usually by the difference in height of two liquid columns.

optical pyrometer A device using Planck's law and measurements of thermal power in the range 0.4 to 0.7 μm, usually approximately 0.66 μm to infer the temperature of the source.

Planck's radiation law A mathematical relationship formulated in 1900 by German physicist Max Planck(1858–1947) to explain the spectral energy distribution of radiation emitted by a blackbody.

Rankine temperature scale A temperature scale based on a temperature of 491.69°R for the triple point of water; named for Scottish engineer William Rankine (1820–1872).

resistance temperature detector (**RTD**) A sensor relating temperature to the electrical resistance of a conductor.

Seebeck effect The voltage produced when there is a temperature gradient along a conductor; named for physicist Thomas Johann Seebeck (1770–1831).

temperature At the human level, a measure of the sensation of hot and cold; at the atomic level, it is a measure of the average linear kinetic energy of an atom or a molecule in a substance.

thermal energy The average kinetic energy associated with the motion of atoms and/or molecules in a substance.

thermal equilibrium When there is no change in the thermometric properties of either system.

thermistor A temperature sensor employing the electrical resistance of a semiconductor as a thermometric property.

thermocouple A temperature sensor consisting of two dissimilar wires bonded together at one end to form a junction; a voltage related to the temperature of the junction is produced between the open ends of the two wires.

thermometer An instrument employing a thermometric property to measure temperature.

thermometric property A property of a system that changes with temperature.

triple point temperature The single temperature at which liquid, vapor, and solid coexist in thermal equilibrium.

Wien's displacement law A mathematical relationship formulated by German physicist Wilhelm Wien (1864–1928) showing that the wavelength for maximum radiative power of a blackbody is inversely proportional to the Kelvin temperature.

Zeroth law of thermodynamics A relationship indicating that if two systems are separately in thermal equilibrium with a third system, they must also be in thermal equilibrium with each other.

Temperature is a measure of the sensation of hot and cold. Inanimate objects that respond to the sensation are used in a thermometer to assign a numerical value to the sensation. Thermometers employing the common Celsius and Fahrenheit scales assign 0°C and 32°F to the freezing point of water, respectively, and assign 100°C and 212°F to the boiling point of water, respectively. Temperature changes are recorded identically on the Celsius and Kelvin scales and on the Fahrenheit and Rankine scales, but the zero value differs on the respective pairs of scales. This article discusses the range of temperatures encountered in nature and the International Temperature Scale of 1990 (ITS-90). It also describes a wide variety of temperature sensors along with their operational temperature range.

1. TEMPERATURE

A person feels warm when standing near a campfire and feels cold when standing in front of an open refrigerator. Temperature is a way of recording the extent of this sensation of hotness and coldness. Inanimate things also respond to hotness and coldness. For example, the pressure of air in an automobile tire decreases when the air cools, and the length of a railroad rail increases when the rail warms. These inanimate changes are used to assign a numerical value to temperature.

A metal spoon taken from a refrigerator is cold to the touch, and water drawn from a hot water tap feels warm. If the spoon is placed in the water, the spoon warms while the water cools. Eventually, both the spoon and the water feel the same to the touch, and we say that thermal equilibrium is attained and that the two have the same temperature. This definition of temperature does not depend on any particular temperature scale. The property of temperature indicates when two objects are in thermal equilibrium.

If a spoon and a fork are placed in a refrigerator, both will come to thermal equilibrium with the environment of the refrigerator, and we would say that each has the same temperature as the refrigerator. We would also find that if the spoon and fork were placed in contact, they would be in thermal equilibrium and, therefore, at the same temperature. Although not surprising, this idea is profound and gives rise to the Zeroth law of thermodynamics: if two systems are separately in thermal equilibrium with a third system, they must also be in thermal equilibrium with each other. One of these three systems could be an instrument for measuring temperature, that is, a thermometer. If a thermometer records a certain temperature when in thermal equilibrium with one of the systems, we would expect the thermometer to record the same temperature when in thermal equilibrium with the third system.

2. THERMOMETRY

A property of a system that changes with temperature is called a thermometric property. Examples of a thermometric property include the following:

- Pressure of a gas
- Volume of a liquid
- Electrical resistance
- Color
- Electrical voltage
- Character of thermal radiation

The algebraic equation chosen to relate temperature to a thermometric property is arbitrary. However, the simplest way, and the one most generally used, is a linear equation of the form $T = mx + b$, where T is the temperature, x is the thermometric property, and m and b are experimentally determined constants. The constants m and b may be determined by assigning numerical values to two temperatures and recording the values of the thermometric property at these two temperatures. Typically, the two temperatures are the freezing point of water and the boiling point of water. These two temperatures are assigned 0 and 100°C on the Celsius scale, respectively, and are assigned 32 and 212°F on the Fahrenheit scale, respectively.

3. TEMPERATURE SCALES

3.1 Celsius and Fahrenheit Scales

To illustrate the thermometer principle and the Celsius scale of temperature, consider the "liquid-in-glass" device depicted in Fig. 1. The thermometer is a glass tube with a reservoir for the liquid at one end and a capillary (narrow cylindrical channel) feeding into the reservoir. Liquid is forced into the capillary when the temperature of the liquid in the bulb increases. Suppose that the level of the liquid is determined by a centimeter scale attached to the side of the thermometer. If the level corresponds to 1.1 cm when the bulb is at the freezing point of water (0°C) and corresponds to 10.3 cm when the bulb is at the boiling point of water (100°C), we write $0 = 1.1m + b$ and $100 = 10.3m + b$ for the two respective cases. Solutions to these two equations yield $m = 10.9$ and $b = -12.0$, and the equation relating temperature to fluid height becomes $T = 10.9x - 12.0$. An unknown temperature is then determined by measuring the fluid level (x) and calculating the temperature (T) using the equation. In practice, the 0 and 100°C temperatures are etched at the fluid level for the freezing point and boiling point of water, respectively. Then, the space between the 0 and 100°C marks is graduated into 100 equal segments and an unknown temperature is read directly from the position of the fluid level. If the thermometer were recording temperature on the Fahrenheit scale, the 0 and 100°C designations would be replaced with 32 and 212°F, respectively, and the space between the marks would be graduated into 180 equal segments. Conversion between the two scales follows from the relation $F = \frac{9}{5}C + 32$.

3.2 Kelvin and Rankine Scales

Mercury is very useful in a liquid-in-glass thermometer because it is liquid at room temperature, does not wet glass or cling to it, and has uniform volume expansion throughout its liquid range. Because mercury remains a liquid down to approximately −40°C, mercury-in-glass thermometers can record temperatures as low as −38.7°C. Mercury remains a liquid for temperatures several hundred degrees Celsius above room temperature, but other factors (e.g., softening of the glass housing) limit the highest measurable temperature to approximately 360°C. The use of a different liquid, notably ethanol, can extend the lower measurable temperature to approximately −115°C. Because of the simplicity of liquid-in-glass thermometers and the relatively large measurable temperature range, they have been widely used for roughly 300 years.

Factors that limit the reproducibility and accuracy of liquid-in-glass thermometers include the following:

- Manufacturing reasonably identical thermometers
- Recording the precise level of the liquid
- Experiencing difficulty in reproducing the ice and steam points of water

A constant volume gas thermometer (Fig. 2) using the pressure of a gas as a thermometric property avoids most of these problems. The great virtue of this thermometer is that for very low gas pressure, the temperature deduced is independent of the gas used.

The three phases of water—vapor, liquid, and solid—exist with no change in any component at a unique temperature called the triple point temperature. Gas in a container is then brought to thermal equilibrium with its surroundings, and this is maintained at the triple point temperature. The pressure of the gas (P_o) is then measured. By definition, the triple point temperature is 273.16 kelvins, symbolized as 273.16 K. When the gas is brought to equilibrium with the surroundings at a temperature other than the triple point, the fluid reservoir of the manometer is raised or lowered so that the gas volume remains constant and the gas pressure (P) is measured. Assuming that for constant volume, pressure is proportional to temperature, the ratio of two temperatures equals the ratio of the corresponding pressures. Knowing the pressure and temperature for the triple point and measuring the pressure for the unknown temperature, the tempera-

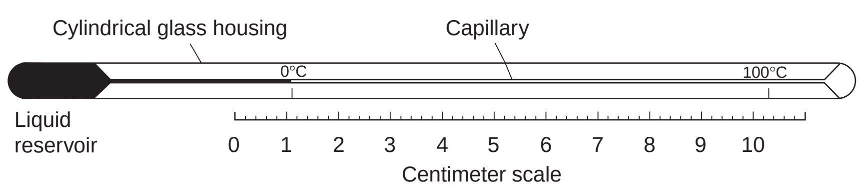

FIGURE 1 A liquid-in-glass thermometer.

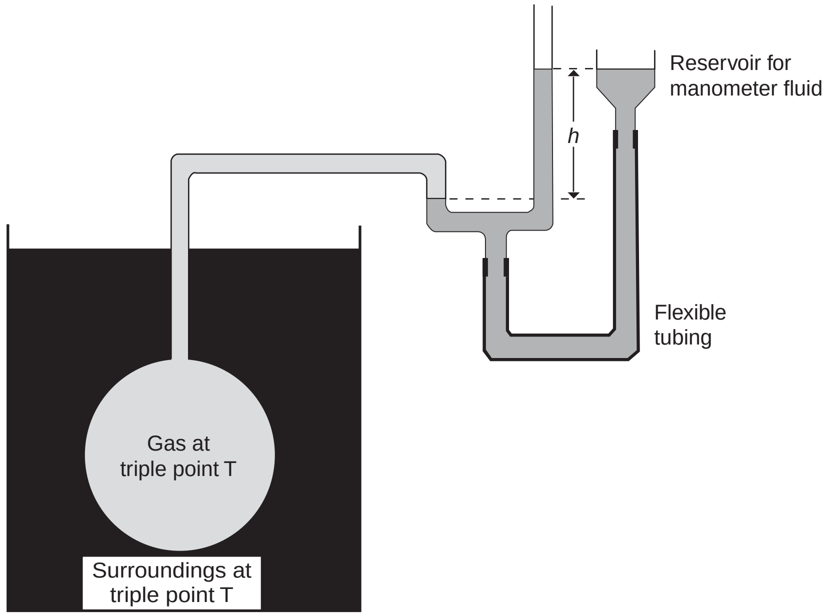

FIGURE 2 Constant volume gas thermometer principle. The apparatus illustrated here for measuring gas pressure is called a manometer. Gas pressure is related to the difference in fluid levels in the manometer. The volume of gas is held constant by raising or lowering the reservoir for the manometer fluid. There is a variety of ways in which to measure the pressure and to ensure constant gas volume.

ture is then computed from the relation

$$T = 273.16\frac{P}{P_o}. \tag{1}$$

Temperatures deduced from Eq. (1) are expressed in kelvins, and the scale is called the Kelvin temperature scale. One kelvin is defined as $\frac{1}{273.16}$ of the triple point temperature of water. A kelvin is equal to a Celsius degree, so that changes in temperature are the same on both the Kelvin and Celsius scales. The freezing point of water on the Kelvin scale is 273.15 K, so that the conversion from kelvins to degrees Celsius becomes $K = C + 273.15$. The lowest temperature on the Kelvin scale is zero and is referred to as absolute zero. The Rankine scale of temperature is developed in the same way as the Kelvin scale by taking the triple point of water to be 491.69°R. A Rankine degree is equal to a Fahrenheit degree. The freezing point of water is 491.67°R, so that conversion between the two scales becomes $R = F + 459.67$.

The random incessant motion of atoms and/or molecules in a substance is called thermal motion. The motion of an atom or molecule always has linear components and in the case of molecules may include vibration and rotation. The average kinetic energy associated with the motion is called thermal energy. The average linear kinetic energy of an atom or molecule is directly proportional to the Kelvin temperature of the substance. At the level of atoms and molecules, it is appropriate to interpret temperature as a measure of the average linear kinetic energy of an atom or a molecule in a substance.

4. RANGE OF TEMPERATURES

Most humans would agree that a temperature of 35°C (95°F) is quite hot and that −10°C (14°F) is rather cold. Yet in 1913, humans recorded a temperature of 56.7°C (134°F) in Death Valley, California, and a temperature of −89.4°C (−129°F) in 1983 in Vostok, Antarctica. As large as these temperature extremes are by human standards, they pale in comparison with other earthbound and extraterrestrial temperatures. Liquid nitrogen at a temperature of −196°C (77 K) is routinely used in cryosurgery to destroy cancerous tumors, magnets used in magnetic resonance imaging (MRI) are cooled with liquid helium at a temperature of −269°C (4.2 K), and the temperature of the filament in an incandescent light bulb operates at approximately 2500°C (2200 K). Low-temperature research laboratories have produced temperatures in the tens of billionths of a kelvin. Extraterrestrial, we find a cosmic background temperature of 2.7 K (−270.5°C), a surface temperature of approximately 5700°C

(6000 K) for our sun, and an interior temperature of approximately 15,000,000 K for the sun. Figure 3 depicts the range of temperatures encountered in nature.

5. THE INTERNATIONAL TEMPERATURE SCALE OF 1990

The International Temperature Scale of 1990 (ITS-90) is the internationally recognized standard. Between 0.65 and 5 K, temperatures on the ITS-90 are defined in terms of the vapor pressure temperature relations of helium-3 and helium-4. Above 5 K, the ITS-90 assigns temperatures to 16 fixed points (Table I). Between the fixed points, temperatures on the ITS-90 are obtained by interpolation using a helium gas thermometer in the range of 3 to 24.5561 K, a platinum resistance thermometer in the range of 13.8033 to 1234.93 K, and an optical thermometer above 1234.93 K.

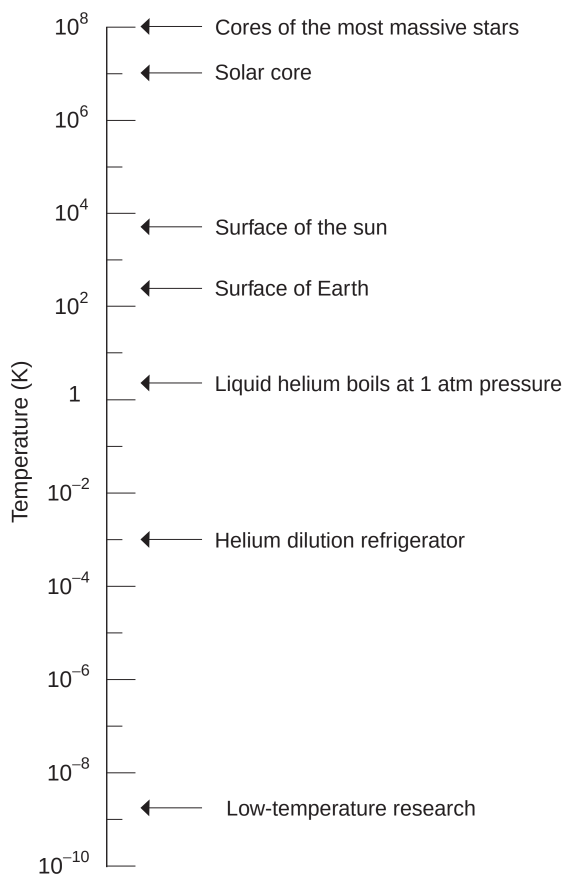

FIGURE 3 A representative few of the temperatures encountered in nature. Note that the scale is logarithmic.

6. TEMPERATURE SENSORS

6.1 Resistance Temperature Detectors

6.1.1 Platinum Resistance Temperature Detector The resistance to the flow of electric charge in a conductor depends on temperature. For metals, the resistance increases as the temperature increases. The algebraic relation between temperature and resistance allows one to determine the temperature of the metal from a measurement of its resistance. Thermometers based on this principle are called resistance temperature detectors (RTDs). Platinum is particularly useful for an RTD because it can be made very pure, is stable and does not oxidize easily, and has a relatively high melting point of 1772°C. In addition, its resistance varies smoothly—nearly linearly—over a wide range of temperatures. Properly calibrated, a platinum resistance thermometer can achieve reproducible readings accurate to less than a thousandth of a Celsius degree.

Figure 4 shows a platinum RTD constructed from fine platinum wire approximately 0.1 mm in diameter. Typically, the sensor has a resistance of 100 ohms (Ω) at 0°C and increases approximately 0.39 Ω for each Celsius degree increase. A second, more modern, and more widely used type of platinum resistance temperature sensor is shown in Fig. 5. The platinum is deposited as a very thin narrow ribbon onto a ceramic base. Typical film

TABLE I

International Temperature Scale Calibration Temperatures

Hydrogen triple point	13.8033 K	−259.3467°C
Hydrogen vapor pressure (∼33 kPa)	∼17 K	−256.15°C
Hydrogen vapor pressure (∼101 kPa)	∼20.3 K	−252.85°C
Neon triple point	24.5561 K	−248.5939°C
Oxygen triple point	54.3584 K	−218.7916°C
Argon triple point	83.8058 K	−189.3442°C
Mercury triple point	234.3156 K	−38.8344°C
Water triple point	273.16 K	0.01°C
Gallium melting point	302.9146 K	29.7646°C
Indium freezing point	429.7485 K	156.5985°C
Tin freezing point	505.078 K	231.928°C
Zinc freezing point	692.677 K	419.527°C
Aluminum freezing point	933.473 K	660.323°C
Silver freezing point	1234.93 K	961.78°C
Gold freezing point	1337.33 K	1064.18°C
Copper freezing point	1357.77 K	1084.62°C

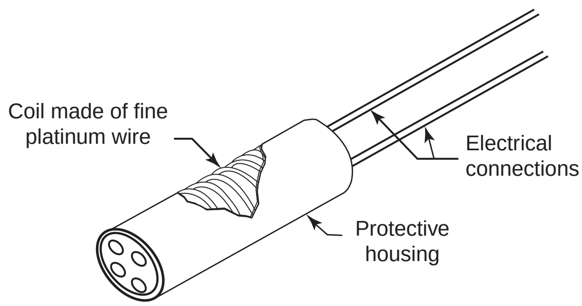

FIGURE 4 A common type of resistance temperature detector employing a fine platinum wire. The cylindrical package may be as small as 3 mm in diameter.

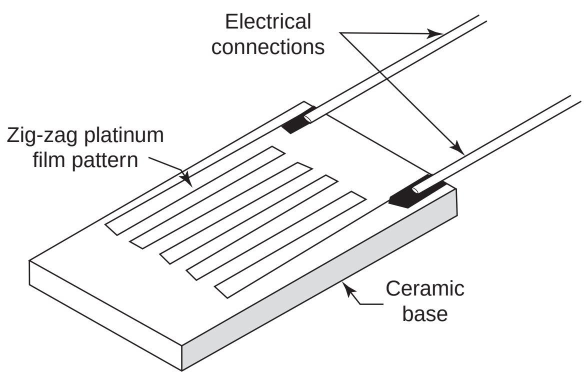

FIGURE 5 A common type of resistance temperature detector employing a thin platinum film. The overall dimensions may be as small as 2 × 2 × 0.5 mm thick.

thickness ranges from 1 to 2 μm with a 10-μm thick protective coating. Precise resistances can be obtained by trimming the length of the film. The standard resistance is 100 Ω at 0°C, but by controlling the dimensions of the film (especially the thickness), a much higher resistance is achievable. A thin film platinum resistance temperature sensor can be bonded to a material to measure temperature in a very local area. Because of the small overall size and good thermal contact, the sensor responds quickly to temperature changes, making it very useful in temperature control applications. Depending on the construction, a platinum resistance temperature sensor can measure temperatures in the range of 10 to 1200 K.

6.1.2 Thermistors

To a first approximation, a semiconductor is a material having electrical properties between a conductor (e.g., copper) and an insulator (e.g., glass). Elemental silicon and germanium, as well as many oxides of metals such as nickel and copper, can have semiconducting properties. The electrical resistance of a semiconductor depends on temperature, but unlike a metal, the resistance decreases as the temperature increases and the relation between resistance and temperature is highly nonlinear. A sensor using such a semiconducting material is called a thermistor. Resistance (R) and Kelvin temperature (T) for a thermistor are generally assumed to be related by $R = R_o e^{\beta(1/T - 1/To)}$, where R_o is the resistance at temperature T_o and, depending on the material, β ranges from 3500 to 4600 K. A platinum wire having a resistance of 100 Ω at 0°C will have approximately 40% more resistance at 100°C. But the resistance of a semiconductor may change by a factor of 50 in the same temperature interval. Thermistors can be made in nearly any stable geometric shape, with the largest overall dimension being approximately 1 mm. Thermistors are relatively cheap, their response time is short, and their intrinsic accuracy is good. The fact that they are highly nonlinear is a disadvantage, as is the limited temperature range, typically −100 to 150°C. Still, thermistors find many uses in this temperature range, for example, as the sensor in a nurse's thermometer.

6.2 Thermocouples

In 1826, Thomas Seebeck discovered that a voltage is produced when there is a temperature gradient along a conductor. This phenomenon is called the Seebeck effect. The voltage produced is called the Seebeck voltage, and the variation of voltage with temperature is called the Seebeck coefficient. Two wires of different composition bonded at one end produce a thermocouple (Fig. 6). A voltage develops between the unconnected ends and is related to the temperature, making a thermocouple useful as a temperature sensor. At 25°C, a thermocouple having one wire made of pure copper and the other wire made of an alloy of copper and nickel called Constantan produces 40.6 microvolts (μV) for each Celsius degree change. The voltage produced by a thermocouple increases monotonically with temperature and is nearly linear over wide ranges of temperature. Thermocouples are widely used in industry, even though sensitive instruments are required to measure the small voltages produced.

Like an ordinary battery, there is a positive and negative polarity to the voltage produced by a thermocouple. When a meter is connected to measure a thermocouple voltage, as shown in Fig. 6, the thermocouple wires and meter connections form two unwanted thermocouple junctions. These two unwanted thermocouple junctions are of

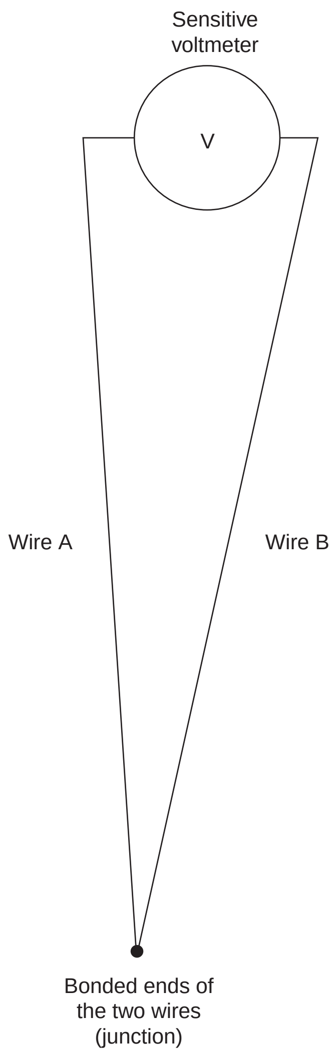

FIGURE 6 Two different metallic wires bonded at their ends constituting a thermocouple. A voltage (V) develops between the open ends when the bond (junction) is heated.

different character because the wires have different composition. The voltages produced at the unwanted thermocouple junctions add to the voltage produced at the thermocouple junction. This problem can be eliminated by using two thermocouples and a reference temperature of 0°C, as shown in Fig. 7. (Although a bath of water and ice is commonly used to produce the 0°C reference, it can be simulated using electronic techniques.) The thermocouple wires and the meter connections now form two identical thermocouple junctions whose voltages cancel each other. The two junctions produce voltages of opposite polarity, so that when the two junctions are at the temperature of the ice bath, the voltage read by the meter is zero. When

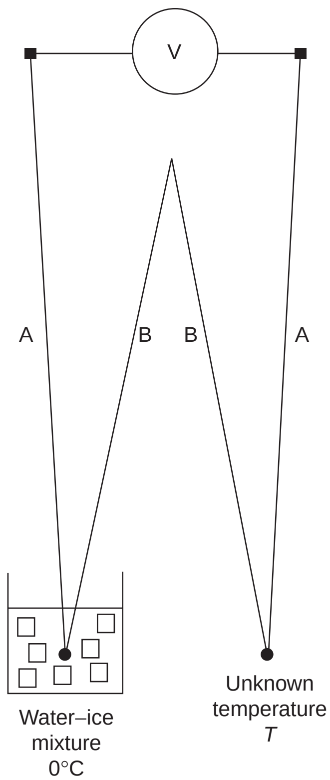

FIGURE 7 Customary manner of measuring temperature with a thermocouple.

one of the thermocouples is removed from the ice bath and is at a different temperature, the voltage read by the meter is not zero and the voltage relates to the temperature difference of the measuring thermocouple and the ice bath. This voltage–temperature relationship may be in the form of a table in a book or may be available in a format suitable for computer use. Because the voltage–temperature relationship is nearly linear, the relation between voltage and temperature can often be suitably represented by a quadratic equation of the form $T = a\mathrm{V} + b\mathrm{V}^2$, where a and b are determined from data for a particular type of thermocouple. The National Institute of Standards and Technology (NIST) maintains a database for a variety of thermocouples. Parameters for functions describing the relation between voltage and temperature are included in the NIST database. Positive features of thermocouples include the following:

- They are relatively inexpensive.
- They are rugged and not easily broken.
- They are small enough to measure temperature at a point.

TABLE II

Characteristics of Commonly Used Thermocouples

Composition A	Composition B	Commercial type	Calibration range (°C)	Sensitivity at 25°C (μV/C°)
Copper	Constantan (alloy of copper and nickel)	T	−270 to ∼400	41
Iron	Constantan	J	−210 to ∼1200	52
Chromel (alloy of nickel and chromium)	Alumel (alloy of nickel and aluminum)	K	−270 to ∼1350	41
Chromel	Constantan	E	−270 to ∼1000	61
Platinum	87% platinum 13% rhodium	R	−50 to ∼1750	6

Source. National Institute of Standards and Technology (n.d.).

- They operate over fairly wide temperature ranges.
- They have relatively short response times.

Negative aspects include the following:

- The low-voltage output is masked by electronic noise.
- Their accuracy is usually limited to approximately 0.5°C.
- They require a known temperature reference, usually 0°C, that is cumbersome unless done electronically.
- Dealing with the nonlinearity is tedious if using calibration tables.

The characteristics of commonly used thermocouples are presented in Table II.

6.3 Radiation Thermometers

A temperature sensor requiring contact with an object (e.g., a thermocouple) cannot withstand a temperature above approximately 2000 K. Thermometers measuring temperatures above that temperature are based on the character of electromagnetic radiation emitted by an object. All matter above a temperature of 0 K emits electromagnetic radiation. A radiator called a blackbody emits more radiation for all wavelength intervals than does any object having the same area and at the same temperature. The ratio of the intensity of radiation from an object to the intensity of radiation from a blackbody at the same temperature is called the emissivity. By definition, the emissivity of a blackbody is 1.0, whereas that for any other object is always less than 1.0.

Perfect blackbodies do not exist. However, they can be approximated to a high degree of accuracy and are very useful in thermometry. Blackbody radiation

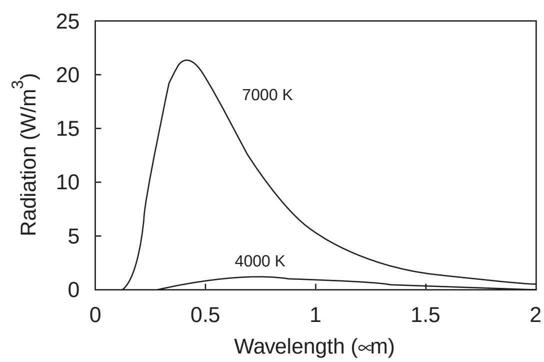

FIGURE 8 Blackbody thermal radiation distributions for temperatures of 4000 and 7000 K.

measured in watts per square meter per wavelength interval in meters as a function of wavelength (λ) is described by Planck's radiation law:

$$R(\lambda, T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT} - 1}, \quad (2)$$

where $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^8$ m/s, and $k = 1.38 \times 10^{-23}$ J/K.

The intensity distributions for blackbodies at temperatures of 7000 and 4000 K are shown in Fig. 8. Two features of blackbody radiation are of particular importance. First, the energy associated with each wavelength depends on the wavelength. Second, the temperature and the wavelength of maximum radiation (λ_m), as noted by the position of the peak in the spectrum, shifts to a longer wavelength as the temperature decreases. The wavelength of maximum radiation and Kelvin temperature (T) are related by Wien's displacement law:

$$\lambda_m T = 2898\ \mu\text{m kelvins}. \quad (3)$$

For temperatures between approximately 4000 and 7000 K, λ_m is between 0.4 and 0.7 μm that are visible.

For temperatures below approximately 4000 K, the radiation is mostly infrared. Two categories of noncontact thermometers are in common use. One type, called optical pyrometer, uses Planck's law and measurements of thermal power in the range of 0.4 to 0.7 μm, usually approximately 0.66 μm, to infer the temperature of the source. The second kind, called infrared thermometer, uses Planck's law and measurements of thermal power in the range of 0.7 to 80 μm to deduce the temperature of the source.

6.3.1 Optical Pyrometer

A schematic diagram of an optical pyrometer is shown in Fig. 9. The operator sights the pyrometer on an object. The optical system allows viewing of both the target and an image of the filament of a lamp. The operator adjusts the current in the filament, changing its color, until it matches the color of the object. The temperature is inferred from a calibration relating temperature to current in the filament. A second design maintains a constant current in the filament and changes the brightness of light from the object by means of a rotatable, energy-absorbing optical wedge. The object temperature is related to the amount of energy absorbed by the wedge, which is a function of its angular position. The optical pyrometer principle can be extended into the infrared region of the electromagnetic spectrum using detectors sensitive to infrared radiation. Typically, optical pyrometers measure temperature to an accuracy of 1 to 2% of the full-scale range.

6.3.2 Infrared Thermometer

An infrared thermometer uses a lens system to focus radiation onto an infrared detector that converts the energy absorbed into an electrical signal. The temperature inferred from the electrical signal is corrected for the emissivity of the source. Using optical filters, infrared thermometers may employ a very narrow range of wavelengths, whereas other systems may use a very broad range of wavelengths. In either case, the energy absorbed is related to temperature using Planck's law. Broadband infrared spectrometers are relatively inexpensive and easy to use, but their accuracy suffers from the fact that emissivity depends on wavelength, thereby making corrections difficult. Narrow-band infrared thermometers do not face this limitation because the emissivity value does not vary appreciably over the wavelengths used (Fig. 10).

Modern technology is continually improving the accuracy of infrared thermometers. For example, fiber-optic sensors allow placement of the instrument controls away from the heat of the object being studied. Recent developments in infrared thermometers have combined pulse laser technology with narrow-band, single-color infrared thermometers to automatically determine emissivity values and accurately correct for true target temperature. This technology incorporates the use of a pulse laser that emits energy within the same narrow bandwidth that the instrument measures the target thermal radiation. The instrument's infrared detector measures the amount of laser energy reflected from the target, and the microprocessor control converts this additional energy into an accurate value to compensate for emissivity. The instrument then displays true target temperatures, corrected for emissivity and accurate to within ± 3 K. Pulse laser technology is very effective with diffuse targets.

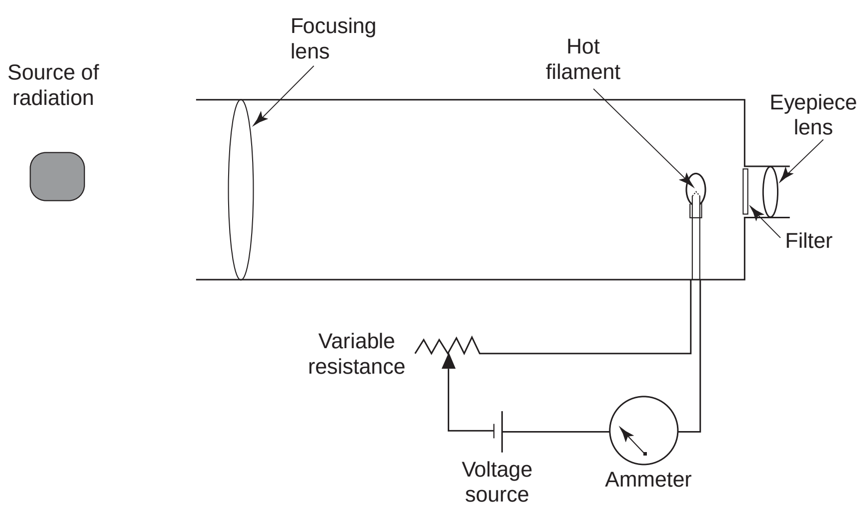

FIGURE 9 Schematic diagram of an optical pyrometer.

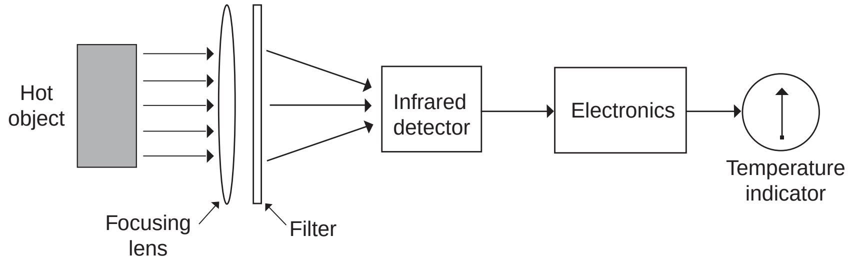

FIGURE 10 Schematic diagram of an infrared thermometer.

6.4 Very Low-Temperature Methods

Measuring temperatures below a few kelvins requires sophisticated techniques. Three of these schemes are called noise thermometry, paramagnetic thermometry, and semiconductor resistance and diode thermometry.

6.4.1 Noise Thermometry

Thermal agitation of electrons in a conductor gives rise to a randomly varying voltage. The average of the square of this voltage is directly proportional to the Kelvin temperature. Properly calibrated, a measurement of the voltage yields the Kelvin temperature. Although the technique requires sophisticated electronic instrumentation, it is one of the few alternatives to gas thermometry for precise determination of thermodynamic temperature. Noise thermometers are very useful for measuring temperatures below 1 K, but in principle they can measure temperatures in the range of a few millikelvins to above 1800 K.

6.4.2 Paramagnetic Thermometry

Many materials can be magnetized by placing them in a magnetic field. The ratio of magnetization to the applied magnetic field is called the magnetic susceptibility. For a class of materials called paramagnetic, the magnetic susceptibility is inversely proportional to the Kelvin temperature. The temperature of a paramagnetic material, such as cerium magnesium nitrate, in intimate contact with some material can be determined from a measurement of the magnetic susceptibility. The technique is useful for measuring temperatures below 4 K.

6.4.3 Semiconductor Resistance and Diode Thermometry

The electrical resistance of a semiconductor depends sensitively on temperature for temperatures below approximately 100 K. Germanium and silicon have proven to be useful for measuring temperatures as low as 0.1 K. The use of ruthenium oxide in a similar mode has pushed the lower limit of temperature measurement to approximately 0.01 K.

A p–n junction diode is a sandwich of two semiconducting materials having different electrical conduction characteristics. When connected to a voltage source, the current in a p–n junction diode depends on temperature. Thermometers using this thermometric property in silicon and gallium–arsenide p–n junction diodes are useful for measuring temperatures in the range of 1 to 300 K.

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Further Reading

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