"It doesn't make a difference what temperature a room is, it's always room temperature."
– Steven Wright

Chapter Two: The Hot and Cold of Industrial Temperature Measurement

Temperature is vitally important both in industrial environments and in our daily lives. Our physical comfort depends on the air temperature. Both the heating and the air conditioning industries are built on the idea of bringing the air temperature to a comfortable level. Cooking and freezing food involve changing the temperature of food to either make it edible and appetizing, or to preserve it so it can be eaten later. The outside temperature governs the choice of clothes we wear, and millions of people are attracted every year to the warmer climes for vacation and relaxation purposes.

Temperature is also important in industrial process environments. In chemical and food processing plants, temperature measurement plays an important role in maintaining food safety and in keeping chemicals at a safe temperature. Also, certain chemical reactions only take place a certain temperatures. In flow measurement, temperature is an essential measurement in computing mass flow when volumetric flow and pressure are also known.

Just as temperature itself is important, so is measuring temperature. Thermostats have a setpoint that represents the desired temperature for a room or building. The first step in controlling the room temperature at the desired setpoint is measuring it. Measuring the internal temperature of food tells us when it is ready to eat. Our decisions about what to do on a given day or weekend are based on the forecast temperature, along with other weather conditions. In an era when global warming is a recognized fact, scientists track the temperature of the oceans to determine how quickly the earth is warming.

While temperature is among the most measured of physical properties, defining it is not so easy.

The temperature that we experience is a subjective quality of the objects we feel as hot or cold. It is this quality that causes us to experience the sensation of heat or coldness. If the object is “hot” it is at high temperature, while if it is “cold” it is at low temperature. What we sense as “hot” or “cold” is caused by molecular motion, and temperature is a measure of the average kinetic energy of the molecules of a substance. The term *kinetic* means “having to do with motion,” so another way of saying this is:

> Temperature is a measure of the average energy of a substance due to the motion of the molecules in the substance. As the average motion of the molecules increases, so does the temperature, and as the average motion of the molecules decreases, the temperature does also.

Change in temperature is also objective, and relates to how two bodies at different temperatures interact with each other. When two bodies are in thermal contact with each other, a form of energy called heat flows from the warmer body to the cooler body. The warmer body becomes cooler, and the cooler body becomes warmer. This transfer of energy continues until the temperatures of the two bodies become equal. Once the temperatures of the two bodies become equal, the transfer of energy in the form of heat ceases. Bodies in such a state are said to be in a state of thermal equilibrium.

The Historical Question How to Measure Temperature

If temperature is understood to be a measure of average molecular motion, how should it be measured? Rather than trying to measure the amount of molecular motion directly, temperature is measured indirectly. By making use of a property that changes in a uniform manner with temperature, temperature can be determined by associating different temperatures with different states of that property.

The instrument used to measure temperature is called a *thermometer*. The term *thermometer* is derived from the Greek words meaning “heat measure.” The first

A thermometer with Fahrenheit and Celsius units recorded use of the word *thermometer* in English occurred in 1633. It is described as "an instrument to measure the degrees of heat and cold in the air."

The liquid-in-glass thermometer is one of the most common means of measuring temperature. This type of thermometer makes use of the fact that liquids generally expand as they are heated and contract when they are cooled. As the temperature rises, the liquid in the glass tube expands, extending along a scale, and the scale on the thermometer indicates the temperature. The temperature is proportional to the length of the liquid column. Although it is no longer commonly used because of its toxicity, mercury was once favored because of its high coefficient of thermal expansion.

Galileo invented the first thermometer in the 1590s. It was an air thermometer made of a glass bulb with a long tube attached. The bulb was heated with the hands and then the tube was held vertical and the open end was partially immersed in a container with liquid in it. When the hands were removed from the bulb, the liquid in the tube rose to a certain height, and remained above the level of the liquid in the container. Although Galileo called this device a *thermoscope* rather than a thermometer, it nonetheless works sufficiently like a thermometer to have earned Galileo the title of the inventor of the thermometer.

The difference between Galileo's thermoscope and a thermometer is that a thermoscope indicates that a change in temperature has occurred, while a thermometer measures temperature change on a scale.

A Matter of Scale

Starting in the early 1700s, a number of scientists tried to devise scales to accurately measure temperature changes. Three physicists and an astronomer came up with the four temperature scales most commonly used today:

Fahrenheit scale

Celsius scale

Kelvin scale

Rankine scale

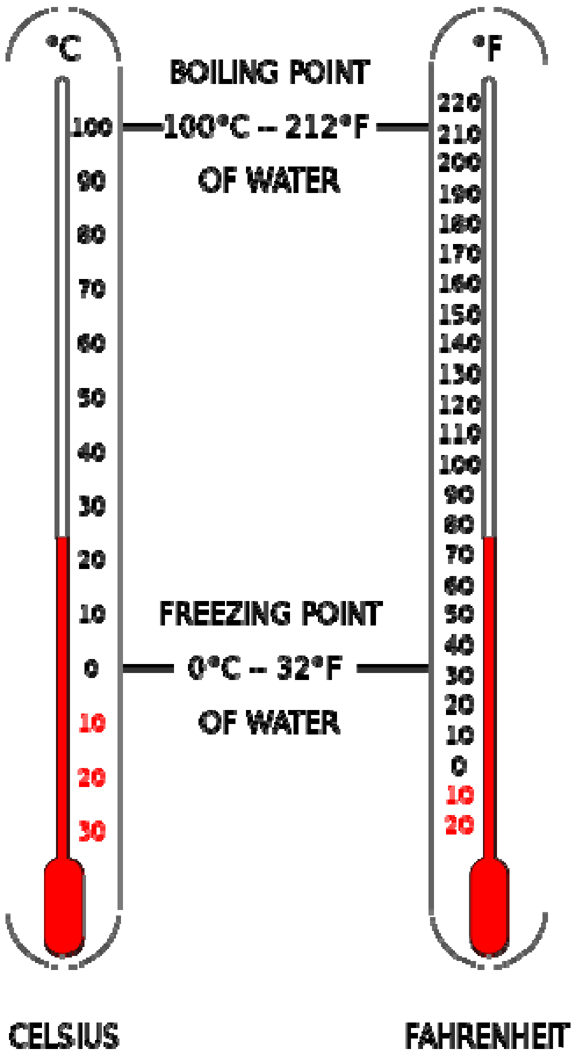
The Fahrenheit Scale: A German physicist named Gabriel Daniel Fahrenheit was the first person to use mercury as a thermometric fluid when he created his thermometer in 1714. Mercury's freezing point is substantially below that of water and its boiling point is significantly higher. Mercury also expands uniformly with changes in temperature. However, Fahrenheit did not use the freezing and boiling points of water as reference points. Instead, he used a mixture of ice, water and salt as a reference for a cold point, and the temperature of the human body as a reference for the warm point. Fahrenheit associated 0 degrees with his mixture of ice, water and salt. An ice and water mixture without the salt read 32 degrees. Fahrenheit found the temperature of the human body to be 96 degrees.

Anders Celsius

Fahrenheit's thermometer has since been recalibrated. Although 32 degrees Fahrenheit (32°F) is still recognized as the freezing point of water, the temperature of the human body is now determined to be 98.6°F and the boiling point of water – which was not acknowledged on the original scale – is now recognized as 212° on the Fahrenheit scale.

Until the 1960s, the Fahrenheit scale was the primary temperature standard for climatic, industrial and medical purposes in most English-speaking countries. In the late 1960s and 1970s, governments phased in the Celsius scale as part of the standardizing process of metrication. Today, the Fahrenheit system is the standard for non-scientific use only in the United States and a few other countries.

The Celsius Scale: A Swedish astronomer named Anders Celsius created a different scale in 1742. In this scale, 0° was the boiling point of water and 100° was the freezing point. A maker of scientific instruments later reversed these points, so the freezing point of water is 0° and the boiling point is 100°. For many years, these degrees were called "degrees centigrade." *Centi-* is a prefix meaning one-hundredth, while *grade* means degree. In 1948, the National Conference on Weights and Measures decreed that "degrees centigrade" should be called "degrees Celsius." Today the Celsius scale is used for practically all purposes throughout the world except in the United States and a few other countries. Even in the United States, most scientists and engineers use the Celsius scale.



It is possible to convert degree readings from Fahrenheit to Celsius, and vice versa. To convert from Celsius to Fahrenheit, the formula is as follows:

$$F = 9/5\ C + 32$$

To convert from Fahrenheit to Celsius, the formula is as follows:

$$C = 5/9\ (F - 32)$$

The Kelvin Scale: The Scottish physicist William Thompson introduced another temperature scale, called a thermodynamic scale because it is based on "absolute zero," in 1848. Thompson was later elevated to the rank of baron, and became Lord Kelvin. In Thompson's scale, known as the Kelvin scale, absolute zero has a value of -273.15°C. This is the temperature at which all gases, if they were to contract as much as possible, would approach thevolume of zero. This is the theoretical lower limit of temperature, and at this temperature all molecular motion would cease. A temperature of absolute zero is theoretically unattainable.

To convert a temperature reading from Celsius to Kelvin, add 273.15, as shown in the following formula:

$$K = C + 273.15$$

Since water freezes at 0°C, it freezes at 273.15 Kelvin (by international agreement, the term "degree" is not used with the Kelvin scale). Since water boils at 100°C, it boils at 373.15 Kelvin. The size of one Kelvin is equal to the size of one Celsius degree.

The Rankine Scale: Another thermodynamic scale sometimes used in Great Britain is the Rankine temperature scale. William McQuorn Rankine, a Scottish civil engineer and physicist best known for molecular physics research, proposed this scale in the mid-1800s. In the Rankine scale, one unit is equal to the size of one Fahrenheit degree. A temperature of 0 degrees Rankine equals -459.67°F. To convert from Fahrenheit to Rankine, add 459.67 to the Fahrenheit value:

$$R = F + 459.67$$

A few engineering fields in the United States measure thermodynamic temperature using the Rankine scale. However, throughout the scientific world, where measurements are made in SI (System International) units, thermodynamic temperature is measured in Kelvin.

Sensing the Change: Methods of Industrial Temperature Measurement

All methods of temperature measurement need to use some type of sensor. A temperature sensor has one or more properties that change in predictable ways as the temperature changes. The changing properties of the temperature sensor are interpreted as changes in temperature by a thermometer, a voltmeter or a similar device.

The five most popular types of temperature sensors – described more completely later in the chapter – are as follows:

Thermocouples: Thermocouples are the most widely used temperature sensors in industrial manufacturing environments. Thermocouples consist of two wires made of different metals that are joined at one end, called the *measurement junction*. The other ends of the wires form a *reference junction*. A current flows in the circuit when the measurement junction and the reference junction are at different temperatures. The resulting voltage is a function of the difference in temperature between the measurement and the reference junctions. The amount of voltage produced at a specific temperature depends on the types of metals used. A device that can interpret the voltage reading as a temperature value is required for measuring the temperature.

RTDs: Resistance temperature detectors, or RTDs, make use of the fact that resistance to the flow of electricity in a wire changes with temperature. Platinum is the most commonly used material for the wire.

RTDs are classified into the following two types:
Wirewound
Thin Film
Thermistors: Like RTDs, thermistors also change resistance with changing temperatures, but they are more sensitive than RTDs or thermocouples. Thermistors change their resistance much more significantly than RTDs with changing temperature. However, this change is highly nonlinear. Because of their extreme sensitivity and

nonlinearity, thermistors are limited to measuring temperatures of a few hundred degrees Celsius. Their applications are further limited since they are less rugged than RTDs.

Infrared Thermometers: Infrared thermometers are non-contact sensors. They are used to measure temperature when contact measurement using thermocouples, RTDs or thermistors is not possible. For example, they are used to measure the temperature of moving objects, such as moving machinery or objects on a conveyor belt. They are also used where contamination is present, for hazardous conditions, or where the distance is too great for contact sensors. Infrared sensors detect the infrared energy given off by materials. The most common design includes a lens to focus the infrared energy onto a detector. The amount of infrared energy is then converted into corresponding units of temperature.

Fiber Optic Temperature Sensors: Fiber optic temperature sensors are a form of temperature measurement that uses optical fibers in making temperature measurements. Most types of fiber optic temperature sensors work by placing a temperature-sensing component on one end of the optical fiber. The other end is attached to a measuring system that collects infrared radiation and processes it into a temperature value.

Other Temperature Measurement Technologies

In addition to the above five types of temperature sensors, there are four other temperature measurement technologies that are not widely used in industrial environments. They are included here for the purpose of completeness.

Fluid Expansion Devices: The term *fluid expansion device* is a fancy name for the familiar household "mercury" thermometer and similar devices. Fluid expansion devices depend on the fact that fluids expand when heated and contract when cooled. Instead of using a separate device to interpret the liquid height and display the temperature, these thermometers contain a scale that allows the temperature to be read off directly from the height of the liquid. These thermometers do not require electric power, are not explosive, and remain stable after repeated uses. However, they must be read manually and do not generate data that is easy to record or transmit. There are other fluid expansion devices available which use gases rather than liquids.

Change of State Temperature Sensors: Change of state temperature sensors include labels, crayons, lacquers or liquid crystals, and pellets. What these devices have in common is that they change in appearance when a certain temperature is reached. In many cases, they can be used only once since this change of state is irreversible. These types of sensors are used in the food industry and are also used with steam traps.

Bimetallic Devices: Bimetallic devices are made by bonding two metal strips. They take advantage of differences in the coefficient of thermal expansion of different metals. When the strips are heated, one side expands more than the other side. As a result, bending occurs in the strips. A mechanical linkage to a pointer interprets this bending as a temperature reading. Bimetallic devices do not require a power supply. They are portable, but are less accurate than thermocouples and RTDs. Bimetallic devices are not accurate enough to record smaller temperature changes.

Integrated Circuit Temperature Sensors: Integrated circuit (IC) temperature sensors have the advantage that they are naturally linear devices; they generate an output that is proportional to the temperature. Typically, IC sensor output is stated in microamps per Kelvin. IC temperature sensors are made of semiconductor materials such as silicon and germanium; they rely on the electrical properties of these materials to produce a proportional voltage output. Voltage is converted to current using a low-temperature-coefficient thin-film resistor.

The Nitty Gritty: Technology of Industrial Temperature Sensors

As mentioned above, this section describes in some detail the technology of the following five primary industrial temperature sensors:

Thermocouples (T/Cs)

Resistance temperature detectors (RTDs)

Thermistors

Infrared (IR) sensors

Fiber optic temperature sensors

Thermocouple Technology

A thermocouple is composed of two wires of dissimilar metals that are joined together at one end. This end, which is where the wires are exposed to the process temperature, is the measuring junction. At the other end of the wires – normally where they are attached to the measurement device – the wires form a reference, or cold, junction.

Measuring Junction

At the measuring junction, the wires are usually either soldered or welded together. There are three types of thermocouple measuring junctions:

Exposed Junction: An exposed junction has no protective assembly or covering sheath. Exposed junctions have the fastest response time, the lowest radiation error and the least conduction error. Their disadvantages are fragility and susceptibility to corrosion. Exposed junction thermocouples are also prone to pick up stray electromagnetic signals unless this is guarded against.

Grounded Junction: A grounded junction is similar to an exposed junction, except that a protective metallic sheath encloses the junction. In a grounded junction, the thermocouple wires are welded directly to the surrounding sheath material, forming a completely sealed junction. A grounded junction is more rugged and is capable of tolerating physical and mechanical abuse. It is also more resistant to corrosion and oxidation. A disadvantage of the grounded junction is slower response time. Grounded junction thermocouples are also more susceptible to conduction errors and radiation errors than are exposed junction thermocouples. Like exposed junction thermocouples, grounded junction thermocouples are also prone to picking up stray electromagnetic signals.

Ungrounded Junction: An ungrounded junction is like a grounded junction except that the junction of the thermocouple wires is not electrically connected to the metallic sheath. An electrical insulator separates the junction from the tip of the closed-end sheath. Like the grounded junction, an ungrounded junction is more rugged and tolerant of abuse. It is also shielded from electromagnetic interference. Its disadvantages are slow response time, susceptibility to conduction errors and susceptibility to radiation errors.

Measuring the Reference Junction Temperature

When the measuring junction and the reference junction are at different temperatures, a current flows from one end of the circuit to the other end. It continues to flow as long as there is a difference in temperature between the two junctions. Thomas Seebeck discovered this phenomenon in 1821, and it is called the Seebeck effect. The resulting voltage is called the Seebeck voltage. This voltage is a function of the difference in temperature between the measuring junction and the reference junction. Although it is approximately linear for small changes in temperature, it is mostly nonlinear with respect to larger changes in temperature.

Measuring the Seebeck voltage directly with a voltmeter at the reference junction does not give an accurate result because the connection between the thermocouple wires and the voltmeter leads creates a new thermoelectric circuit. In addition, since the voltage read by the voltmeter is proportional to the difference in temperature between the measuring junction and the reference junction, it is necessary to know the temperature at the reference junction to determine the temperature of the measuring junction. The output in such a measurement is usually in millivolts or microvolts.

There are several methods used to take into account the temperature of the reference junction in determining the temperature of the measuring junction, including:

Ice Bath: In the ice bath method, a junction is created within the circuit and inserted into an ice bath. This junction now becomes the reference junction, and it is at the temperature of 32°F. Since the voltage reading at the measuring junction is proportional to the difference in temperatures between the reference junction and the measuring junction, and the temperature at the reference junction is known, the temperature at the measurement junction can be determined from the voltage reading at the measurement junction.

Hardware Compensation: A second method used to take into account the temperature of the reference junction is hardware compensation. A variable voltage source is inserted into the thermoelectric circuit. This voltage source generates a compensating voltage in accordance with the ambient temperature, adding a correct voltage that cancels unwanted thermoelectric signals. Canceling these unwanted signals leaves only the voltage from the measuring junction.

Hardware compensation has the advantage that it is not necessary to actually measure the ambient temperature at the reference junction. A disadvantage of this method is that it is necessary to have a separate compensation circuit for each type of thermocouple. The circuitry used in hardware compensation also adds some error in the temperature measurement.

Software Compensation: Software compensation can be implemented when a programmable measurement system is used. In software compensation, the temperature at the reference junction is measured with a temperature sensor. Usually either a thermistor or an integrated circuit (IC) sensor is used. Once the temperature of the reference junction is known, software is used to calculate the temperature at the measuring junction. Software calculates the temperature by using the reference tables or functions built into software programs that correlate specific temperatures with voltage values for different types of thermocouples.

Thermocouple Types

Thermocouples are made up of two dissimilar metals, and they are classified according to the type of metal used to make them. Industry specifications recognize a number of types of thermocouples, which have been given alphabetical letter designations. Different thermocouple types have different temperature ranges. However, these ranges are not absolute, as other factors such as wire thickness influence the temperature range. Table 2-1 gives different types of thermocouples along with their metal composition and their temperature ranges.

Table 2-1
Thermocouple Types

T/C Type	Metal Composition	Temperature Range	Comments
J	Iron/Copper-Nickel	32°F to 1382°F	Not recommended for low temperatures; oxidizes rapidly due to presence of iron
K	Nickel-Chromium/Nickel-Aluminum	-328°F to 2282°F	Most commonly used type; wide temperature range
E	Nickel-Chromium/Copper-Nickel	-328°F to 1652°F	Highest voltage change per degree
T	Copper/Copper-Nickel	-328°F to 662°F	Performs well with moisture present; used for low temperature and cryogenic applications
S	Platinum-10% Rhodium/Platinum	32°F to 2642°F	Used for very high temperatures; subject to contamination; more expensive due to noble metals
R	Platinum-13% Rhodium	32°F to 2642°F	Used for very high temperatures; subject to contamination; more expensive due to noble metals
B	Platinum-30% Rhodium/Platinum-6% Rhodium	32°F to 3092°F	Subject to contamination; used for very high temperatures; used in the glass industry
N	Nickel-14.2% Chromium-1.4% Silicon/Nickel-4.4% Silicon-0.1% Magnesium	-450°F to 2372°F	An alternative to type K; more stable at high temperatures

RTD Technology

The history of RTD technology goes back to Sir William Siemens. About 50 years after Seebeck's discovery concerning thermoelectricity, Siemens discovered that there is a relation between temperature change and the resistivity of metals. In making this discovery, Siemens relied on research done by Sir Humphry Davy. Siemens established the use of platinum as the element of an RTD.

The basic principle of an RTD is that as temperature increases or decreases, the resistivity of certain metals increases or decreases in a predictable and repeatable manner. The most commonly used metals are platinum, copper, and nickel. There are several reasons why these metals are used. One reason is that these metals react in a predictable way as temperature changes. Even though they do not react in a completely linear manner with temperature change, they are substantially more linear than thermocouples. Second, these metals are available in nearly pure form. Third, these metals have ductility, which means that they can all be processed into very fine wires. This is especially important when manufacturing wirewound RTDs.

There are two types of RTDs: wirewound and thin film. Wirewound RTDs consist of wire wound on a bobbin, which is enclosed in a glass or metal container. For thin film RTDs, a film is etched onto a ceramic substrate, and then sealed. RTDs are more accurate and stable than thermocouples, but cannot be used to measure temperatures higher than 660°C.

Thermistor Technology

The thermistor is another resistance-based temperature sensor. The term *thermistor* is derived from the phrase "thermally sensitive resistor." The resistance of thermistors also changes with changes in temperature, but the amount of change in resistance per degree is much greater in a thermistor than in an RTD. This makes a thermistor a much more sensitive device than an RTD. However, the resistance change in a thermistor is very nonlinear. As a result, thermistors are normally used only over a very small temperature span.

Thermistors are not as widely used as RTDs, and they are not very widely used in industrial applications. There are several reasons for this. One is that they have a limited span. Second, they are subject to permanent decalibration if exposed to high temperatures. Third, they are quite fragile and should not be exposed to vibration or shock. Despite their lack of popularity in industrial applications, thermistors have achieved wide use in the food transportation and service industry.

Infrared Technology

Infrared (IR) sensing is usually done by means of an infrared thermometer. An infrared thermometer measures the infrared energy emitted by materials at temperatures above absolute zero, and uses this value to determine the temperature. One basic design includes a lens that focuses infrared energy onto a detector. This energy is then converted to an electrical signal that can be displayed in temperature units. Ambient temperature variations must be compensated for to give an accurate reading. Using this arrangement, it is possible to determine the temperature of an object without making physical contact with the object being measured.

The ability to make non-contact temperature measurement of objects makes infrared technology well suited for measuring temperature in situations where probe-type sensors do not produce accurate results. Examples include objects at a distance, moving objects, objects in a vacuum, objects in an electromagnetic field or applications requiring a fast response.

While designs for IR thermometers have been around since the 19th century, the technology to create practical measuring instruments from these designs was not available until the 1930s. Since that time, many advances have been made in the use of infrared thermometers, and they have gained wide use in research and industry.

Infrared thermometers include both fixed and portable types. Portable infrared thermometers include portable infrared thermocouples and point-and-shoot infrared thermometers. Fixed infrared thermometers include fixed infrared thermocouples, online infrared thermometers and linescanners. Infrared cameras or devices based on thermal imaging technology typically are high-end infrared products, which can cost in the range of $20,000 to $100,000. These products incorporate many features that make them different from other temperature sensors.

The following sections describe the three most common types of infrared thermometers used in industry:

- Infrared thermocouples
- Portable (point-and-shoot) and fixed (online) infrared thermometers
- Infrared linescanners

Infrared Thermocouples

Infrared thermocouples, despite their name, are not actually thermocouples. Instead, they are a type of thermometer that contains an infrared detector. The output from infrared thermocouples emulates the output from particular thermocouple types. If someone wishes to replace a type K thermocouple with a non-contact form of measurement, an infrared thermocouple is available for that thermocouple type. By emulating the output from a particular thermocouple type, infrared thermocouples can replace thermocouples and provide the input that a loop controller, programmable logic controller (PLC), transmitter, or recorder is expecting. Different infrared thermocouple models are designed to match particular temperature requirements. Exergen (Watertown, MA) was among the first companies to receive a patent on infrared thermocouples, in 1992.

Many infrared thermocouples contain a sensing detector called a thermopile. A thermopile is an array of thermocouple junctions that are connected together. The thermopile contains a black material that absorbs infrared radiation. The temperature of the source is proportional to the amount of infrared radiation absorbed by the thermocouple, and the thermocouple junctions produce a corresponding voltage output.

Dexter Research Center (Dexter, Michigan) is a major supplier of infrared sensing thermopile detectors. Dexter's thermopiles are hermetically sealed in an atmosphere of inert gas.

Infrared Thermometers

Infrared thermometers are available in both portable and fixed models. Portable models use a point-and-shoot method. If you point the thermometer at the material or object whose temperature you want to measure, you can read the temperature of the object on the thermometer display. Some models are available with circular laser sighting. These models show the actual area whose temperature is being measured with a red circular display. Portable models can be used to measure the temperature of many different devices. Examples of applications include measuring the temperature of electrical circuits, automobile engines, tires, concrete, steam traps, furnaces, food transportation units, heat-treating units and plastics.

Fixed infrared thermometers are also called online thermometers. Online thermometers are used to measure the temperature of materials in a fixed location , such as a process control loop. Fixed thermometers are available in a variety of body formats, operating wavelengths and output signals. Materials that are extremely hot, moving or inaccessible are ideal candidates for online systems.

Infrared Linescanners

Infrared linescanners contain an infrared thermometer, a rotating mirror and accompanying electronics. As the mirror scans across the product's surface, the thermometer can take a large number of individual temperature measurements. If the product is moving, two-dimensional data can be obtained. Output from the linescanner is transmitted to a personal computer, and a thermal map of the surface of the product is displayed on the computer monitor. Linescanners are used in the manufacturing of flat glass and glass windshields, and in metals manufacturing.

Fiber Optic Temperature Sensor Technology

Fiber optic temperature sensors use optical fibers in making temperature measurements. Luxtron claims to be the first company to commercialize fiber optic temperature sensor technology. Luxtron, founded in 1978, calls its pioneering temperature sensing method Fluoroptic® Thermometry. Other technologies employed by Luxtron include Radiation Thermometry and Optical Thin Film Monitoring.

It's Hard to Play Favorites: The Relative Advantages of Different Temperature Sensors

Each temperature sensor has its own merits. Thermocouples and RTDs comprise the vast majority of industrial temperature measurements, but infrared and fiber optic technology comes in handy for certain situations.

RTDs tend to respond more slowly than thermocouples. RTDs also cannot be used at high temperatures. At temperatures greater than660°C, thermocouples or infrared thermometers must be used.

However, RTDs do have several advantages over thermocouples in industrial applications. One is that RTDs are inherently more stable than thermocouples. Typical stability for RTDs is rated at ±0.5º per year. Second, RTDs tend to be more accurate than thermocouples. The requirement that thermocouples be cold-junction compensated builds in an inherent amount of inaccuracy in thermocouples that does not have a parallel in RTDs.

Infrared thermometers can measure the temperature of objects at higher temperatures than RTDs and most thermocouples. They also can measure objects and processes at a distance, since they do not need to have contact with the object or process being measured.

In technology, linescanners fall between infrared thermometers and thermal imaging cameras. Linescanners take a large number of individual temperature measurements, and work well in measuring moving objects and processes.

Fiber optic temperature sensors function well in harsh environments, including radio frequency (RF), microwave and high voltage environments. Though they are more expensive than the other temperature sensing methods, fiber optic temperature sensors succeed in some applications where temperature cannot be measured reliably by other means.

Table 2-2 describes the advantages and disadvantages of thermocouples, RTDs, thermistors and IC sensors.

Table 2-2
Relative Advantages of Different Temperature Sensors

Quality	Thermocouples	RTDs	Thermistors	IC Sensors
Range	-400 – 4200ºF	-200 – 1475ºF	-100 º – 500ºF	-70º – 300ºF
Accuracy	Less accurate than RTD	More accurate than T/C	More accurate than RTD	Highly accurate
Ruggedness	Highly rugged	Sensitive to strain & shock	Less rugged than T/Cs	Sensitive to shock
Linearity	Highly nonlinear	Somewhat nonlinear	Highly nonlinear	Highly linear
Drift	Subject to drift	Less subject to drift than T/C	Less subject to drift than T/C	More subject to drift than RTDs
Cold Junction Compensation	Required	None	None	None
Response	Fast response	Relatively slow response	Faster than RTD	Faster than RTD
Cost	Low cost except for noble metal T/Cs	Higher cost than T/C	Low cost	Low cost
Ease of Use	Application complex due to multiple types	High ease of use	High ease of use within limited parameters	Application can be complex in semiconductor applications

Temperature Units

Table 2-3 gives conversion formulas for common temperature units:

Table 2-3
Common Temperature Unit Conversions

From	To Fahrenheit	To Celsius	To Kelvin
Fahrenheit (degrees F)	°F	(F-32)*5/9	(F-32)*5/9+273.15
Celsius (degrees C)	(C*9/5)+32	°C	C+273.15
Kelvin (K)	(K-273.15)*9/5+32	K-273.15	K

Table 2-4 gives common values for different temperature measurement points:

Table 2-4
Common Temperature Measurement Values

	Fahrenheit	Celsius	Kelvin
Body Temperature	98.6°	37°	310.2
Boiling Point of Water	212°	100°	373
Freezing Point of Water	32°	0°	273
Hot Day	86°	30°	303
Cold Day	35°	2°	275
Room Temperature	68°	20°	293
Surface of the Sun	10,100°	5600°	5900