UNIT - II

THERMAL SENSORS

Temperature measurement is a vital part of most industrial operations and is typically accomplished by a temperature sensor--a thermocouple or a resistance temperature detector (RTD)--in contact with a solid surface or immersed in a fluid. Although these sensors have overlapping temperature ranges, each has certain application-dependent advantages.

Choosing the perfect sensor for a particular application therefore requires an understanding of the basics of temperature sensors.

There are four basic types of temperature measuring devices, each of which uses a different principle:

1. Mechanical Sensors.
2. Thermojunctive (thermocouples)
3. Thermoresistive (RTDs and thermistors)
4. Radiative (infrared and optical pyrometers)

Each of these is defined and the discussed in this course.

MECHANICAL Sensors:

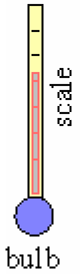
Principle of Operation

A change in temperature causes some kind of mechanical motion, typically due to the fact that most materials expand with a rise in temperature. Mechanical thermometers can be constructedto use liquids, solids, or even gases as the temperature-sensitive material.

The mechanical motion is read on a physical scale to infer the temperature. The examples include:

1) *Liquid-in-glass thermometer*

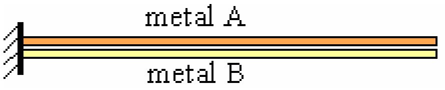
The most common and well-known thermometer is the liquid-in-glass thermometer.



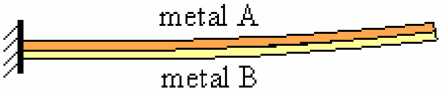
As the temperature rises, the liquid expands, moving up the tube. The scale is calibrated toread temperature directly. Usually, mercury or some kind of alcohol is used for the liquid.

2) *Bimetallic strip thermometer*

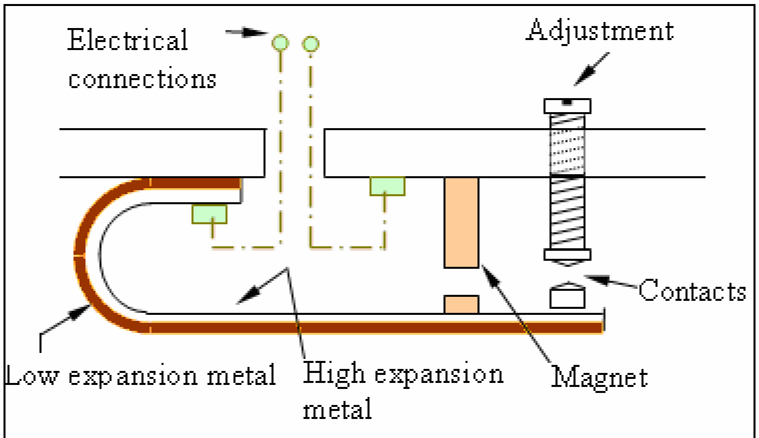
Two dissimilar metals are bonded together into what is called a bimetallic strip as shownbelow.



Suppose metal A has a smaller coefficient of thermal expansion than does metal B. As temperature increases, metal B expands more than does metal A, causing the bimetallicstrip to curl upwards as shown below.



One common application of bimetallic strips is in air-conditioning thermostats, where a bimetallic strip is used as the arm of a switch between electrical contacts. As the room temperature changes, the bimetallic strip bends as discussed above. When the bimetalic strip bends far enough, it makes contact with electrical leads which turn the heat or air conditioning on or off.

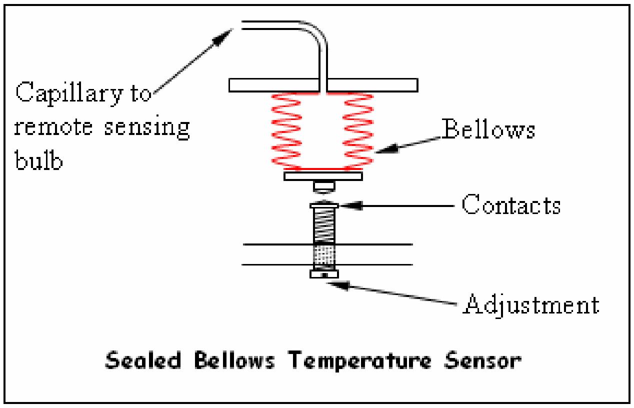


Bi-Metallic Thermostat

Another common application is for use as oven thermometers or wood burner thermometers. These thermometers consist of a bimetallic strip wound up in a spiral,attached to a dial which is calibrated into a temperature scale.

3) Sealed Bellows

The sealed bellows type is filled with a gas, vapor or liquid, which responds to change in temperature by variation in volume and pressure causing expansion or contraction.

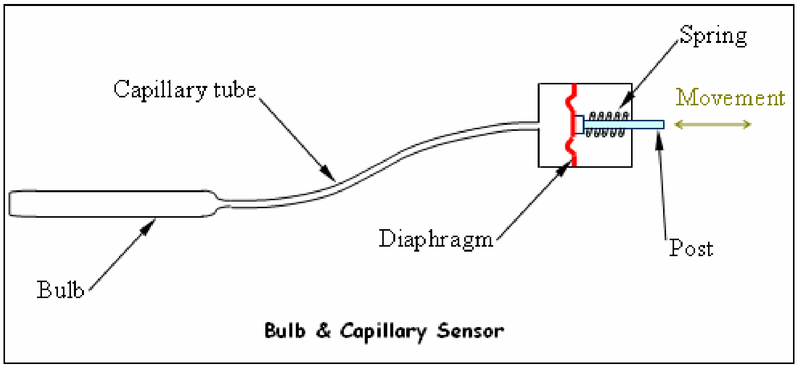


Sealed Bellows Temperature Sensor

4) Bulb and Capillary Sensor

Bulb and capillary elements are used where temperatures are to be measured in ducts, pipes, tanks or similar locations remote from the controller.

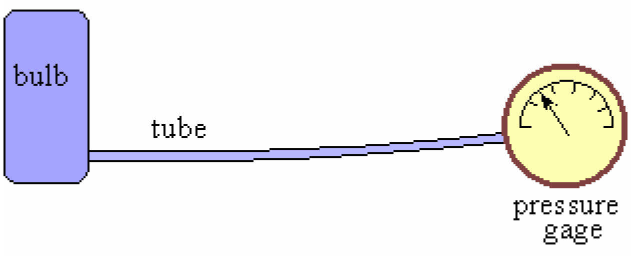
The bulb is filled with liquid, gas or refrigerant depending on the temperature range required. Expansion of the fluid in the heated bulb exerts a pressure which is transmitted by the capillary to the diaphragm and there translated into movement.



Bulb & Capillary Sensor

5) Pressure thermometer

A pressure thermometer, while still considered mechanical, operates by the expansion of a gas instead of a liquid or solid. (Note: There are also pressure thermometers which use a liquid instead of a gas.)



Suppose the gas inside the bulb and tube can be considered an ideal gas. The ideal gas lawis:

$PV = m R T$

Where:

- P is the pressure,
- V is the volume of the gas,
- m is the mass of the gas,
- R is the gas constant for the specific gas (not the universal gas constant), and
- T is the absolute temperature of the gas.

The bulb and tube are of constant volume, so V is a constant. Also, the mass, m, of gas in the sealed bulb and tube must be constant. Hence, the above equation reduces to $P = kT$, where k is constant.

A pressure thermometer therefore measures temperature *indirectly* by measuring pressure. The gage is a pressure gage, but is typically calibrated in units of temperature instead.

A common application of this type of thermometer is measurement of outside temperature from the inside of a building. The bulb is placed outside, with the tube running through the wall into the inside. The gage is on the inside. As T increases outside, the bulb temperature causes a corresponding increase in pressure, which is read as a temperature increase on the gage.

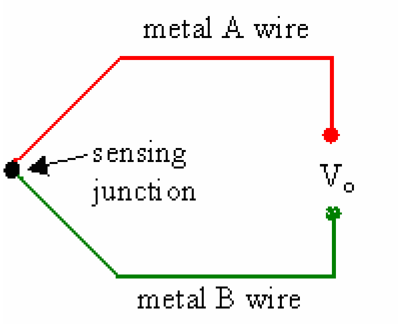
THERMOCOUPLES

A thermocouple is made up of two dissimilar metals, joined together at one end, that produce a voltage (expressed in millivolts) with a change in temperature. The junction of the two metals, called the sensing junction, is connected to extension wires. Any two dissimilar metals may be used to make a thermocouple.

Principle of Operation

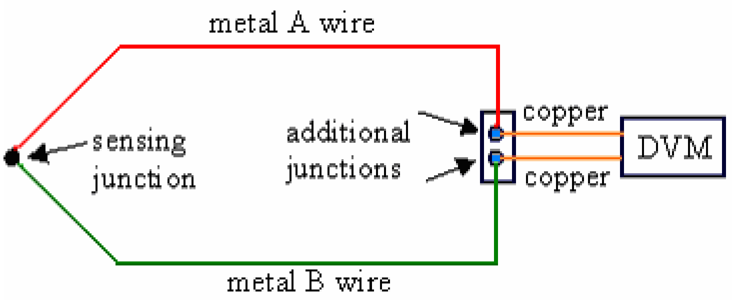
1. When two dissimilar metals are connected together, a small voltage called a *thermo- junction voltage* is generated at the junction. This is called the *Peltier effect*.
2. If the temperature of the junction changes, it causes voltage to change too, which can bemeasured by the input circuits of an electronic controller. The output is a voltage proportional to the temperature difference between the junction and the free ends. This is called the *Thompson effect*.
3. Both of these effects can be combined to measure temperature. By holding one junction at a known temperature (reference junction) and measuring the voltage, the temperatureat the sensing junction can be deduced. The voltage generated is directly proportional to the temperature difference. The combined effect is known as the *thermo-junction effect* or the *Seebeck effect*.

The figure below illustrates a simple thermocouple circuit.



The voltage is measured to infer the temperature. In practical operation, wires A and B are connected to a digital voltmeter (DVM), digital multimeter (DMM), digital data acquisition system, or some other voltage measuring device. If the measuring device has very high input impedance, the voltage produced by the thermo-junction can be measured accurately.

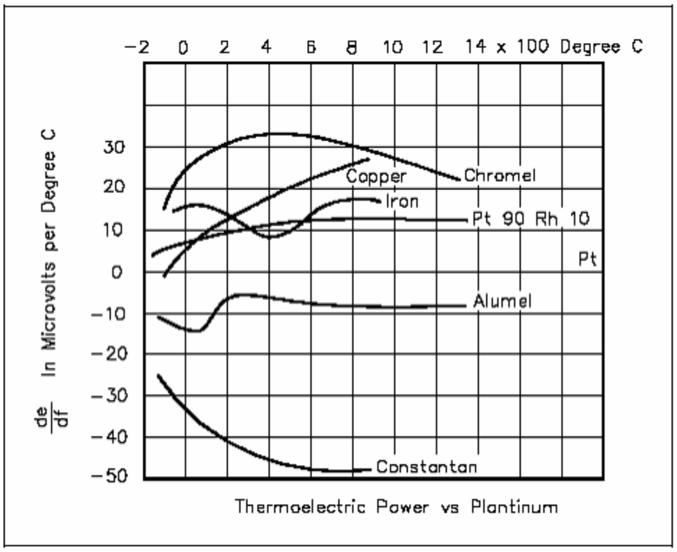
However, the main problem with thermocouple temperature measurement is that wires A and B must connect to the leads of the voltmeter, which are generally made of copper. If neither wire Anor wire B is itself copper, connecting to the DVM creates *two more thermo-junctions*! (Thermocouple metals are typically not the same as those of the DVM leads.) These additional thermo-junctions also produce a thermo-junctive voltage, which can create an error when trying to measure the voltage from the sensing junction.



Thermocouple Materials

Thermocouples may be constructed of several different combinations of materials. The performance of a thermocouple material is generally determined by using that material with platinum. The most important factor to be considered when selecting a pair of materials is the "thermoelectric difference" between the two materials. A significant difference between the two materials will result in better thermocouple performance. The figure below illustrates the characteristics of the more commonly used materials when used with platinum. For example: Chromel-Constantan is excellent for temperatures up to 2000°F; Nickel/Nickel-Molybdenum sometimes replaces Chromel-Alumel; and Tungsten-Rhenium is used for temperatures up to 5000°F. Some combinations used for specialized applications are Chromel-White Gold, Molybdenum-Tungsten, Tungsten-Iridium, and Iridium/Iridium-Rhodium.

The figure below illustrates the thermocouple material characteristics when used with Platinum.



Characteristics of Thermocouple Types

Of the infinite number of thermocouple combinations, the Instrument Society of America (ISA) recognizes 12 of them. Most of these thermocouple types are known by a single-letter designation; the most common are J, K, T, and E. The compositions of thermocouples are international standards, but the color codes of their wires are different. For example, in the U.S. the negative lead is always red, while the rest of the world uses red to designate the positive lead. Often, the standard thermocouple types are referred to by their trade names. For example,

1. A *type K* thermocouple has the color *yellow*, and uses *chromel – alumel,* which are thetrade names of the Ni-Cr and Ni-Al wire alloys.
2. A *type J* thermocouple has the color *black*, and uses *iron* and *constantan* as itscomponent metals. (Constantan is an alloy of nickel and copper.)
3. A *type T* thermocouple has the color *blue,* and uses *copper* and *constantan* as its component metals.
4. A type S thermocouple uses Pt/Rh-Pt
5. A type E thermocouple uses Ni/Cr-Con
6. *A type N thermocouple uses Ni/Cr/Si-Ni/Si*

Each calibration has a different temperature range and environment, although the maximum temperature varies with the diameter of the wire used in the thermocouple. Variations in thealloy composition and the condition of the junction between the wires are sources of error in temperature measurements. The standard error of thermocouple wire varies from ±0.8 °C to ±4.4 °C, depending on the type of thermocouple used. The K type thermocouple is recommended for most general purpose applications. It offers a wide temperature range, low standard error, and has good corrosion resistance. In fact, many digital multi-meters (DMMs)can measure temperature by plugging in a type K thermocouple with standard connections.

The voltage produced by a thermocouple varies *almost*, but not exactly, linearly with temperature.

Therefore, there are no simple equations to relate thermocouple voltage to temperature. Rather, voltage is tabulated as a function of temperature for the various standard thermocouples. In order to convert the millivolt reading to its corresponding temperature, you must refer to tables like the one shown below. These tables can be obtained from the thermocouple manufacturer, and they list the specific temperature corresponding to a series of millivolt readings. *By convention, the reference temperature for thermocouple tables is 0ºC.*

Temperature V/s Voltage Reference Table for Type J

Temperature (°C)	**voltage (mV)**
0.0	0.000
10.0	0.507
20.0	1.019
30.0	1.537
40.0	2.059
50.0	2.585
60.0	3.116
70.0	3.650
80.0	4.187
90.0	4.726
100.0	5.269

Choosing a thermocouple type

Because thermocouples measure in wide temperature ranges and can be relatively rugged,they are very often used in industry. The following criteria are used in selecting a thermocouple:

1. Temperature range
2. Chemical resistance of the thermocouple or sheath material
3. Abrasion and vibration resistance
4. Installation requirements (may need to be compatible with existing equipment; existingholes may determine probe diameter).

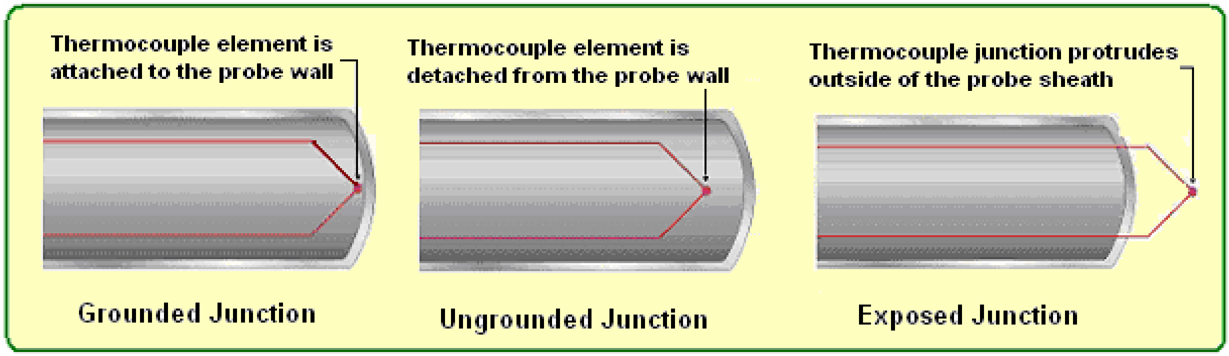
Standard Specifications

- Diameters: Standard diameters: 0.010", 0.020", 0.032", 0.040", 1/16", 1/8", 3/16", and1/4" with two wires.
- Length: Standard thermocouples have 12 inch immersion lengths. Other lengths arecustom made.
- Sheaths: 304 stainless steel and Inconel are standard.
- Insulation: Magnesium Oxide is standard. Minimum insulation resistance wire to wire orwire to sheath is 1.5megohms at 500 volts dc in all diameters.
- Calibration: Iron-Constantan (J), *chromel – alumel* (K), Copper-Constantan (T), and Chromel-Constantan (E) are standard calibrations.
- Bending: Easily bent and formed. Bend radius should be not less than twice the diameter of the sheath.
- Polarity: In the thermocouple industry, standard practice is to color the negative lead red.
- Thermocouple Junctions: Sheathed thermocouple probes are available with one of threejunction types: grounded, ungrounded or exposed.

Grounded Junction- In this type, the thermocouple wires are physically attached to the inside of the probe wall. This results in good heat transfer from the outside, through the probe wall to the thermocouple junction. The grounded junction is recommended for the measurement of static or flowing corrosive gas and liquid temperatures and for high pressure applications. The junction of a grounded thermocouple is welded to the protective sheath giving faster response than the ungrounded junction type.

Ungrounded Junction- In an underground probe, the thermocouple junction is detached from the probe wall. Response time is slowed down from the grounded style, but the ungrounded offers electrical isolation of 1.5 M1/2 at 500 Vdc in all diameters. An ungrounded junction is recommended for measurements in corrosive environments where it is desirable to have the thermocouple electronically isolated from and shielded by the sheath. The welded wire thermocouple is physically insulated from the thermocouple sheath by MgO powder (soft).

Exposed Junction- In the exposed junction style, the thermocouple protrudes out of the tip of the sheath and is exposed to the surrounding environment. This type offers the best response time, but is limited in



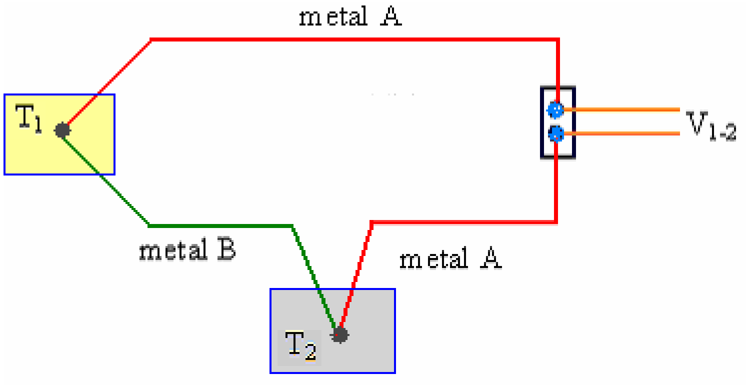
use to non-corrosive and non-pressurized applications. The junction extends beyond the protective metallic sheath to give accurate fast response. The sheath insulation is sealed where the junction extends to prevent penetration of moisture or gas which could cause errors.In summary, the exposed junction provides the quickest response time followed by grounded junction. Temperature measurement decisions can make or break the expected results of the process. Choosing the correct sensor for the application might be a difficult task, but processing that measured signal is also very critical.

There are three laws or rules that apply to thermocouples:

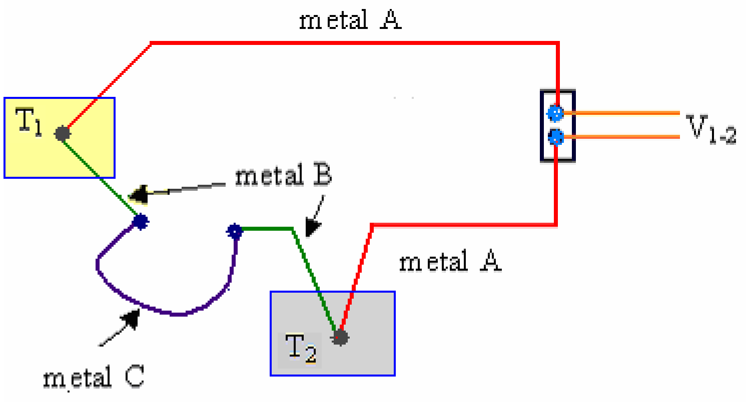
1) *Law of intermediate metals*

"A third (intermediate) metal wire can be inserted in series with one of the wires without changing the voltage reading (provided that the two new junctions are at the same temperature)".

Consider the setup below, where a rectangle around a thermo-junction indicates a constant temperature bath (e.g. a pot of boiling water or an ice-water bath).



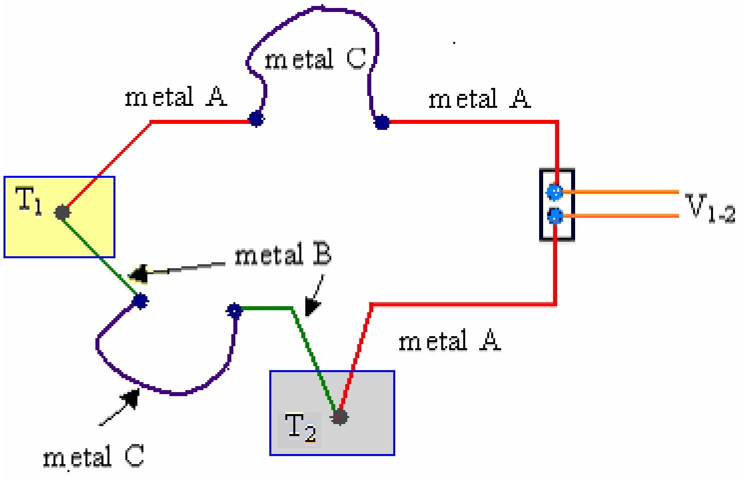
The law of intermediate metals states that the voltage reading, V_{1-2} does not change if one adds a third (intermediate) wire in line with any of the wires in the circuit, as sketched below:



In the above diagram, it is assumed that both of the new junctions (between metal B and metal C) are at the same temperature, i.e. ambient temperature, T_a.

One can easily see that the law of intermediate metals must hold here, since whatever voltage is generated at one of the new junctions is canceled exactly by an equal and opposite voltage generated at the other new junction.

Likewise, metal C can be inserted anywhere else in the circuit without any effect on the output voltage, provided that the two new junctions are at the same temperature. For example, consider the following modified circuit:



Again, if the two new junctions (this time between metals A and C) are at the same temperature, there is no net effect on the output voltage.

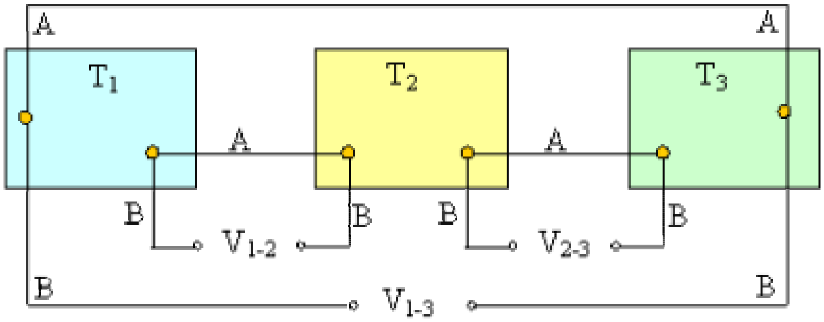
2) *Law of intermediate temperatures*

"If identical thermocouples measure the temperature difference between T_1 and T_2, and the temperature difference between T_2 and T_3, then the sum of the corresponding voltages V_{1-2} + V_{2-3} must equal the voltage V_{1-3} generated by an identical thermocouple measuring the temperature difference between T_1 and T_3".

Mathematical statement of the law of intermediate temperatures:

$V_{1-3} = V_{1-2} + V_{2-3}$ for any three temperatures, T_1, T_2, and T_3.

Consider the setup below, where six thermo-junctions are shown, two in each constant temperature bath. Note: To avoid clutter in the diagram, the copper leads of the DVM are no longer shown. Also, for brevity, letters A and B indicate metal A and metal B; two different types of thermocouple wires.



By the notation convention adopted here:

$V_{1\text{-}3} = V_{1\text{-}R} - V_{3\text{-}R}$,

which can be written as:

$V_{1\text{-}3} = (V_{1\text{-}R} - V_{2\text{-}R}) + (V_{2\text{-}R} - V_{3\text{-}R})$

But since (also by definition):

$V_{1\text{-}2} = V_{1\text{-}R} - V_{2\text{-}R}$, and

$V_{2\text{-}3} = V_{2\text{-}R} - V_{3\text{-}R}$,

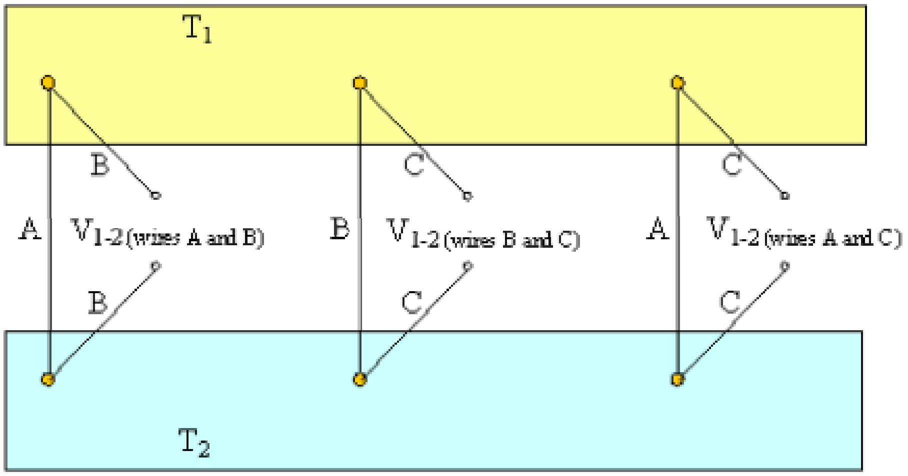
it follows directly that:

$V_{1\text{-}3} = V_{1\text{-}2} + V_{2\text{-}3}$.

3) *Law of additive voltages*

"For a given set of 3 thermocouple wires, A, B, and C, all measuring the same temperature difference $T_1 - T_2$, the voltage measured by wires A and C must equal the sum of the voltagemeasured by wires A and B and the voltage measured by wires B and C".

Consider the setup below, where six thermo-junctions are shown, three in constant temperature bath T_1, and three in constant temperature bath T_2. As above, letters A, B, and C indicate different types of thermocouple wires.



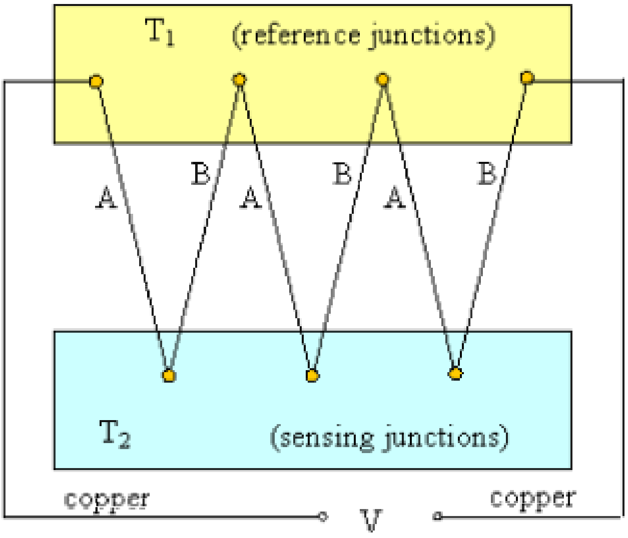
The law of additive voltages can be stated mathematically as:

$V_{1\text{-}2\,(\text{wires A and C})} = V_{1\text{-}2\,(\text{wires A and B})} + V_{1\text{-}2\,(\text{wires B and C})}$

Or, rearranging in terms of voltage *differences*, $V_{1\text{-}2\,(\text{wires A and B})} = V_{1\text{-}2\,(\text{wires A and C})} - V_{1\text{-}2\,(\text{wires B and C})}$.

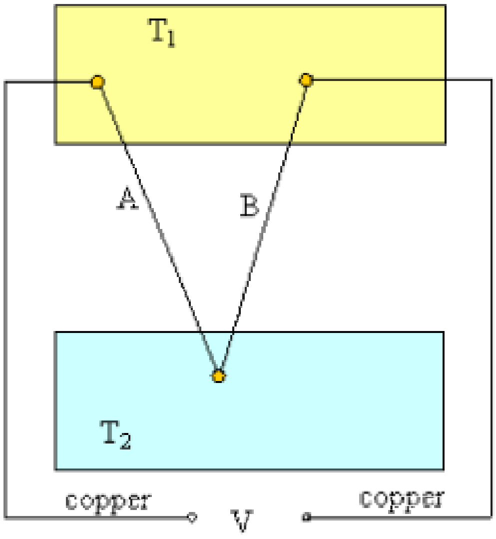
Thermopile

A *thermopile* is defined as several thermocouples connected in series. For example, athermopile with three sensing junctions is shown below:



As T_2 is increased, the output voltage increases significantly. The advantage of a thermopile (ascompared to just one sensing junction) is *increased sensitivity*.

Here, the voltage output is three times that which is generated by just one thermocouple underotherwise identical conditions, as sketched below:



With enough sensing junctions, a thermopile can actually generate a useful voltage. Forexample, *thermopiles are often used to control shut-off valves in furnaces*.

THERMO-RESISTIVE TEMPERAURE MEASURING DEVICES

A change in temperature causes the electrical resistance of a material to change. The resistance change is measured to infer the temperature change.

There are two types of thermo-resistive measuring devices:

1) Resistance temperature detectors (RTD) and

2) Thermistors

Resistance Temperature Detectors

A resistance temperature detector (abbreviated RTD) is basically either a long, small diameter metal wire wound in a coil or an etched grid on a substrate, much like a strain gage. Platinum is the most common metal used for RTDs.

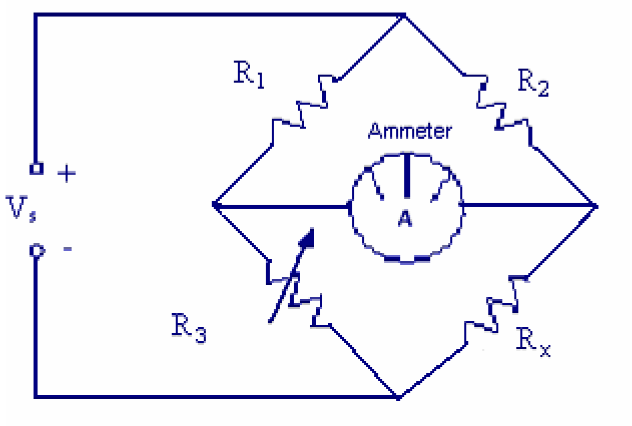
Principle of Operation

Resistance Temperature Detectors (RTD) operates on the principle that the electrical resistanceof a metal changes predictably in an essentially linear and repeatable manner with changes in temperature. RTD have a positive temperature coefficient (resistance increases with temperature). The resistance of the element at a base temperature is proportional to the length of the element and the inverse of the cross sectional area.

A typical electrical circuit designed to measure temperature with RTDs actually measures a change in *resistance* of the RTD, which is then used to calculate a change in temperature. The resistance of an RTD increases with increasing temperature, just as the resistance of a strain gage increases with increasing strain.

Bridge Circuit Construction

The figure below shows a basic bridge circuit which consists of three known resistances, R1,R2, and R3 (variable), an unknown variable resistor RX (RTD), a source of voltage, and a sensitive ammeter.



Bridge Circuit

Resistors R1 and R2 are the ratio arms of the bridge. They ratio the two variable resistances for current flow through the ammeter. R3 is a variable resistor known as the standard arm that is adjusted to match the unknown resistor. The sensing ammeter visually displays the current that is flowing through the bridge circuit. Analysis of the circuit shows that when R3 is adjusted so that the ammeter reads zero current, the resistance of both arms of the bridge circuit is the same. The relationship of the resistance between the two arms of the bridge can be expressed as:

$$\frac{R_1}{R_3} = \frac{R_2}{R_x}$$

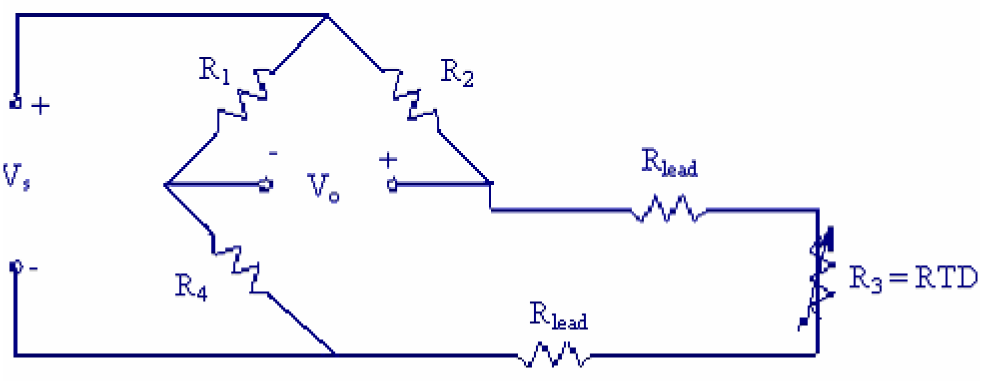
Since the values of R1, R2, and R3 are known values, the only unknown is Rx. The value of Rx can be

$$R_x = \frac{R_2 R_3}{R_1}$$

calculated for the bridge during an ammeter zero current condition. Knowing this, resistance value provides a baseline point for calibration of the instrument attached to the bridge circuit. The unknown resistance, Rx, is given by:

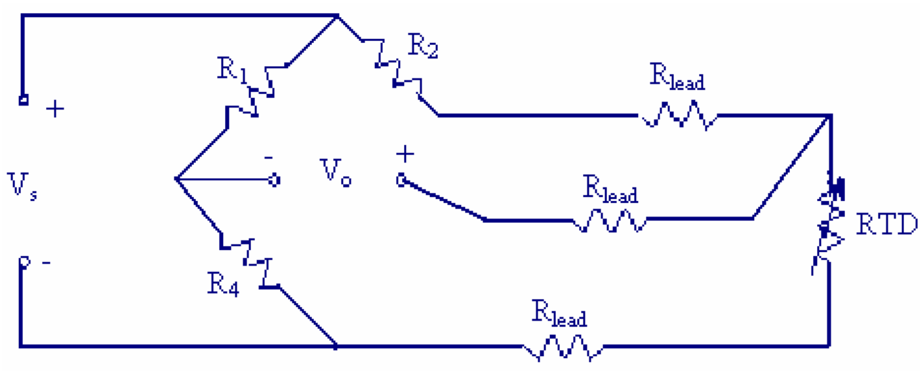
RTD Bridge Circuit Operation

One simple circuit is the quarter bridge Wheatstone bridge circuit, here called a ***two-wire RTD bridge circuit***.



R_{lead} represents the resistance of one of the wires (called *lead wires*) that run from the bridge to the RTD itself. Lead resistance was of no concern in strain gage circuits because R_{lead} remained constant at all times.

For RTD circuits, however, some portions of the lead wires are exposed to changing temperatures. Since the resistance of metal wire changes with temperature, R_{lead} changes with T, which can cause errors in the measurement. This error can be non-trivial - *changes in lead resistance may be misinterpreted as changes in RTD resistance*. Furthermore, there are two lead wires in the two-wire RTD bridge circuit shown above, which doubles the error. A clever circuit designed to eliminate the lead wire resistance error is called a *three-wire RTD bridge circuit*. The three-wire RTD bridge circuit is shown below.



It is still a quarter bridge circuit, since only one of the four bridge resistors has been replaced by the RTD. However, one of the lead wires has been placed on the R_2 leg of the bridge instead of the R_3 leg.

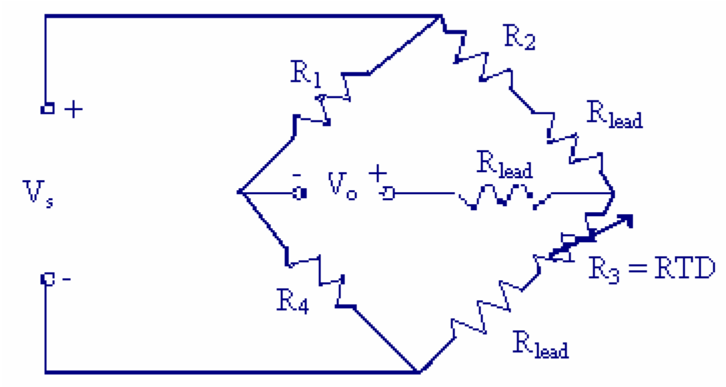
To analyze this circuit, assume that $R_1 = R_4$, and $R_2 = R_3$ initially, when the bridge is balanced. Recall the general formula for a Wheatstone bridge:

$$V_o = V_s \frac{R_3 R_1 - R_4 R_2}{(R_2 + R_3)(R_1 + R_4)}.$$

Notice that R_3 and R_2 have opposite signs in the above equation. So, if the lead wire resistance in leg 2 (top) and that in leg 3 (bottom) are the *same, the lead resistances cancel each other out*, with no net effect on the output voltage, thus eliminating the error.

What about the third lead resistance, R_{lead} of the middle wire? Well, since V_o is measured with a nearly infinite impedance device, *no current flows in the middle lead wire*, so its resistance does not affect anything!

The following re-drawn equivalent circuit may help explain why the lead resistances cancel out:



In the above diagram, it is clear that if R_{lead} changes equally in leg 2 and leg 3 of the bridge, its effect cancels out.

Advantages: Linear resistance with temperature, good stability, wide range of operating temperature, interchangeable over wide temperature range.

Disadvantages: Small resistance change with temperature, responses may be slower, subject to self heating, transmitter or three to four wire leads required for lead resistance compensation, external circuit power required.

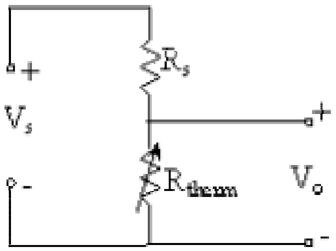
Thermistors

Thermistors are temperature sensitive semiconductors that exhibit a large change in resistance over a relatively small range of temperature. There are two main types of thermistors: positive temperature coefficient (PTC) and negative temperature coefficient (NTC). NTC thermistors exhibit the characteristic of resistance falling with increasing temperature. These are most commonly used for temperature measurement.

A *thermistor* is similar to an RTD, but a *semiconductor material* is used instead of a metal. A thermistor is a *solid state* device and has larger *sensitivity* than does an RTD. Unlike RTD's, the temperature-resistance characteristic of a thermistor is non-linear, and cannot be characterized by a single coefficient. Furthermore, unlike RTDs, the resistance of a thermistor *decreases* with increasing temperature.

Thermistors cannot be used to measure high temperatures compared to RTDs. In fact, the maximum temperature of operation is sometimes only 100 or 200°C.

Manufacturers commonly provide resistance-temperature data in curves, tables or polynomial expressions. Linearizing the resistance-temperature correlation may be accomplished with analog circuitry, or by the application of mathematics using digital computation. A typical thermistor circuit is shown below.



From the circuit diagram, it is clear that this is a simple voltage divider. R_s is some fixed (supply)resistor. R_s and the supply voltage, V_s, can be adjusted to obtain the desired range of output voltage V_o for a given range of temperature.

Advantages: Large resistance change with temperature, rapid response time, good stability, high resistance eliminates difficulties caused by lead resistance, low cost and interchangeable.

Disadvantages: Non-linear, limited operating temperature range, may be subjected to inaccuracy due to overheating, current source required.

RADIATIVE TEMPERATURE MEASURING DEVICES

Two types of radiative measuring devices are:

1. Infrared pyrometers, and
2. Optical pyrometers.

Infrared Pyrometer

Infrared temperature sensors also known as pyrometers or non-contact temperature sensorsare used to measure the temperature of an object without contact. This is different from most temperature measurement devices, which require direct contact with the measured media. Non- contact methods of temperature measurement are advantageous when contact methods are impossible or impractical, such as when the target is inaccessible or so hot that contact devices will not survive.

Principle of Operation

Infrared temperature sensors use the principle that any object emits an amount of energy that isa function of its temperature. This function dictates that as the temperature of an object rises, sodoes the amount of energy it emits.

"An infrared temperature sensor determines temperature by measuring the intensity of energygiven off by an object."

Calculating the temperature of an object from the measured emitted energy seems straightforward. However, the quantity of energy emitted by an object is not a function of temperature only. The other variable besides temperature that affects emissions is emissivity. From a practical standpoint, emissivity is an inherent surface characteristic that can fluctuate with changes to surface oxidation, texture, composition, and microstructure. When it comes to non-contact temperature measurement, all that is really important is knowing that emissivity is a correction factor greater than 0 but less than 1 that enables infrared temperature sensors to output the correct surface temperature.

<u>Mathematical statement of Infrared Temperature Measurement:</u>

The amount of energy a surface emits is a function of temperature and emissivity, therefore to correctly determine surface temperature from a measurement of emitted energy, it is imperative to know something about fundamentals of radiation and surface's emissivity. The fundamental equation for radiation from a body is the ***Stefan-Boltzmann equation:***

$$E = \varepsilon\sigma T^4,$$

where:

- E is the emissive power radiated per unit area (units of W/m^2).
- ε is the emissivity, defined as the fraction of blackbody radiation emitted by an actual surface. The emissivity must lie between 0 and 1, and is dimensionless. Its value depends greatly on the type of surface. A blackbody has an emissivity of exactly 1.
- σ is the Stefan-Boltzmann constant:

  $$\sigma = 5.669\text{x}10^{-8}\ \frac{W}{m^2K^4}.$$

- T is the *absolute* temperature of the surface of the object (units of K). The following is a list of the emissivity of several common surfaces:

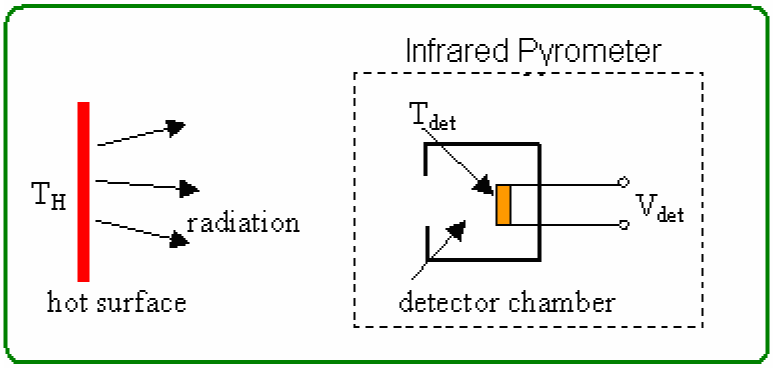
surface	**emissivity,** ε
aluminum (anodized)	0.84
aluminum (polished)	0.03
asphalt pavement	0.85 to 0.93
glass	0.62 to 0.95
human skin	approx. 0.95
water (deep)	0.95 to 0.96

The emissivity of other materials can be found in heat transfer textbooks. Once sufficient information about the surface's emissivity is obtained, the temperature sensor can be programmed to compensate for emissivity.

Calibration of Infrared Temperature Measurement

The challenge that perplexes manufacturers and users of infrared temperature sensors is definitively quantifying emissivity. Some surfaces have a predictable emissivity; others have an emissivity that will change significantly with no discernable pattern. Experience has sorted out which surfaces are easy to measure and which are difficult. With that, different types of non- contact temperature sensors have been developed that eliminate, or at least reduce, errors caused by emissivity variations.

An infrared pyrometer infers the temperature of a hot surface by measuring the temperature of a detector inside a detector chamber as shown below:



The detector itself is usually a thermopile. It measures T_{det}, the temperature of the detector inside the chamber. T_{ind} is the *indicated* temperature, which is calculated from T_{det}, from the known geometry and the radiation equations. T_{ind} is calibrated as a function of T_H for a body of some assumed emissivity.

The instrument is set up such that T_{ind} is a function of the voltage output. The instrument typically displays a temperature, i.e. T_{ind}, rather than voltage V_{det}.

T_{ind} can be thought of as an *uncorrected* estimate of T_H, since the emissivity of the object may not be the same as that assumed by the infrared pyrometer. In other words, if the actual emissivity of the object is not the same as the assumed emissivity, T_{ind} will be incorrect.

To correct for the actual emissivity of the object:

$$T_H = \left(\frac{\varepsilon_{assumed}}{\varepsilon_{actual}} \right)^{1/4} T_{ind}$$

In the above equations, ***absolute temperatures*** must be used.

Type of Infrared Temperature Sensors

Infrared temperature sensors fall into one of three categories: single-wavelength, dual wavelength and multi-wavelength.

1. Single wavelength temperature sensors, also referred to as single-color temperature sensors, measure all of the energy emitted from a target at one wavelength and calculate the average temperature of the measured area. They require that the target emissivity be relatively constant, or else error is introduced. Single-wavelength temperature sensors are appropriate for measuring an unobstructed target of constant emissivity.
2. Dual-wavelength temperature sensors, also known as two-color or ratio pyrometers, measure the energy emitted from a target at two different wavelengths, take a ratio of the energies, and calculate the temperature. Different from single-wavelength sensors, dual wavelength sensors tend to measure the hottest point in the target area and are less sensitive to emissivity variations. However, severe emissivity variations still introduce error. Dual wavelength temperature sensors are recommended for applications with intervening media such as dirty optics, scale, steam, dust, or water spray. Also, they are appropriate for targets with low or varying emissivity and situations with a partially filled field of view caused by mechanical obstructions or a small target.
3. Multi-wavelength sensors use sophisticated electronics to combine signals measured from multiple wavelengths and then calculate the temperature of surfaces with dramatic, yet repeatable, variations in emissivity. Multi wavelength sensors provide the samebenefits of a dual-wavelength sensor, but are recommended for non-grey body materials like aluminum, copper, zinc, and stainless steel.

Once the most appropriate type of sensor has been chosen considering the emissivity characteristics of the measured target, the rest of the challenge is selecting a sensor package appropriate for the sensor's operating environment and adjusting for other potential causes of error. Operating conditions to consider when selecting a sensor package include ambient temperature, cleanliness, humidity, electromagnetic radiation, atmosphere, and accessibility. Other causes of error are those conditions that artificially either add to or subtract from the amount of energy transmitted from the target to the sensor. Such sources include background energy that is reflected off of a surface into the sensor, mechanical obstructions that block emitted energy, and windows, thin films, or intervening media that interfere with specific wavelengths.

Optical Pyrometer

An optical pyrometer is useful for measuring very high temperatures (even flames). The optical pyrometer uses an infrared radiation-sensitive sensor, e.g. a photodiode or a photoresistor, to compare the radiation from the unknown with that of the radiation from an internal incandescent source. The accuracy of the optical pyrometer is very much a function of the emissivity of the device that is radiating the heat. The obvious advantage in using an optical pyrometer at very high temperatures is that the measurement is non-contacting.

This approach is very expensive, and due to the variability in emissivity of many physicalbodies, it is not very accurate. However, for making non-contact measurements on very high temperature bodies such as molten glass and molten steel, the optical pyrometer excels.

Basic Characteristics are as follows:

- Infrared radiation sensitive
- Accuracy= f (emissivity)
- Useful at very high temperatures
- Non-contacting
- Very expensive
- Not very accurate

Summarizing

The two most common type of temperature sensors are Thermocouples and RTD's. Although these sensors have overlapping temperature ranges, each has certain application-dependent advantages. These are summarized below.

Temperature Sensor Selection Guide		
	RTD	**Thermocouple**
Temperature Range	–200°C to 850°C –328°F to 1562°F	–190°C to 1821°C –310°F to 3308°F
Accuracy	±0.001°F to 0.1°F	±1°F to 10°F

Response Time	Moderate	Fast
Stability	Stable over long periods <0.1% error/5 yr.	Not as stable 1°F error/yr.
Linearity	Best	Moderate
Sensitivity	High sensitivity	Low sensitivity

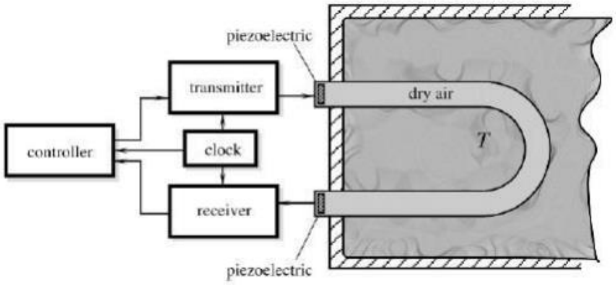
An RTD is the sensor of choice when sensitivity and application flexibility are the most important criteria.

When it comes to component cost, an RTD is more expensive than a thermocouple.

Acoustic Temperature Sensor:

Under extreme conditions, temperature measurement may become a difficult task. These conditions include a cryogenic temperature range, high radiation levels inside nuclear reactors, and so forth. Under such unusual conditions, acoustic temperature sensors may come in quite handy. An operating principle of such a sensor is based on a relationship between temperature of the medium and speed of sound. An acoustic temperature sensor is composed of three components: *an ultrasonic transmitter, an ultrasonic receiver, and a gas-filled hermetically sealed tube.*

The transmitter and receiver are ceramic piezoelectric plates which are acoustically decoupled from the tube to assure sound propagation primarily through the enclosed gas, which, in most practical cases, is dry air. Alternatively, the transmitting and receiving crystals may be incorporated into a sealed enclosure with a known content whose temperature has to be measured; that is, an intermediate tube in not necessarily required in cases where the internal medium, its volume, and mass are held constant. When a tube is used, care should be taken to prevent its mechanical deformation and loss of hermeticity under the extreme temperature conditions. A suitable material for the tube is Invar. The clock of low frequency (near 100 Hz) triggers the transmitter and disables the receiver. The piezoelectric crystal flexes, transmitting an ultrasonic wave along the tube. The receiving crystal is enabled before the wave arrives at its surface and converts it into an electrical transient, which is amplified and sent to the control circuit. The control circuit calculates the speed of sound by determining the propagation time along the tube. Then, the corresponding temperature is determined from the calibration numbers stored in a look-up table. In another design, the thermometer may contain only one ultrasonic crystal which alternatively acts either as a transmitter or as a receiver. An electronic circuit converts the received pulses into a signal which corresponds to the tube temperature. The idea behind such a sensor is in the temperature modulation of some mechanical parameters of a timekeeping element in the electronic oscillator. This leads to the change in the oscillating frequency. In effect, such an integral acoustic sensor becomes a direct converter of temperature into frequency.

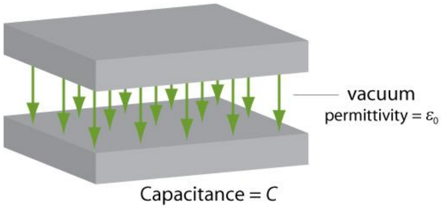


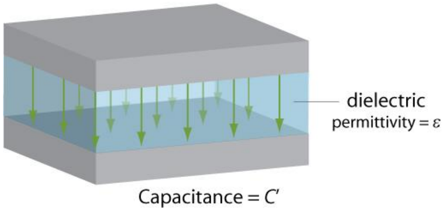
An acoustic thermometer with an ultrasonic detection system.

Dielectric Constant and Refractive Index thermo sensors:

The dielectric constant is the characteristic of an insulating material or a dielectric which represents its ability to store electrical energy in an electrical field. It shows how easily a material tends to be polarized when placed in an external electric field. Refractive Index, also called index of refraction, is the measure of how light propagates through a material. It determines to what extent the light rays can bend, or refract, when passing from one medium to another. It is defined as the ratio of speed of light in a vacuum to the speed of light in a medium.

The dielectric constant is the property of an insulator which determines its ability to hold electrical charge in an electrical field. It simply identifies the extent to which an insulating material can hold electrical charge before it’s being polarized or loses its electrical properties. It is the permittivity of a material compared to the permittivity of a free space or vacuum. The refractive index, or index of refraction, is a measure of how fast a light travels through a material. It is a dimensionless number which determines the extent to which the light rays is refracted or bent when passing from one medium to another.





$$\boxed{\kappa = C'/C} \qquad \boxed{\kappa = \varepsilon/\varepsilon_0}$$

GAS THERMOMETER:

Gas thermometry reduces temperature to measurement of pressure or a gas volume in a closed vessel followed by temperature calculation using the measurement results and the ideal gas laws. A *gas thermometer* is a primary instrument for determination of thermodynamic temperature. In practice, temperature scales are used in which a simple and convenient secondary thermometer is used and methods of transfer of thermodynamic temperature from a primary instrument to the secondary thermometer are employed. This requires use of precise primary instruments reproducing thermodynamic temperature, instruments for realization of the temperatures of phase equilibrium of substances (for determination of the constants of the primary instruments), i.e., representing the so-called fixed points and, of course, the secondary thermometer itself together with simple and convenient methods for its calibration. The simplest thermometer is a gas thermometer which consists of a glass or metallic gas-impermeable reservoir connected with an arrangement intended for pressure measurement in the reservoir.

A schematic drawing of a gas thermometer is shown in Figure 1: reservoir 3 is immersed into a medium whose temperature is to be measured; gauge 1 is connected via capillary 2 to the reservoir; the reservoir and the capillary are filled with a working gas. A gas thermometer allows the determination of pressure p and volume V of mass m of the ideal gas with molecular weight μ converting from thermodynamic state 1 to state 2, with the gas mass m = Vpμ/TR remaining constant in both states. Depending on the character of gas transition from 1-to-2 state, three gas thermometers are distinguished: those of constant volume, constant pressure and constant temperature.

A constant-volume gas thermometer is used at low temperatures (typically with helium as a working substance) and possesses the highest sensitivity. At high temperatures, when gas desorption on reservoir walls becomes pronounced and helium penetrates through the walls, gas thermometers of other design are used with nitrogen as a working substance. For precise temperature determination, corrections are made for gas no ideality, thermal expansion of the reservoir. Since the reservoir of a gas thermometer is connected with a manometer via a capillary, then volume of a gas above the manometer mercury and inside the capillary, whose temperature varies from the value to be measured to room temperature. With change of the bulb temperature, the amount of a gas contained will changes. A difference of the gas temperature in the bulb and volume of gas requires the appropriate corrections. For technical measurements, use is made of filled-system gas thermometers working at temperatures from –150 to 600°C. At a temperature up to 600°C nitrogen is used as a working gas, while above 600°C argon is used. The scale of a filled-system gas thermometer (T = f(p)) is obtained using a knowledge of a volume of the instrument components.

A gas thermometer is a thermometer that measures temperature by the variation in volume or pressure of a gas.

Helium Low Temperature Thermometer:

In case of helium, the helium at very low temperature can be used due to the fact that Helium has weak inter atomic forces, hence it can retain its liquid state even close to absolute. So instead of Helium gas, its liquid state can be used in thermometers.

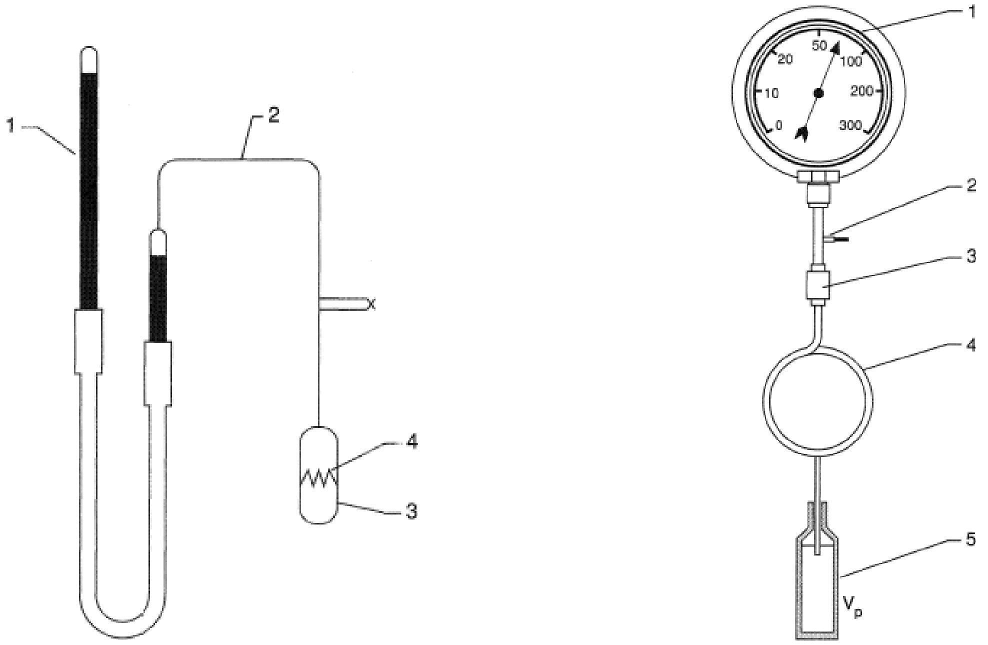


Figure 1. Schematic diagram of a Gas/ He thermometer.

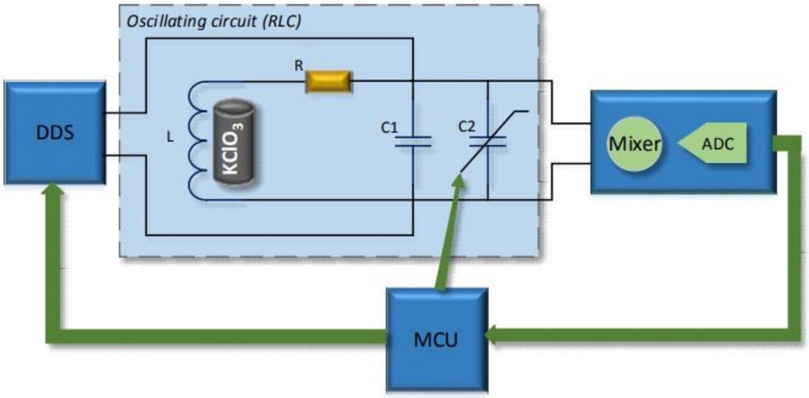
Nuclear Quadruple Resonance thermometry:

The temperature change can be traced by the change of other physical properties of probe (volume, pressure, electrical resistance, radiation intensity, etc.) related to the temperature of certain laws. But all these properties are not allowed to achieve such precision temperature measurement as a method for measuring the nuclear quadrupole resonance (NQR) effect, which occurs at the atomic and molecular level, and allows the realization of a thermometer with measurement accuracy of 0,001 K

The technique of Nuclear Quadrupole Resonance thermometry is described. It is shown that the N.Q.R. thermometer exhibits unique properties of sensitivity, range, and reproducibility that are all desirable qualities for a temperature standard. The response to temperature is a unique characteristic of the working substance. The nuclear quadrupole resonance (NQR) absorption frequency of the chlorine nucleus of potassium chlorate, KCIO3, decreases with increasing temperature. The temperature frequency relationship is determined by the molecular properties of the materials used in the temperature probe: thus once this relationship has been established. The main part of NQR thermometry is oscillating circuit in which it uses RLC circuit to provide high sensitivity, which is located in capsule with heat sensitive material. This oscillating circuit consists of parallel-connected inductance L, Capacitance C and Series connected Resistors R, due to changes in these elements caused by the temperature difference, resonant frequency contour work starts.

The main advantages of NQR thermometry are:

- Extremely high precision and sensitivity.
- Wide Measuring Range.
- Time stability of metrological characteristics
- Frequency output



Structure of quadrupole resonance thermometer

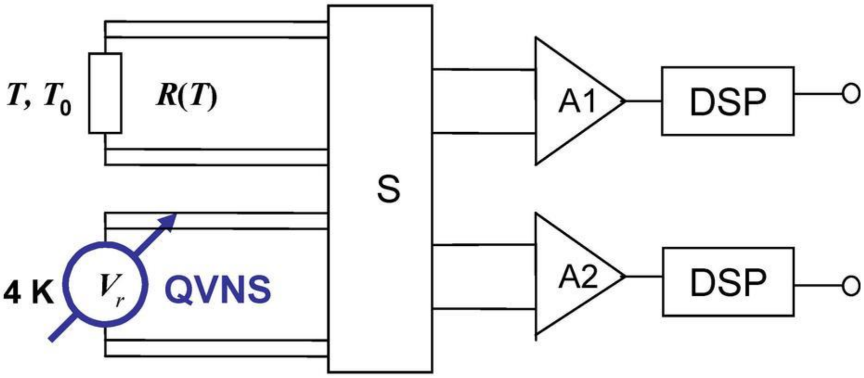
Noise Thermometry:

In communication systems, noise is an error or undesired random disturbance of a useful information signal.

Johnson noise thermometry (JNT) is a primary temperature measurement technique based on the fundamental properties of thermal fluctuations in conductors. We measure these fluctuations with respect to quantum voltage noise sources (QVNS). NT uses wide-band spectral analysis, digital signal processing, and pulse-quantized voltage synthesis. The JNT methods directly compare measured thermal noise voltages to an AC Josephson Quantized Voltage Noise Source (QVNS) (see Figure 1). In the absolute measurement mode, the noise power of the QVNS is programmed to balance that of a thermally generated Johnson noise source, resulting in a thermodynamic temperature independent of any fixed-point reference. In the relative measurement mode, the process is repeated at another temperature and another synthesized noise power, resulting in a thermodynamic temperature ratio. Both methodologies represent a significant advance over conventional JNT methods, which have less flexibility and functionality. Specific advances of the NIST JNT systems are:

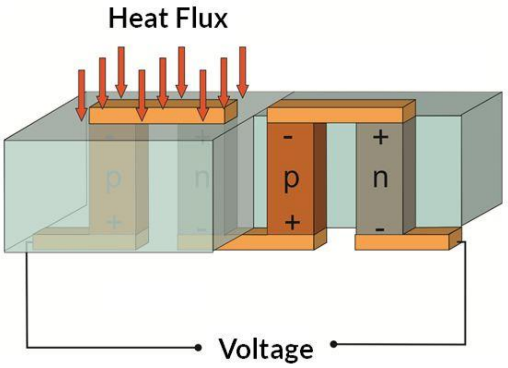
- high resolution (~1 Hz) spectral densities with a bandwidth approaching 1MHz;

- application of the fastest available Fast Fourier Transform (FFT) subroutines for near-real time processing;
- frequency domain cross-correlation analysis;
- QVNS synthesized pseudo-noise waveforms of matched spectral densities;
- ultra-low noise and high common-mode rejection pre-amplifiers;
- Simultaneous matching of both noise powers and time constants.



Heat Flux Sensors:

Heat Flux Sensors are based on the Seebeck effect. When heat passes through the sensor, the sensor generates a voltage signal. This voltage signal is proportional to the heat passing through the sensor. Heat Flux Sensors is a highly sensitive Seebeck Sensor. The sensitivity of a Seebeck Sensor depends on the thermocouple material quality used in the sensor and the number of thermocouples used. A thermocouple consists of two separate thermopiles (n-type and p-type). These thermopiles are highly integrated in the sensor substrate, which leads to high sensitivity sensor modules.



HF = V / S

where

HF = Heat Flux, V= Voltage and S= Sensor sensitivity.

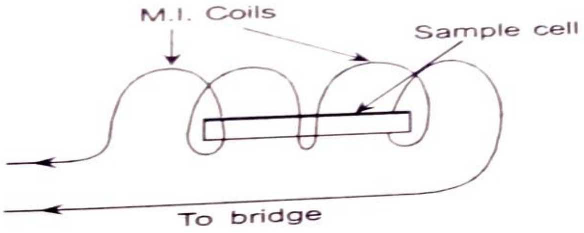
Magnetic thermometer:

Magnetic thermometers increase its efficiency as temperature decreases, which make them extremely useful in measuring very low temperatures with precision. Magnetic thermometers are typically used at temperatures below 1K (-485F). The magnetic moments in the thermometric material may be of either electronic or nuclear origin (earth salt).

Thermometer whose operation is based on Curie's law, which states that the magnetic susceptibility of noninteracting dipole moments is inversely proportional to absolute temperature.

For higher temperatures, an ion is selected with a large magnetic moment in a crystalline environment with a high density of magnetic ions. In contrast, for low temperature use the magnetic exchange interactions between the magnetic ions should be small, which is accomplished by selecting an ion with a localized moment and by maintaining a large separation between the magnet ic ions by means of magnetic atoms. (M.I.- Mutual Inductance : the production of an electromotive force in a circuit by a change in the current in an adjacent circuit).

Materials	Temperature Range (in K)
Cerlum Magnesium Nitrate (CMN)	0.01-2.5
Chromic Methylammonium Alum (CMA)	0.3-30
Manganous Ammounium Sulphate (AMS) and Godolinium Sulphate (GS)	0.9-80



Nuclear Thermometer:

The main specificities of the temperature measurements in nuclear environments are the presence of a radiation field damaging the sensors and cables, the need to monitor rapid transients of complex systems or slow transients in disposals of nuclear waste materials, and the high temperatures in aggressive radioactive mixtures (corium). In addition, temperature measurements are used for special applications like for example the detection of leaks. Progress in temperature measurements generally mean progress in safety and economics of the process operation, which require accuracy, reliability and stability, i.e. limited drift of the instrumentation.

To extract information on thermal characteristics of highly excited nuclear systems, the temperature of a system with fixed number of particles N at an energy E is defined according to the statistical mechanics as:

$$\frac{1}{T} = \frac{\partial S(E,N)}{\partial E} = \frac{\partial \ln \rho(E,N)}{\partial E},$$

where, S is the entropy of the system, and ρ the density of states at energy E.

In order to apply this formula to obtain a temperature, two conditions have to be fulfilled:

1. – The system has to be in full statistical equilibrium, i.e. each of the states included in ρ(E,N) has to be populated with equal probability, and

2. – The density of states has to be known.

For nuclear systems these two conditions can be critical. The degree to which equilibrium is reached in high-energy heavy-ion collisions is not a priori known as the dynamical evolution of a nuclear system is still not fully understood. What concerns the nuclear state density, it is well known only at low energies.

Population approaches → Based on this concept. The value of the nuclear temperature is extracted from the yields of the produced clusters assuming a Boltzmann distribution:

$$Yi \sim \exp(-Ei/T).$$

Kinetic approaches → Based on the concept of a canonical ensemble. The value of the temperature is extracted from the slope of the measured particle kinetic-energy spectra; due to this, the method is named slope thermometer. Two processes are studied within this approach: Thermal evaporation from the compound nucleus. Sudden disintegration of an equilibrated source into observed nucleons and light nuclei or gammas.

Thermal-energy approaches → The excitation energy at the freeze-out is extracted by measuring the evaporation cascade from a thermalized source. The temperature at the freeze-out is then obtained from the deduced excitation energy.