Overview of Temperature Measurement

The Big Three
- Thermocouples
- Resistance Temperature Detectors (RTD’s)
- Thermistors

Smaller Players
- Infrared Thermometry
- Non-Electronic Temperature Gauges
- Thin-Film Heat Flux Gauge

How to Choose Which One
- Standards, cost, accuracy, stability, sensitivity, size, contact/non-contact, temperature range, etc.
What Are Thermocouples?

• Thermocouples operate under the principle that a circuit made by connecting two dissimilar metals produces a measurable voltage when a temperature gradient is imposed between one end and the other.

• They are inexpensive, small, rugged and accurate when used with an understanding of their peculiarities.

Thermocouples - Principle of Operation

• In 1821, T. J. Seebeck observed the existence of an electromotive force at the junction formed between two dissimilar metals. This is known as the Seebeck effect.

• Seebeck effect is actually the combined result of two other phenomena, Thomson and Peltier effects:
  • Thomson observed the existence of an EMF due to the contact of two dissimilar metals at the junction temperature.
  • Peltier discovered that temperature gradients along conductors in a circuit generate an EMF.
  • The Thomson effect is normally much smaller than the Peltier effect.
Thermocouple Properties

- If two wires of dissimilar metals are joined at both ends and one end is heated, current will flow.
- If the circuit is broken, there will be an open circuit voltage across the wires.
- Voltage is a function of temperature and metal types.
- For small $\Delta T$’s, the relationship with temperature is linear.
- For larger $\Delta T$’s, non-linearities may occur.

Measuring the Thermocouple Voltage

If you attach the thermocouple directly to a voltmeter, you will have problems because you have just created another junction. Your displayed voltage will be proportional to the difference between $J_1$ and $J_2$ (and hence $T_1$ and $T_2$).
External Reference Junction

A solution is to put $J_2$ in an ice-bath; then you know $T_2$, and your output voltage will be proportional to $T_1 - T_2$.

Law of Intermediate Metals

Insertion of an intermediate metal into a thermocouple circuit will not affect the emf voltage output so long as the two junctions are at the same temperature and the material is homogeneous.
Other Types of Thermocouples

Various types of thermocouples exist based on the metals used to create them. Shown below is a “Type J” thermocouple.

If the two terminals, J₃ and J₄, aren’t at the same temperature, an incorrect reading will result.

![Diagram of a Type J thermocouple]

Isothermal Block

The isothermal block is an electrical insulator but good heat conductor. The voltages for J₃ and J₄ will cancel out as long as J₃ and J₄ are isothermal. Thermocouple data acquisition set-ups include these isothermal blocks.

![Diagram of an isothermal block setup]

If we eliminate the ice-bath, then the isothermal block temperature is our reference temperature.
Software Compensation

- How can we find the temperature of the isothermal block? Use another type of temperature sensor like a Thermistor or Resistance Temperature Device (RTD).
- Once the temperature is known, the voltage associated with that temperature can be subtracted off.
- Then why use thermocouples at all?
  - Thermocouples are cheaper, smaller, more flexible and rugged, and operate over a wider temperature range.
- Most data acquisition systems have software compensation built in. For instance, if you use Labview you’ll need to know if you have a thermistor or RTD so the correct calibration curves can be applied.

### Thermocouple Types

<table>
<thead>
<tr>
<th>TYPE</th>
<th>METAL</th>
<th>STANDARD COLOR CODE</th>
<th>RESISTANCE PER FOOT 20 AWG</th>
<th>SEEBECK COEFFICIENT B (°C)</th>
<th>% STANDARD WIRE ERROR (SEE APPENDIX B)</th>
<th>NBS SPECIFIED MATERIAL RANGE (°C)</th>
</tr>
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<tbody>
<tr>
<td>B</td>
<td>Platinum - 80% Rhodium (1.508)</td>
<td>-</td>
<td>0.20</td>
<td>6.0</td>
<td>30.4</td>
<td>1200 to 1600</td>
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<td>E</td>
<td>10% Chromium - 20% Nickel (1.469)</td>
<td>-</td>
<td>0.27</td>
<td>58.5</td>
<td>1 to 4</td>
<td>200 to 1000</td>
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<tr>
<td>J</td>
<td>Iron - 25% Chromium (1.256)</td>
<td>-</td>
<td>0.36</td>
<td>60.2</td>
<td>1 to 2.5</td>
<td>200 to 700</td>
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<tr>
<td>K</td>
<td>Nickel - 20% Chromium (1.316)</td>
<td>-</td>
<td>0.59</td>
<td>39.4</td>
<td>1 to 2.5</td>
<td>200 to 1372</td>
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<tr>
<td>N</td>
<td>Nickel (1.287)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L</td>
<td>Nickel - 10% Chromium (1.469)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>Platinum (1.653)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>Platinum - 10% Rhodium (1.508)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T</td>
<td>Copper - 30% Constantan (1.170)</td>
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<td>0.30</td>
<td>38</td>
<td>0.5 to 3.5</td>
<td>-</td>
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<tr>
<td>W-Re</td>
<td>Tungsten - 5% Platinum (1.653)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>200 to 2300</td>
</tr>
</tbody>
</table>

**Type K**

- Temperature Range vs. Wire Size vs. Error

- Error

- Wire Size AWG
Thermocouple Material Vs EMF

- Types T, J, and K are most commonly used thermocouples.

![](chart.png)

Thermocouple Types

- Type B – very poor below 50°C; reference junction temperature not important since voltage output is about the same from 0 to 42 °C.
- Type E – good for low temperatures since $dV/dT$ is high for low temperatures.
- Type J – cheap because one wire is iron; high sensitivity but also high uncertainty (iron impurities cause inaccuracy).
- Type K – popular type since it has decent accuracy and a wide temperature range; some instability (drift) over time.
- Type N – most stable over time when exposed to elevated temperatures for long periods.
- Type T – good accuracy but low max temperature (400 °C); one lead is copper, making connections easier; must watch for heat being conducted along the copper wire.
Thermocouple Types - Continued

• Type K (chromel–alumel) is the most common general purpose thermocouple. It is inexpensive and available in a wide variety of probes. They are available in the −200 °C to +1350 °C range. The type K was specified at a time when metallurgy was less advanced than it is today and, consequently, characteristics vary considerably. Another potential problem arises in some situations since one of the constituent metals, nickel, is magnetic. One characteristic of thermocouples made with magnetic material is that they undergo a step change when the magnetic material reaches its Curie point. This occurs for this thermocouple at 354 °C. Sensitivity is approximately 41 µV/°C.

• Type E (chromel–constantan) has a high output (68 µV/°C) which makes it well suited to cryogenic use. Additionally, it is non-magnetic.

• Type J (iron–constantan) is less popular than type K due to its limited range (−40 to +750 °C). The Curie point of the iron (770 °C) causes an abrupt change to the output characteristics which sets the upper temperature limit. Type J thermocouples have a sensitivity of about 50 µV/°C.

B, R, and S

• Types B, R, and S thermocouples use platinum or a platinum–rhodium alloy for each conductor. These are among the most stable thermocouples, but have lower sensitivity, approximately 10 µV/°C. The high cost of these makes them unsuitable for general use. Generally, type B, R, and S thermocouples are used only for high temperature measurements.

• Type S thermocouples use a platinum–rhodium alloy containing 10% rhodium for one conductor and pure platinum for the other conductor. Like type R, type S thermocouples are used up to 1600 °C. In particular, type S is used as the standard of calibration for the melting point of gold (1064.43 °C).
Thermocouple Types - Continued

Chromel-gold/iron

- In chromel-gold/iron thermocouples, the positive wire is chromel and the negative wire is gold with a small fraction (0.03–0.15% ) of iron. It can be used for cryogenic applications (1.2–300 °K and up to 600 °K). Both the sensitivity and the temperature range depends on the iron concentration. The sensitivity is typically around 15 µV/°K at low temperatures and the lowest usable temperature varies between 1.2 and 4.2 °K.

Sheathing and Special Limits of Error

- “Special Limits of Error” wire can be used to improve accuracy.
- Sheathing of wires protects them from the environment (fracture, oxidation, etc.) and shields them from electrical interference.
- The sheath should extend completely through the medium of interest. Outside the medium of interest it can be reduced.
- Sometimes the bead is exposed and only the wire is covered by the sheath. In harsher environments, the bead is also covered. This will increase the time constant.
- Platinum wires should be sheathed in non-metallic sheaths since they have a problem with metallic vapor diffusion at high temperatures.
Potential Thermocouple Problems

- De-calibration
  - If thermocouples are used for very high or very low temperatures, wire properties can change due to diffusion of insulation or atmosphere particles into the wire, cold-working, or annealing.
  - In-homogeneities in the wire - these are especially bad in areas with large temperature gradients; especially common in iron. Metallic sleeving can help reduce their effect.
- Shunt Impedance
  - As temperature goes up, the resistance of many insulation types goes down. At high enough temperatures, this creates a “virtual junction”. This is especially problematic for small diameter wires.
- Galvanic Action
  - The dyes in some insulations form an electrolyte in water. This creates a galvanic action with a resulting emf potentially many times that of the thermocouple. Use an appropriate shield for a wet environment. “T Type” thermocouples have less of a problem with this.
- Inaccurate ice-point

Potential Problems - Continued

- Thermal Shunting
  - It takes energy to heat the thermocouple, which results in a small decrease in the surroundings’ temperature. For tiny spaces, this may be a problem.
  - Use small wire (with a small thermal mass) to help alleviate this problem. Small-diameter wire is more susceptible to de-calibration and shunt impedance problems. Extension wire helps alleviate this problem. Have short leads on the thermocouple, and connect them to the same type of extension wire which is larger. Extension wire has a smaller temperature range than normal wire.
- Noise
  - Several types of circuit set-ups help reduce line-related noise. You can set your data acquisition system up with a filter, too.
  - Small-diameter wires have more of a problem with noise.
- Conduction along the thermocouple wire
  - In areas of large temperature gradient, heat can be conducted along the thermocouple wire, changing the bead temperature.
  - Small diameter wires conduct less of this heat.
  - T-type thermocouples have more of a problem with this than most other types since one of the leads is made of copper which has a high thermal conductivity.
Thermocouple Systems Check

- Make sure materials are clean, especially for high temperatures.
- Check the temperature range of materials. Materials may degrade significantly before the highest temperature listed.
- Make sure you have a good isothermal junction.
- Use enough wire that there are no temperature gradients where it’s connected to your DAQ system.
- If you’re using thermocouple connectors, use the right type for your wire.
- If you’re using a DAQ system, use the right set-up for thermocouples.
- Check the ice-point reference.
- Provide proper insulation for harsh environments.
- Pass a hair-dryer over the wire. The temperature reading should only change when you pass it over the bead.
- Mount a thermocouple only on a surface that is not electrically live.

RTD’s - Resistance Temperature Detectors

- Resistivity of metals is a function of temperature.
- Platinum is often used to construct an RTD because of its wide temperature range and excellent stability. Nickel or nickel alloys are used as well, but they aren’t as accurate.
- RTD’s are more accurate but also larger and more expensive than thermocouples.
Resistive Temperature Detectors

- Each type of temperature sensor has a particular set of conditions for which it is best suited. RTD’s offer several advantages:
  - A wide temperature range (approximately -200 to 850°C).
  - Good accuracy (better than thermocouples).
  - Good interchangeability.
  - Long-term stability.

- Sheathing: stainless steel or inconel, glass, alumina, quartz.
- Metal sheath can cause contamination at high temperatures and is best below 250°C.
- At very high temperatures, quartz and high-purity alumina are best to prevent contamination.

Resistance Measurement

- A Wheatstone Bridge is a common circuit for measuring change in resistance. Bridge output voltage is a function of the RTD resistance.
- Modern instruments can often read the change of resistance directly.
Potential Problems

- Response time is longer for RTD’s than for thermocouples. Response time can easily be 10 seconds or more.
- RTDs are more fragile than thermocouples.
- An external current must be supplied to the RTD. This current can heat the RTD, altering the results. For situations with high heat transfer coefficients, this error is small since the heat is dissipated to air. For small diameter RTD’s and still air this error is the largest. Use the largest RTD possible and smallest external current possible to minimize this error.

Thin Film RTD’s

- Thin-film RTD elements are produced by depositing a thin layer of platinum onto a substrate.
- A pattern is then created that provides an electrical circuit that is trimmed to provide a specific resistance.
- Lead wires are then attached and the element coated to protect the platinum film and wire connections.

OMEGA’s FE206, 100 Ω, Class “A” Thin-film element, see page C-85.
**Wire-Wound RTDs**

- Two types of wire-wound elements:
  - Those with coils of wire packaged inside a ceramic or glass tube (the most commonly used wire-wound construction).
  - Those wound around a glass or ceramic core and covered with additional glass or ceramic material (used in more specialized applications).

![Typical wire-wound RTD element](image)

**Thermistors**

- A **Thermistor** is a type of resistor whose resistance is dependent on temperature.
- Thermistors differ from RTD’s in that the material used in a thermistor is generally a ceramic or polymer, while RTD’s use pure metals.
- The temperature response is also different - RTD’s are useful over larger temperature ranges.
- Many NTC (Negative Temperature Coefficient) thermistors are made from a pressed disc or cast chip of a semiconductor such as a sintered metal oxide.
- Most PTC (Positive Temperature Coefficient) thermistors are of the "switching" type, which means that their resistance rises suddenly at a certain critical temperature. The devices are made of a doped polycrystalline ceramic containing barium titanate (BaTiO3) and other compounds.
Thermistors

• Like RTD’s, Thermistors also measure the change in resistance with temperature.
• Thermistors are very sensitive (up to 100 times more than RTD’s and 1000 times more than thermocouples) and can detect very small changes in temperature. They are also very fast.
• Due to their speed, they are used for precision temperature control and any time very small temperature differences must be detected.
• They are made of ceramic semiconductor material (metal oxides).
• Downside - the change in thermistor resistance with temperature is very non-linear.

Thermistor Non-Linearity
Resistance/Temperature Conversion

- Standard thermistors curves are not provided as much as with thermocouples or RTD’s. You often need a curve for a specific batch of thermistors so calibrating them is often left to the customer.
- Thermistors do not do well at high temperatures and show instability with time (but for the best ones, this instability is only a few millikelvin per year).

Choosing RTDs, Thermocouples, or Thermistors

- Cost – thermocouples are cheapest by far, followed by RTD’s.
- Accuracy – RTD’s or thermistors.
- Sensitivity – thermistors.
- Speed – thermistors.
- Stability at high temperatures – not thermistors.
- Size – thermocouples and thermistors can be made quite small.
- Temperature range – thermocouples have the highest range, followed by RTDs.
- Ruggedness – thermocouples are best if your system will be taking a lot of abuse.
Infrared Thermometry

• Infrared thermometers measure the amount of radiation emitted by an object.
• Peak magnitude of radiation is most often found in the infrared region.
• Surface emissivity must be known. This can add a lot of error.
• Reflection from other objects can introduce error.
• Surface whose temperature you’re measuring must fill the field of view of your camera.
• Accuracy is often in the 0.5-1% of full range. Uncertainties of 10°F are common, but at temperatures of several hundred degrees, this is small.

Benefits of Infrared Thermometry

• Can be used for:
  • Moving objects.
  • Non-contact applications where sensors would affect results or be difficult to insert.
  • Hazardous conditions.
  • Large distances.
  • Very high temperatures.
Emissivity

• To derive temperature, surface emissivity must be known.
• You can look up emissivities, but it’s not easy to get an accurate number, especially if the surface condition is uncertain or non-uniform.
• Highly reflective surfaces introduce a lot of error.
• Narrow-band spectral filtering results in a more accurate emissivity value.

Ways to Determine Emissivity

• Measure the temperature with a thermocouple and an infrared thermometer. Back out the emissivity. This method works well if emissivity doesn’t change much with temperature or you’re not dealing with a large temperature range.
• For temperatures below 500°F, place an object covered with masking tape (which has $\varepsilon=0.95$) in the same atmosphere. Both objects will be at the same temperature. Back out the unknown emissivity of the surface.
• Drill a long hole in the object. The hole acts like a blackbody with $\varepsilon=1.0$. Measure the temperature of the hole, and find the surface emissivity that gives the same temperature.
• Coat all or part of the surface with dull black paint which has $\varepsilon=1.0$.
• For a standard material with known surface condition, look up $\varepsilon$. 
Non-Electronic Temperature Gauges

- Crayons – You can buy crayons with specified melting temperatures. Mark the surface, and when the mark melts, you know the temperature at that time.

- Lacquers – Special lacquers are available that change from dull to glossy and transparent at a specified temperature. This is a type of phase change.

- Pellets – These change phase like crayons and lacquers but are larger. If the heating time is long, oxidation may obscure crayon marks. Pellets are also used as thermal fuses; they can be placed so that when they melt, they release a circuit breaker.

- Temperature sensitive labels – These are nice because you can peel them off when finished and place them in a log book.

- Liquid crystals – They change color with temperature. If the calibration is known, color can be determined very accurately using a digital camera and appropriate image analysis software. This is used a fair amount for research.