Hoyt White Paper

RTD's vs Thermocouples, What is the Best Choice for an Analog Meter Solution?

Background

Temperature reigns as the most often measured process parameter in industry. While temperature measurement utilizes sensors of many forms, the actual measurement of temperature is accomplished via only five basic sensor types: Thermocouple (T/C), Resistance Temperature Detector (RTD), Thermistor, Infrared Detector, and via semiconductor or integrated circuit (IC) temperature sensors.

Of these five common types, the thermistor is perhaps the most commonly applied for general purpose applications. Semiconductor sensors dominate most printed circuit board or board level sensing applications. Infrared is used for non-contact line-of-sight measurement. But for industrial applications that typically employ remote sensing, thermocouples and RTD's reign as the most popular sensor types.

Most industrial applications require that a temperature be measured remotely, and that this signal be transmitted some distance. An industrial transmitter or transducer like the Hoyt Electric M100 series is commonly used to amplify, isolate, and convert the low-level sensor signal to a high level signal suitable for monitoring or retransmission.

With respect to these transmitters, your choice of sensor type is generally limited to T/C, or RTD. But given the wide variety of RTD and T/C types, how do you choose the best sensor type for your specific application?

This paper will look at important characteristics of these two main industrial sensor types and offer information to help you select the best type for your application.

Part 1: Explores the Thermocouple.

Part 2: Explores the RTD

Part 3: Explores how to use them in metering

The Basics of Temperature Measurement Using Thermocouples

You are probably somewhat familiar with the thermocouple, or you wouldn't be reading this whitepaper. But there are important points about thermocouples that must be understood and that will help you to make an informed selection between sensor types and avoid potential problems in your application.

First, we need to clear up a common misconception about how thermocouples work. You may have been told something like "a thermocouple produces a small voltage created by the junction of two dissimilar metals". This simplification of the thermocouple is at best only half true, and very misleading.

The reality is that it is the temperature difference between one end of a conductor and the other end that produces the small electromotive force (EMF), or charge imbalance, that leads us to the temperature difference across the conductor.

OK, simple enough, but how do you actually measure this emf in order to discern its relationship to temperature?

The "EMF" or electromotive force refers to a propensity level, or potential for current flow as a result of the charge separation in the conductor. We refer to this propensity for current flow between two points as its potential difference, and we measure this difference of potential in volts. But in order to actually measure the emf or voltage difference, we need two points of contact. That is, we must complete the circuit by adding a return electrical path.

If we simply choose to use the same metal as a return path, the temperature difference between the ends of your original conductor would simply create an equal and opposite EMF in the return path that would result in a net EMF of zero--not very useful for measuring temperature. This relationship is expressed by the "Law of Homogeneous Material" as follows (see Wikipedia.org):

"A thermoelectric current cannot be sustained in a circuit composed of a single homogeneous material by the application of heat alone, and regardless of how the material may vary in cross-section. That is, temperature changes in the wiring between input and output will not affect the output voltage, provided all wires are made of the same material as the thermocouple. No current flows in the circuit made of a single metal by the application of heat alone."

This emf or voltage can be used for measuring temperature through either a DC millivoltmeter or Pyrometer scaled to match the characteristics of voltage output of the 2 dissimilar metals. Both Analog and Digital versions can be used.

Different conductive metals will produce different levels of emf or charge separation relative to the thermal gradient across the metal. Thomas Seebeck discovered this principle in 1822 and it is known today as the "Seebeck Effect". Thus, we can apply the "Seebeck Effect" and make it useful for measuring temperature by using a different metal for our return path, and then relating the differences in charge separation between the two metals to the temperature between the ends.

We join these metals at the start of our return path by forming a junction between them—that is, the junction simply joins our circuit and is not the source of the emf, as is often inferred by the traditional definition of a thermocouple.

Now at the other end of our closed thermocouple circuit, we can measure a voltage between the two wires that will be proportional to the temperature between the ends. By the Law of Homogeneous Materials expressed earlier, the thermocouple wires can each pass into and out of cold areas along their path without the measuring instrument detecting the temperature changes along the path because the emf created as the continuous wire enters and leaves an area will sum to zero and have no net effect on our final measurement.

We still have a conceptual problem though—how do we measure the voltage at the open end of our thermocouple without introducing additional “thermocouple” voltages into our measurement system. That is, the connection points of the T/C to the measurement system (which is typically copper) will itself act as a thermocouple.

It turns out that the effect of these additional thermocouples on our measurement system can be minimized by simply making sure the connections are at the same temperature. This principle is expressed by “The Law of Intermediate Materials” as follows (see Wikipedia.org):

“The algebraic sum of the thermoelectric emf’s in a circuit composed of any number of dissimilar materials is zero if all of the junctions (normally at the cold junction) are maintained at a uniform temperature. Thus, if a third metal is inserted in either or both wires while making our cold junction connections, then as long as the two new junctions are at the same temperature, there will be no net voltage contribution generated by the new metal in our measurement system.”

So, our ability to overlook these unintended thermocouples in our measurement will depend on how well we can maintain both cold junction connections at the same temperature. This is often easier said than done and small thermal gradients will usually occur, often as a result of the self-heating of components across the circuit board.

Other thermal gradients can be driven by heat generated from adjacent circuits, nearby power supplies, or via variable wind currents or cooling fans in the system. For any thermocouple transmitter or transducer, special care must be taken to minimize these sources of error (more on this later).

A third law for thermocouples that helps us combine emf’s algebraically is “The Law of Successive or Intermediate Temperatures” stated as follows (see Wikipedia.org):

“If two dissimilar homogeneous materials produce thermal emf1 when the junctions are at T1 and T2, and produce thermal emf2 when the junctions are at T2 and T3 , then the emf generated when the junctions are at T1 and T3 will be emf1 + emf2, provided T1<T2<T3.”

Still, our measurement of the open-end voltage across our thermocouple only relates the thermoelectric voltage to the difference in temperature between both ends. That is, we need to know the temperature of the cold junction at one end and to extract the sensed temperature from the other end (hot junction).

Ideally, if both connections made at the measuring end were at 0°C, their thermoelectric equivalent voltage contributions to our measurement would be 0mV, and we could easily determine the sensed temperature directly from our measured voltage. Since this can’t be easily assured, the actual temperature of the cold junction connection point is usually measured separately. Then the measured T/C signal can be compensated for the thermoelectric contribution of the connection point or “cold junction", and we can extract the actual temperature of the remote end of our thermocouple by a mathematical combination of either the measured temperature or its thermoelectric equivalent voltage.

Although we could form a thermocouple by joining any two dissimilar conductors, a number of standard thermocouple types are available that utilize specific metals combined to produce larger predictable output voltages with respect to their thermal gradients. The most common types are Type J or Type K listed below.

Common Thermocouple Types and Their Applications

TYPE K

Chromel (Nickel & Chromium) – **Alumel** (Nickel & Aluminum)

MEASURE RANGE:

-184°C to 1260°C

Sensitivity: 39uV/°C

Most common general purpose type with a wide temperature range and lowest cost. Good for high temperatures with good corrosion resistance. Positive lead is non-magnetic, while the negative lead is magnetic. Good for clean oxidizing atmospheres but vulnerable to sulfur attack and should be kept from sulfurous atmospheres.

TYPE J

Iron - Constantan

MEASURING RANGE:

0°C to 760°C

Sensitivity: 55uV/°C

Second-most common type but limited in range. Good for general purpose dry applications where moisture is not present. Positive iron wire is magnetic, while negative wire is non-magnetic. Lower service life due to fine wire size and rapid oxidation of iron wire at temperatures above 540°C, not recommended for sulfurous atmospheres above 540°C. Ok for use in vacuum, air, and reducing or oxidizing atmospheres up to 760° and in the heavier gage sizes. Limited sub-zero use due to rusting and embrittlement of the iron wire. Should not be used above 760°C due to an abrupt magnetic transformation at the Curie point of iron (~770°C) which changes its characteristic and can cause permanent de-calibration.

TYPE E

Chromel (Nickel & Chromium) **– Constantan**

MEASURING RANGE: 0°C to 982°C

Sensitivity: 76uV/°C

Non-magnetic with highest output voltage offering the best sensitivity and suitable for cryogenic use. Recommended for use up to 900°C in oxidizing or inert atmospheres. Vulnerable to sulfur attack and should be kept from sulfurous atmospheres.

Other Notable Points of Consideration for Thermocouples

• All TC types are color-coded and the RED wire is always the Negative Lead (opposite the convention used for DC power where Red typically denotes positive).

• One of the greatest advantages of thermocouples is their small point of contact that delivers generally fast response times.

• Thermocouple wires are very fine by design, as this helps to prevent the mass of the wire from affecting the sensed temperature at the point of contact (the junction). But this has a disadvantage in that the wires can be very delicate and may break easily. Special care must be taken to reduce the strain imposed on the thermocouple wires.

• Because thermocouple wire is often very fine, it will have generally higher resistance. The emf or voltage produced by a thermocouple is also very small. As a result, errant current flow through the thermocouple can produce an IR drop that can negatively affect the thermoelectric voltage being measured across the thermocouple. Thus, measurement equipment must have a very high input impedance so as not to introduce excess current flow that can affect the measured voltage. For example, you cannot obtain an accurate measurement of T/C millivolts using a low-cost hand-held meter because your meter would load the thermocouple with at least a few microamperes of current which is enough to add error to your measurement. Meters must be calibrated for use with a Thermocouple and are specific to that usage. Hoyt Electric carries Pyrometers for such an application.

• Be aware of the error current introduced by thermocouple break detection circuitry which can negatively affect your measurement. Small break currents passing through high resistance T/C wire will drive IR voltage drops that generate voltage error. This will not normally be a problem as long as the break current is kept small and constant, or calibrated out at the factory or in the field. For example, 10uA of break current in 100Ω of T/C wire would produce 10uA*100Ω=1mV of error. This doesn't sound like much, but if you divide 1mV of IR drop by the nominal sensitivity of a J-Type T/C (1mV/55uV/C), you would get an IR error up to 18.2C.

• Again, the low thermoelectric voltages, high conductor impedances, and high impedance inputs of the measuring equipment make long thermocouple wires an easy pickup for errant signals from nearby equipment and power lines. This usually means that additional filtering in the form of a low-pass filtering may be required, in particular for removing power-line noise. Most modern instruments already include this filtering.

• Thermocouples will exhibit higher levels of drift over time than other sensor types.

• The junction of a thermocouple is commonly grounded and often in direct contact with surrounding case metal which drives a faster response time, but can be troublesome for noise pickup and potential ground loop error. Ungrounded junction sensors are available where isolation is required, but usually with an increase in response time. You may also use a grounded sensor if you connect your sensor to an isolated transmitter.

RTD

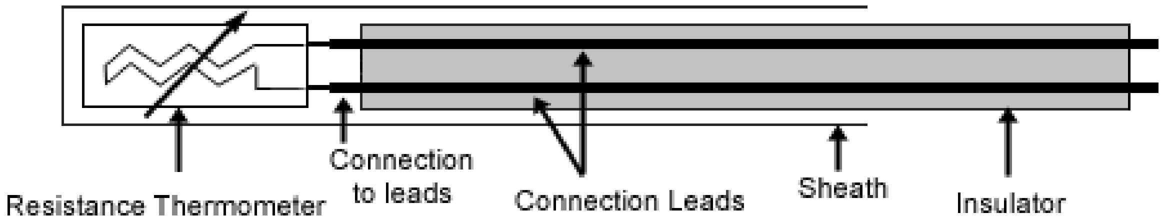
The Basics of Resistance Temperature Detectors

An RTD or Resistance Temperature Detector is a passive circuit element whose resistance increases with

increasing temperature in a predictable manner. The traditional RTD element is constructed of a small coil of platinum, copper, or nickel wire, wound to a precise resistance value around a ceramic or glass bobbin. The winding is generally done using one of two styles: birdcage or helix.

The birdcage winding keeps the platinum wire loosely wound on the bobbin allowing it to expand and contract freely over temperature in order to minimize any stress-induced change in resistance.

This style of winding is generally limited to laboratory use as it has poor resistance to shock and vibration. The helix wire-wound RTD uses a bifilar wound coil wrapped around a bobbin and then sealed with molten glass, ceramic cement, or some other high-temperature insulating coating. The helix winding style helps protect the wire element from shock and vibration induced changes to its resistance, but it may still be prone to stress induced resistance change due to the different coefficients of thermal expansion of the wire coil and bobbin material.



More recently, RTDs are also being constructed using a thin-film of platinum or nickel-iron metal deposited on a ceramic substrate and then laser-trimmed to a desired reference resistance. The advantage offered by this construction is that the thin-film elements can achieve a higher resistance with less metal, and over smaller areas. This makes them smaller, cheaper, and faster responding than their older wire-wound counterparts.

The most common RTD element material is Platinum, as it is a more accurate, reliable, chemically resistant, and stable material, making it less susceptible to environmental contamination and corrosion than the other metals. It's also easy to manufacture and widely standardized with readily available platinum wire available in very pure form with excellent reproducibility of its electrical characteristics. Platinum also has a higher melting point, giving it a wider operating temperature range.

RTD ELEMENT MATERIAL	USABLE TEMPERATURE RANGE
Platinum	-260°C to +650°C
Nickel	-100°C to +300°C
Copper	-75°C to +150°C
Nickel/Iron	0°C to +200°C

For an RTD sensor, it is the wires which connect to the sensing element and the wire insulation which generally limits the maximum application temperature of the sensor.

Measuring the temperature of an RTD involves measuring this resistance accurately. To measure the resistance, it is necessary to convert it to a voltage and use the voltage to drive a differential input amplifier. The use of a differential input amplifier is important as it will reject the common mode noise on the leads of the RTD and provide the greatest voltage sensitivity. The RTD signal is generally measured one of two ways: either by connecting the RTD element in one leg of a Wheatstone bridge excited by a constant reference voltage, or by running it in series with a precision current reference and measuring the corresponding IR voltage drop. The latter method is generally preferred as it has less dependence on the reference resistance of the RTD element.

Meter Loading

Meter loading refers to the negative effect resulting when some current is shunted away from the RTD element through the voltmeter, or other measuring instrument in order to make the measurement. This is historically only a problem with the older D'Arsonval analog meters, as modern DVM's and measuring instruments usually employ high impedance inputs in the tens of meg-ohms. Their high input impedance coupled to the relatively low impedance RTD output signal reduces meter loading to the nanoampere range, where it is normally not a significant factor. It's only mentioned here to make you aware of it and to check that your measuring instrument does indeed have high input impedance. Note that a standard 100Ω platinum RTD with 1mA of excitation feeding a meter with 10MΩ of input impedance will only be loaded by 10nA or 10ppm (i.e. 0.001A*100Ω/10MΩ = 10nA).

Hoyt carries Digital instrumentation and transducers that utilize an RTD that can measure and/or retransmit an analog output signal vs. temperature, such as a 0-10VDC or 4/20 MADC for use in a control or long distance measurement. Temperature controllers also have an RTD input to measure heating/cooling applications that require precise temperature measurements.

In summary, the sensitivity of an RTD sensor refers to its change in resistance per degree change in temperature. It is both a function of its base resistance and its Temperature Coefficient of Resistance (TCR). A sensor with higher sensitivity is not necessarily more accurate, but the larger signal it produces will tend to be less susceptible to lead-wire effects and electrical noise, as it generally improves the signal-to-noise ratio of the sensor interface. A larger resistance also produces the same output voltage with less excitation current, which helps to mitigate self-heating effects in the sensor element by allowing lower currents to be used to excite it.

Thermocouples versus Resistance Temperature Detectors (RTD)

Many users simply look to fill the basic needs of their application and do not worry much about their choice of temperature sensing technology. That is, they will make a selection based simply on temperature range and their own bias, perhaps based on their familiarity with a particular sensor type.

At a minimum, an informed sensor choice should first consider the following:

- Measurement range, including the range extensions of shutdown, startup, and process used.
- The response time.
- The sensor stability, accuracy, and sensitivity in the application environment.

When we start to cross the boundaries between choosing one type of sensor over another, the optimum choice between thermocouple and RTD can be difficult. There is a lot of overlap between these sensors at the more popular lower end of the operating temperature range. So for sensors that cover the same operating range, and applications where response time is not a driving issue, plus stability, accuracy, and sensitivity are acceptable, we really have to drill deeper and compare characteristics between sensors to find the best fit for a given application.

Below summarizes many of the comparative differences between thermocouple and RTD sensor types.

Characteristic	**Thermocouple (T/C)**	**Resistance Temperature Detector (RTD)**
Measurement Range	Wide, -250°C to +2600°C	Narrower, -200°C to +850°C, often limited to a lower temperature by its insulation.
Output Signal	Voltage wrt difference in end-to-end temperature	Resistance change wrt actual temperature
Accuracy	Less accurate, 2-4°C typical	More accurate, up to 1°C typical
Long Term Stability	Fair, limited to shorter periods	Good, stable over long periods
Stability/Drift	Good, but more subject to drift	Excellent, better long-term stability
Sensitivity	Lower	Higher sensitivity
Interchangeability	Good	Excellent
Linearity	Fair linearity, special linearization generally required.	Better linearity, special linearization still required, but to a lesser degree
Self-Heating Error	No self-heating error	Some self-heating error, but low
Extension Cable	High effect, must match T/C type and is more expensive	Lower effect, can use different material, but ultimately limited by lead wire resistance
Response Time	Fast (≤ 0.1 seconds typical), but CJC has thermal lag	Slower (1 to 7 seconds typical)
Repeatability	Reasonable	Better & greater standardization
Hysteresis	Excellent	Good
Signal Strength	Low, prone to EMI	Higher, more EMI resistant
Vibration/Shock Resistance	Good resistance	Less resistant than T/C
Robustness/Ruggedness	Very good	Good
Sensor Dimensions	Very small to very large	Small to medium
Measurement Area	Small, single point-of-contact	Larger, whole element must contact, 1" typical
Fine Wire Diameter	Small down to 0.25mm diameter	Larger up to 3mm diameter
Reference Junction	Required and a significant source of measurement error. Usually requires a stable ambient at cold junction.	Not required and not a source of error
Excitation Required	Not required, self-powered	Yes, reference voltage or current source
Lead-Wire Resistance	High, but often mitigated by mating technology	Must be considered wrt maximum added resistance and potential resistive imbalance between leads
Cost	Less expensive	More expensive
Complexity	Very simple and less subject to mechanical stress	Physically larger and has a more complex construction making it more subject to mechanical stress
Calibration Ease	More difficult and adds CJC calibration	Less difficult, no CJC to contend with
Noise Immunity	Lower noise immunity but often mitigated by good wiring practice. Small signals and high impedance leads can easily pick up noise.	Better noise immunity than a T/C

Conclusion: What is best solution for the application?

In general, if your application requires the highest accuracy, cost is not a concern, and your operating ambient is less than 800°C, then the choice of an RTD over a thermocouple sensor is probably the right one. The RTD is more accurate, more stable, more repeatable, and offers a more robust output signal with better sensitivity and linearity than a thermocouple. However, the RTD does have a narrower operating range with a lower maximum operating temperature, it is generally more expensive, and it does require excitation which might drive the need for an external power source (a Wheatstone bridge for example).

If you instead decide that a thermocouple is best for your application, perhaps because of its lower cost, wider temperature range, faster response time, and simpler construction, plus its many physical sizes and wider range of configurations available, then you might start by picking a Type K thermocouple until you can find a specific reason to choose another type. That is, type K is the most common and least expensive of available T/C types, and it also has a wide operating temperature range with high sensitivity. It is constructed from nickel-based metals which have good resistance to corrosion and are cheaper than the comparable platinum-based metals.

So with this in mind, why would you choose anything else? Well, it does have one lead that is magnetic (the Red or negative lead), and this might not work well around electric motors. It is also vulnerable to sulfur attack and should not be used in sulfurous atmospheres.

Whatever your choice may be, Hoyt has metering for your application. Hoyt has been building Analog meters for Exhaust Gas Temperature (EGT) since the 1950’s as well as Pyrometers for Kiln manufacturers. Need lower temp measurement? Hoyt can do those too! Hoyt carries a complete line of Analog and Digital meters and controllers to fit your application and has the expertise to explain what might work better for your products.

Joe Legerstee – Hoyt Electrical Instrument Works 7-13-17