TEMPERATURE – WHICH SENSOR IS BEST?

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Question: What's best – Thermocouple – Resistance Thermometer – Thermistor – Silicon IC?

Answer: It depends. Are you measuring body temperature? The weather? An oven? A hot or cold industrial process? Do you need high accuracy? Wide measurement range? High sensitivity? Long term stability? Low cost? What physical form?

Each has its own advantages and limitations. We'll examine and compare them. (We haven't included non-contact infrared measurement.) This paper is for users, not sensor designers, so we won't delve into theory or measurement circuitry.

A Quick Comparison.

Thermocouples: Widest measurement range, many physical design possibilities, modest cost, lowest accuracy, lowest sensitivity. Require cold junction compensation. Fairly linear.

Resistance Thermometers (RTDs): Wide measurement range, moderately higher cost, high accuracy, medium sensitivity. Fairly linear.

Thermistors: Narrow measurement range, very high sensitivity. Highly non-linear. Cost and accuracy choices "all over the map". High accuracy available at higher cost.

Silicon ICs (Integrated Circuits): Measurement range similar to thermistors, modest cost, good accuracy, good sensitivity. High linearity.

Note that sensitivity and linearity are important primarily to people who design measurement circuitry and instruments, not users. Just be sure to pay attention to the specs of whatever instruments or devices you use.

Measurement Ranges.

Figure 1 shows typical measurement ranges. Silicon IC sensors generally run between -55 and 150^{O}C (-67 and 302^{O}F) or less. Thermistors ranges are similar overall: specific thermistors cover different ranges. Resistance sensors (RTDs) usually have either platinum or nickel sensing elements. Platinum can be as wide as -200 to 600^{O}C (-328 to 1112^{O}F) or beyond depending on how they are manufactured. Nickel is more limited. There are many types of thermocouples, all with different ranges. Combined they cover -270 to 1700^{O}C (-454 to 3100^{O}F) although generally with less accuracy.

Accuracy. Most sensors are calibrated and tested at either freezing or room temperature, 0^{O}C (32^{O}C) or 25^{O}F (77^{O}F) and so have best accuracy near those temperatures. Rated accuracies get looser at higher or lower temperatures.

Thermocouples come in many different types. Together they cover the widest temperature range but with lower accuracy and sensitivity than the others. Standard accuracy near room temperature is typically $\pm$2.2^{O}C (4.0^{O}F) with special accuracy of $\pm$1.1^{O}C (2.0^{O}F) available.

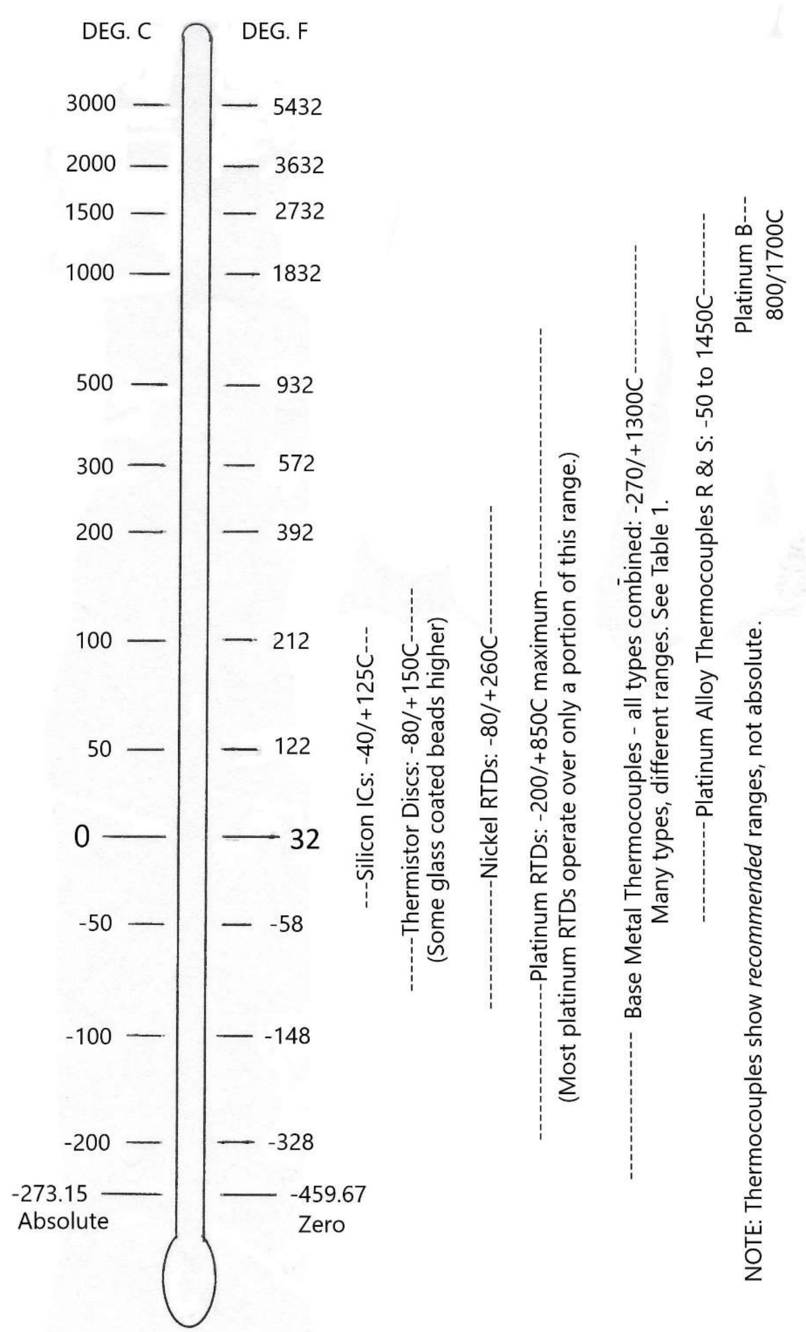

Figure 1: Typical Temperature Sensor Ranges.

Platinum RTDs offer the best accuracy over a wide temperature range. Standard industrial grade sensors usually are $\pm$0.25^{O}C (0.45^{O}F) at 0^{O}C, loosening as the temperature rises or falls. Tighter tolerances are available.

Thermistors and silicon sensors vary widely. Some thermistors are very loosely toleranced but at very low cost. Precision interchangeable thermistors can be $\pm$0.1^{O}C (0.18^{O}F) between 0^{O}C and 70^{O}C (32 to 158^{O}F). Some specialty types may be even better. Silicon IC accuracies generally are $\pm$0.5^{O}C (0.9^{O}F) or looser but $\pm$0.1^{O}C (0.18^{O}F) is available near 25^{O}C (77^{O}F).

Thermocouples. A thermocouple is nothing more than two dissimilar metals, usually alloys, welded or otherwise joined together. The junction produces a small voltage (millivolts) that varies with temperature. Several combinations have been studied and documented as standard types with published voltage-versus temperature tables. Some are better at low temperature, other high. Different metals are best suited to different atmospheres, especially at high temperatures. The standard types are designated by letters: Type J, Type K, Type S etc. See Table 1 for comparisons.

Thermocouple Type	Recommended Range (Deg. C)	ANSI Standard Error Limits (Tighter special limits also available)	Notes (For probes, the atmosphere refers to inside the probe.)
Base Metals			
E: Chromel vs Alumel	-200 to 900^{O}C	0 to 900^{O}C: 1.7^{O}C or 0.5% -200 to 0^{O}C: 1.7^{O}C or 1.0%	Oxidizing, inert. Avoid reducing & vacuum. Highest sensitivity.
J: Iron vs Constantan	0 to 750^{O}C	0 to 750^{O}C: 2.2^{O}C or 0.75%	Reducing, Inert, vacuum. Avoid oxidizing & moisture at high temperatures.
K: Chromel vs Alumel	-200 to 1250^{O}C	0 to 1250^{O}C: 2.2^{O}C or 0.75% -200 to 0^{O}C: 2.2^{O}C or 2%	Oxidizing, inert. Avoid reducing & vacuum. Wide range. Most popular.
N: Nicrosil vs Nisil	-270 to 1300^{O}C	0 to 1300^{O}C: 2.2^{O}C or 0.75% -270 to 0^{O}C: 2.2^{O}C or 2%	Similar to K but more stable at high temperatures.
T: Copper vs Constantan	-200 to 350^{O}C	0 to 350^{O}C: 1.0^{O}C or 0.75% -200 to 0^{O}C: 1.0^{O}C or 1.5%	Mild oxidizing, reducing, inert, vacuum. Can take moisture. Preferred type below 0^{O}C.
Platinum Alloys			
R: Pt-13% rhodium vs Platinum	0 to 1450^{O}C	0 to 1450^{O}C: 1.5^{O}C or 0.25%	Oxidizing, inert. High temperature. Avoid reducing. Avoid metallic vapors. Do not insert in metal tubes.
S: Pt-10% Rhodium vs Platinum	0 to 1400^{O}C	0 to 1450^{O}C: 1.5^{O}C or 0.25%	Same as R.
B: Pt-30% Rhodium vs Pt-6% Rhodium	800 to 1700^{O}C	800 to 1700^{O}C: 0.5%	Same as R. Highest temperature. Often used for glass.

Table 1: Thermocouple Comparisons.

Type K is most common, followed by J. T is the best below zero. Platinum-rhodium alloys R, S and B serve the highest temperatures but are much less sensitive. Tungsten-rhenium alloys which go even higher are available. These commonly are called types C, D and G but do not have official ANSI or other official standards.

Thermocouple wire made from the two metals or alloys is readily available. To make a thermocouple junction simply weld or join the two wires together. Wire is available in heavy or light gauges, all the way down to 0.001 inch diameter (delicate, but good for measuring rapid changes). It comes with various insulation choices, depending on the temperatures measured. For very high temperatures uninsulated wire may be strung through ceramic insulators.

One thing you should be aware of: *cold junction compensation*. *Any* two unlike metals, including the connection to copper, forms a thermocouple. Wires running from the sensor to the readout must be thermocouple wire, not copper. At the readout the thermocouple wire connections to copper create two additional thermocouples whose voltages vary with ambient temperature. This is called the *cold junction voltage* and is an error. All thermocouple instruments compensate by adding a temperature sensor near the connection to create an equal and opposite voltage. You cannot accurately read a thermocouple's temperature by simply reading its millivolts without compensation. For long wire runs *thermocouple extension wire* is available, less expensive wire not suited for high temperatures.

Thermocouples are approximately but not exactly linear. Millivolts versus temperature is defined by complex equations and published in degree-by-degree tables. Most modern measurement instruments convert millivolts to degrees digitally. The tables can easily be found by an on-line search such as Thermocouple Reference Tables. As of this writing our favorite is www.thermocoupleinfo.com, a resource of Reotemp Instrument Corp. The basic reference (US NIST – National Institute of Standards & Technology) is at https://srdata.nist.gov/its90/download/download.html.

Resistance Thermometers (RTDs).

RTD stands for **R**esistance **T**emperature **D**etector. RTDs measure a metal's change in resistance, usually a well-constructed coil of fine gauge wire or a metal film deposited on a ceramic substrate. Platinum is most common, followed by nickel and copper. All three increase in resistance by a fraction of a percent per degree C.

Platinum has the widest range and best stability; in fact, specially constructed elements made from very high purity platinum are used by standards laboratories to define the International Temperature Scale between -259.3^{O}C and +961.8^{O}C (-225.5^{O}Fand +1763.2^{O}F). Industrial and commercial grade ranges differ depending on construction methods, materials and other factors. Published data can run from -200 to +850^{O}C (-328 to +1562^{O}F) but most sensors have a more limited range. The most common accuracy is $\pm$0.25^{O}C (0.45^{O}F) at 0^{O}C but tighter (and looser) tolerances are available. Deposited film elements generally cost less but have lower measurement range and long-term stability than wire.

Most platinum RTDs are 100 ohms at 0^{O}C but 200, 500 and 1,000 ohms also are offered. Deposited film elements tend to be higher, often 1,000 ohms. Resistance versus temperature is approximately but not exactly linear. Most (not all) industrial grade sensors follow the European or DIN standard, 100 ohms at 0^{O}C, 138.5 ohms at 100^{O}C. Refer to published tables. Imperfections reduce sensitivity slightly: some film elements may be slightly lower, high purity platinum RTDs may be slightly higher.

Nickel (nickel alloy) sensors can be less expensive but are limited to about -80 to 260^{O}C (-112 to 500^{O}F). They are about 75% more sensitive than platinum but less linear and more subject to high temperature drift. Copper is linear but very temperature-limited and subject to drift due to oxidation and so is seldom used as an RTD element. Those that are offered generally have lower resistances such as 25 ohms at 25^{O}C (77^{O}F). A common use is monitoring the temperature rise of motors and generators.

About the connections: cable wire resistance can add significant errors. For a 100 ohm platinum sensor, one ohm of lead resistance adds 2.5^{O}C (4.5^{O}F) to the reading. Almost all RTD readout instruments include 3-wire or 4-wire resistance compensation circuitry which requires 3 or 4 wires running from the sensor. In simple terms, the extra wire allows the lead resistance to be measured and electronically subtracted.

Thermistors. Thermistors vary all over the map: high accuracy to very loose, large, small, low and high resistances, expensive and cheap, negative and positive temperature coefficients, different materials and applications. In this paper we'll look only at precision measurement thermistors.

Thermistors are a “black art”. Made from a mixture of metal oxides and binders, they are pressed together and fired similar to ceramics. Their characteristics are affected not only by the materials used but also by the firing time and cycle and other factors. Your author once worked at YSI Inc. who pioneered and at the time manufactured precision thermistors. (They later sold off that product line.) After firing a run of thermistors they would process a few to completion and test them at multiple temperatures. If they did not pass' the entire run would be discarded. Thermistors from good runs were precisely ground to the correct resistance in a tightly-controlled temperature bath before coating, then tested again after coating.

All precision measurement thermistors are NTC: Negative Temperature Coefficient. They are the direct opposite of RTDs: narrow temperature range, highly sensitive, highly nonlinear, resistance decreasing with rising temperature. They are very good for precise, sensitive measurement of modest temperatures such as, for instance, body temperature, controlled fluid baths and indoor/outdoor temperatures.

Originally most measurement thermistors were coated with epoxy, some with glass for higher temperature range and improved high-temperature stability. Chip thermistors meant for surface-mount soldering to circuit boards now are also available.

As a rough approximation thermistor resistances decrease about 4% for every deg. C increase in temperature. Initial 25^{O}C resistance can be anywhere between 100 ohms and 100,000 ohms. Their high sensitivity and resistance means that a couple ohms of connection wire resistance won't matter. For example, for a 1,000 ohm thermistor at 25^{O}C a 1^{O}C change will equal about 40 ohms. Two-wire connections are fine.

Their high nonlinearity adds complexity to readout design. Resistance versus temperature can only be approximated by complex equations over portions of their temperature range. Narrow ranges can be linearized by analog means but accurate temperature readings over wide ranges require digital techniques.

Silicon Integrated Circuit (Bandgap) Sensors.

Integrated circuit (IC) temperature sensors operate over temperatures similar to other ICs, typically -40 to 125°C (-40 to 250°F) or -55 to 150°C (-67 to 302°F) depending on the type and grade chosen. Their range is similar to thermistors and they are available with a variety of analog or digital outputs. Because they are nearly linear and have built-in signal conditioning they are easier to apply than thermistors. They are available with a wide variety of accuracies and package styles; however, they're not commonly used in conventional temperature probes.

The Basics. IC temperature sensors measure the voltage drop, or bandgap voltage, of a P-N junction as illustrated in Figure 2(a). A forward biased diode or bipolar transistor's voltage decreases by about 2 millivolts per °C temperature increase.

The exact value will vary with current and other factors. Higher current increases the voltage drop. To achieve accuracy the ICs actually measure the voltage difference between two identical sensors biased at different currents. Figure 2(b) shows the concept. Sensors made this way are called *bandgap* temperature sensors.

Transistors, not diodes, are used as the sensors. A circuit known as the Brokaw bandgap reference circuit (Figure 3) often is used. If R1 and R2 are not the same, currents IC1 and IC2 will differ. Both bases are at the same voltage so the voltage across R3 equals the difference between the two bandgap (base-emitter) voltages. Additional circuitry converts this difference to the final analog or digital output.

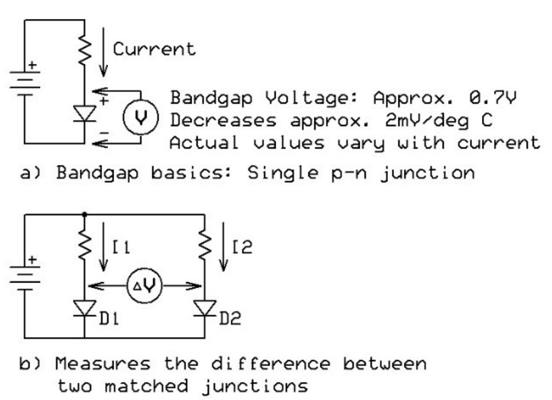

Figure 2: Bandgap Sensor Basics

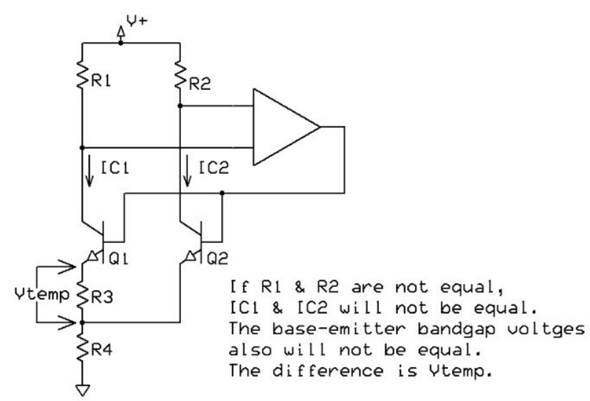

Figure 3: Brokaw Bandgap Temperature Circuit

Wide Variety Available. Most silicon IC sensors use the same sensing technology but offer a wide range of output types. Analog sensors are available with either voltage or current outputs. Current outputs typically are 1 microamp per Kelvin. (Kelvin – absolute temperature – equals Celsius plus 273.15.) Voltage types usually but not always are 10mV/deg C or 10mV/deg F. Most cannot go negative, so some have offset (elevated) zeroes to allow positive output below zero degrees. As mentioned earlier most specify 0.5°C (0.9°F) or looser accuracy but 0.1°C (0.18°F) near room temperature is available

Digital sensors offer various communication or bus choices. Most popular are I^2C (Inter-Integrated Circuit), some of which are also compatible with SMBus™ (System Management Bus). Others offer other 1- 2- or 3-wire communication, the 4-wire SPI (Serial Peripheral Interface) bus and UART (Universal Asynchronous Receiver Transmitter) communication. We won't dive into these busses here: that could be one or several articles in themselves.

A variety of package styles (enclosures) are available including most standard IC packaging. They are offered by many IC manufacturers: Texas Instruments, Analog Devices, Maxim and many others. The multitude of sensor offerings makes it impossible to summarize here. Go to your favorite IC distributor and start searching!

Temperature probes with IC sensors are not very common. Most IC packages do not lend themselves to assembly into probes. Many applications involve monitoring ambient air temperature or compensating for changes (such as thermocouple cold junction compensation) rather than making liquid measurements.

Other Silicon Sensors.

We'll briefly mention two other types but not cover them in detail. First – cryogenic sensors using silicon diodes. One example is the CY670 Series from Omega Engineering. These can measure accurately down to 1.4K (Kelvin - degrees absolute). Go to www.Omega.com and search for either CY670 or cryogenic.

The other – silicon thermistors. Their resistance changes with temperature but, unlike NTC thermistors, increases with temperature, approximately linearly. Measurement range is typically -40 or -60^{O}C to +125 or 150^{O}C. Manufacturers include Texas Instruments (TMP61 series and others) and NXP Semiconductors (KTY81 & KTY82 series). For details visit www.TI.com, www.NXP.com or your favorite electronics distributor. Search for these part numbers or for silicon thermistors.

Sensor Assemblies.

This will be brief. Sensor assemblies could be a full paper in itself. Many manufactures offer standard or custom sensor assemblies. Here are two. Omega Engineering (www.omega.com) is well known for a variety of temperature sensors, assemblies and instruments (and many other products). For industrial sensors we like JMS Southeast (www.jms-se.com). You can learn more on their web sites.

Temperature probes are common – tubes (usually metal) with a sensor at the tip end and wires coming out the back, sort of like a thermometer with wires. The sensor usually is a thermocouple, RTD or thermistor.

For industrial use the probe often must be protected from high pressures and flows, sometimes with abrasives or even small rocks or solid particles. Protective *thermowells* can be used. These are larger diameter solid metal closed-end tube-like enclosures, gun-drilled down the middle so you can insert a probe, usually ¼ inch diameter. Here's a link to some basic info on thermowells: https://www.jms-se.com/thermowell.php.

Thermocouples also lend themselves to other types of assemblies. They are just wires, so temperature can be monitored by welding or gluing the measurement junction to a surface. Or, surface mount sensors are offered which can be bolted or screwed down. The junction also may be exposed directly to air, gas or nonconductive liquids to measure temperature. Fine gauge wire, even as fine as 0.001 inch, is sometimes used to monitor rapid temperature changes.

Most silicon ICs, as mentioned earlier, are packaged similarly to other ICs, not suitable for standard probe assemblies. They often are assembled to circuit boards for air temperature monitoring or temperature compensation applications.

Conclusion.

We've examined and compared the four most often used temperature sensor types. No one type is best: it depends on your application, temperature range, accuracy needs and other requirements. Thermocouples cover the widest range but are least sensitive and accurate. Resistance thermometers cover a wide range with better accuracy but usually cost more. Thermistors and silicon sensors are most sensitive over a narrower range and are available with a variety of accuracies and costs. Silicon IC sensors usually include either analog or digital signal conditioning.

The exploration of sensor assemblies was necessarily brief but we've provided a couple manufacturer links to explore.