Temperature Sensors

What is the best sensor to measure temperature?

There is no such thing… depends on the temperature range, the accuracy needed, the environment, the cost, etc.

We have looked at RTDs, which have their electrical resistance vary with temperature. We then studied how to measure resistance.

NOTE: While we talked about measuring resistance in the context of thermometry, the tips we used are general, and apply to measuring resistance for other reasons too. We will revisit this later today and in future lectures.

Thermistors

- Solid-state semiconductor device
  - Positive temperature coefficient (PTC) devices increases resistance with temperature increase
  - Negative temperature coefficient (NTC) devices decreases resistance with temperature increase
- Relationship between R and T is non-linear, but has a very steep slope
  - Increases the sensitivity of the device
  - Resistance change of 3%/°C
  - Limits range of operation

Thermistors

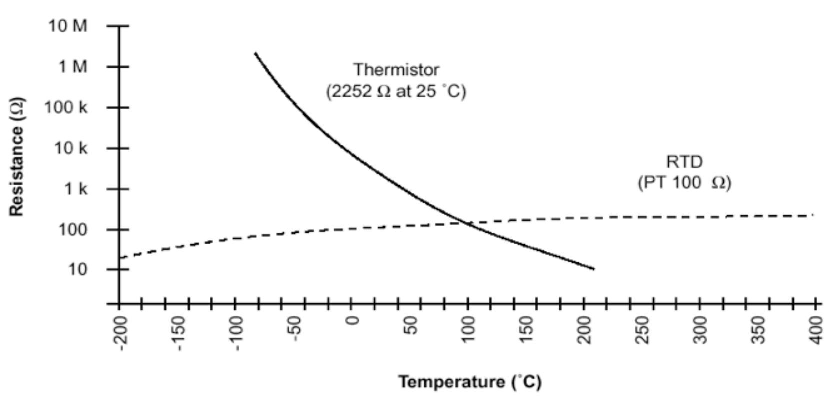
Non-linear resistance vs. temperature means:

- •High sensitivity
- •Reproducibility not as good as Pt RTD
- •Calibration important, and must be done at several points.
- •Resistance can be chosen: Ω to MΩ
- •Temperature range small, but can be chosen in range of interest

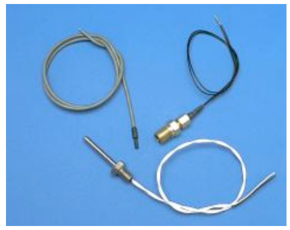
Devices can be tiny - therefore fast response time. Much cheaper than Pt RTDs.

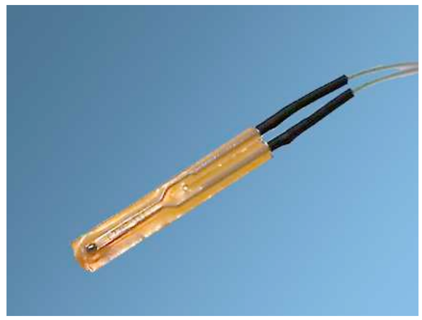
Chemical stability not as good… long term drift due to thermal cycling.

Thermistor vs RTD



Thermistors





Thermistor Functional Form

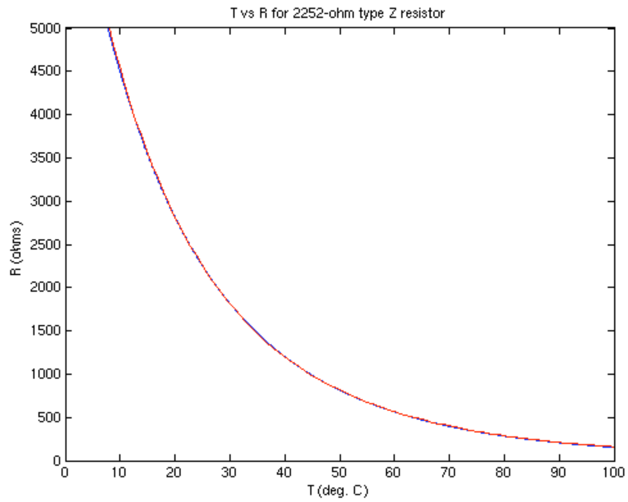
- Relationship between R and T given by the Steinhart-Hart equation

[redacted]

R_T - resistance at temperature T

a, b, c, d - constants given by device manufacturer

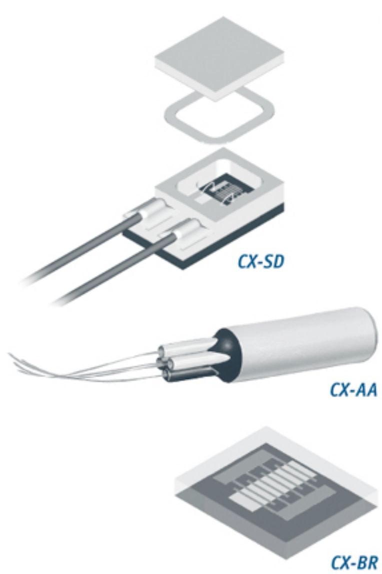
T - temperature in K

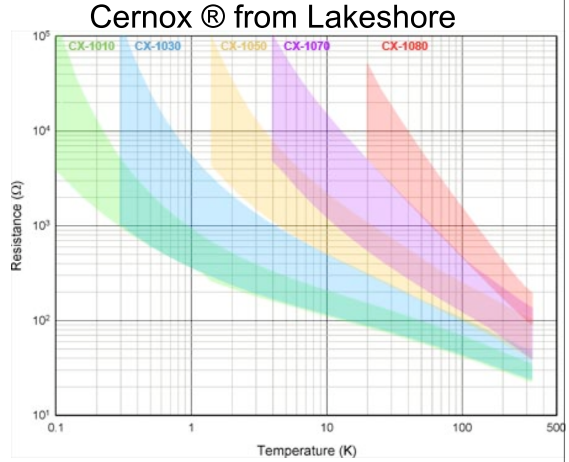


Higher resistance makes lead wire effects negligible. Self-heating problem identical to RTDs - best to still use a bridge.

Cryogenic Sensor

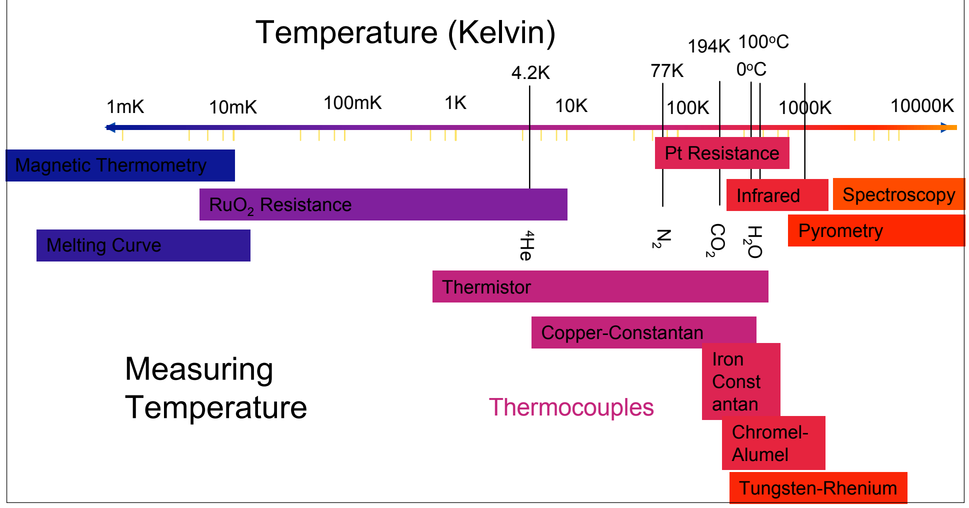
Cernox ® from Lakeshore





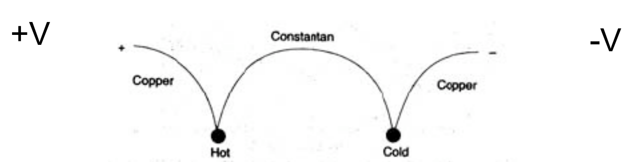
Each device must be calibrated for accurate use, but general form is similar, so a 1-pt calibration often used

Temperature Ranges



Thermocouples

Two dissimilar metals in contact generate a potential difference between junctions at different temperatures



Seebeck Effect

Relies on the correlation between the electric potential and thermal gradient.

The size of the effect, and reproducibility has lead to established pairs of metals.

Standard Thermocouples

Need to keep a "reference junction" at a known temperature. Tables for 0ºC (see Omega catalog!).

Electronic compensation can be used if the reference junction isn't at 0ºC.

Thermocouple pair		ISA	Colour coding
Iron	Constantan	J	White/Red
Chromel	Alumel	K	Yellow/Red
Copper	Constantan	T	Blue/Red
Chromel	Constantan	E	Purple/Red
Platinum—10% rhodium	Platinum	S	Black/Red
Platinum—13% rhodium	Platinum	R	Black/Red
Platinum—30% rhodium	Platinum—6% rhodium	B	Gray/Red
Tungsten—26% rhenium	Tungsten	G	White/Red

Figure 3.6 shows that the thermocouple voltage is relatively linear with temperature, particularly in the range above room temperature. The output is in the millivolt range, but the device is of low resistance and is reasonably sensitive.

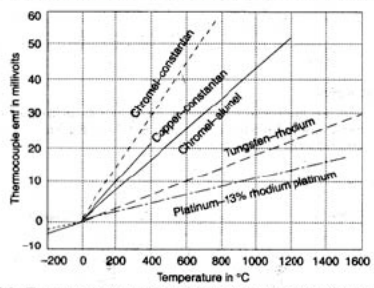
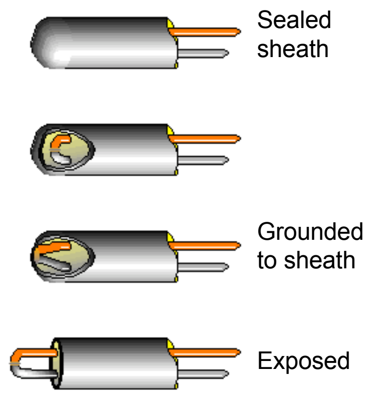


Fig. 3.6 Thermocouple output voltage (mV) versus temperature: reference junction at 0°C.

Thermocouples

- Work over a wide range of temperature
- No self-heating
- mV output, but reasonable sensitivity ($\Delta V/ \Delta T$ large).
- Use the "Thermocouple Laws":
    - Thermal emf unaffected by temperature elsewhere in the circuit if the two metals are homogeneous
    - A third homogeneous metal inserted in the circuit doesn't affect emf [this is the voltmeter].
- Cheap! Rugged!
- Can be small for fast response.
- Good linearity, but not particularly accurate.

- Isolated from sheath
  - \+ Wires well protected
  - \- Slow response time (75 sec)
- Grounded to sheath
  - \+ Wires well protected
  - \+ Reasonable response time (40 sec)
- Exposed
  - \+ Fast response time (2 sec)
  - \- Wires exposed to damage (physical/chemical)



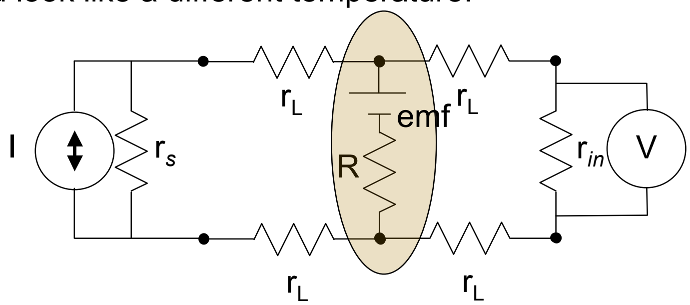
Thermocouples

Standard Type	Positive Leg Metal	Negative Leg Metal	Temperature Range
B	70.4% Pt 29.6% Rh	93.9% Pt 6.1% Rh	870 - 1700 0°C
E	90% Ni 10% Cr	55% Cu 45% Ni	0 - 900 0°C
J	99.5% Fe	55% Cu 45% Ni	0 - 750 0°C
K	90% Ni 10% Cr	95% Ni 5% other	0 - 1250 0°C
N	84.4% Ni 14.2% Cr 1.4% Si	95.5% Ni 4.4% Si	0 - 1250 0°C
R	87% Pt 13% Rh	100% Pt	0 - 1450 0°C
S	90% Pt 10% Rh	100% Pt	0 - 1450 0°C
T	100% Cu	55% Cu 45% Ni	-200 - 350 0°C

*Modified from *Temperature Sensors, The Watlow Educational Series Book Four*

Seebeck Effect

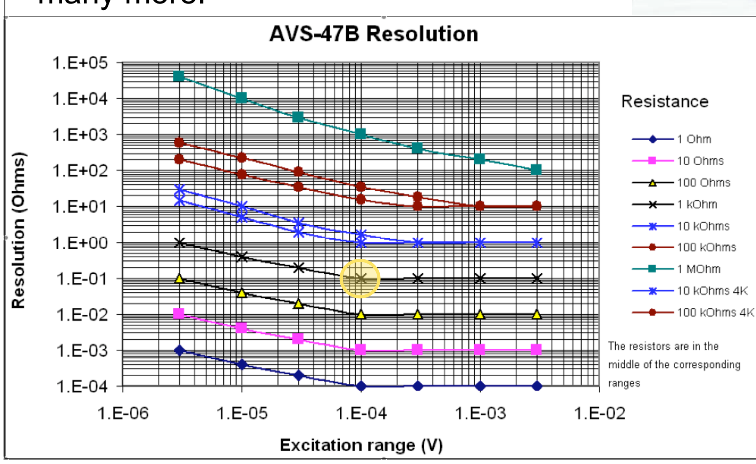
The emf generated by the Seebeck effect can be present in RTDs and thermistors too!   This is an unwanted effect that would look like a different temperature.



Avoid it by reversing current: emf doesn't change, but IR does. We can do this with positive and negative DC currents, or use an AC signal.

Cryogenic AC Resistance Bridge

At low temperature, the self-heating effect is even more pronounced, so ALL these techniques are used, plus many more.



$P=V^2/R$

$=10^{-8}/10^3$

$=10^{-11}$ W

$\Delta R/R=$

$.1/10^3 = 10^{-4}$

Junction Semiconductor Sensors

Silicon transistors configured in a circuit that has measurable and predictable I-V. Different configurations possible.

Benefits:

- Cheap
- Integrated with other silicon circuits (for memory, communication, amplification, processing, etc.)

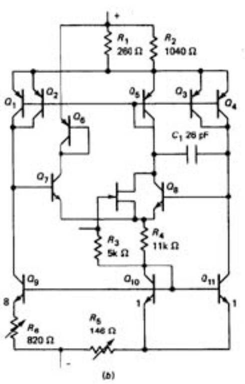
Disadvantages

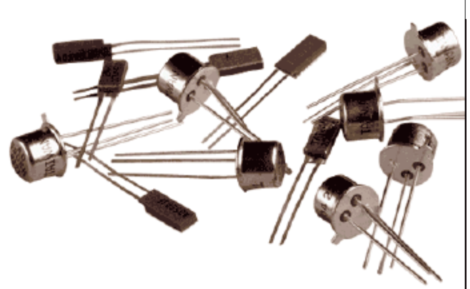
- Needs power, not rugged, not standardized, limited temperature range

AD590 IC Temperature Sensor

Operating Principle: Transistor's current in saturation depends on

$$I_C = e^{qV_{EB}/k_B T}$$





Optical Thermometry

$$E(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \cdot \frac{1}{\exp(hc/k\lambda T) - 1}$$

where c is the velocity of light, h is Planck's Constant and k is Boltzmann's constant.

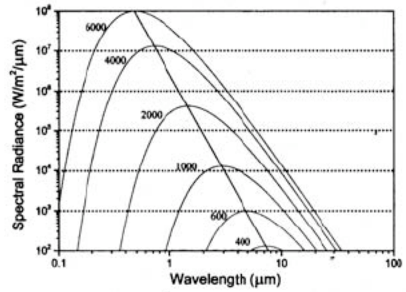


Fig. 3.9 Thermal emission (W/m²/μ) as a function of wavelength λ for a body at temperature T(K).

$$E(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{exp(hc/k_B \lambda T) - 1}$$

Hot bodies radiate electromagnetic energy depending on their temperature.

$$M_\nu(T) = \frac{2\pi\nu^2}{c^2} \frac{h\nu}{e^{h\nu/k_B T} - 1}$$

M=energy emitted per unit frequency.

The surface of the material matters: emissivity of a material $\varepsilon<1$, and can depend on temperature.

Infrared Photometry

$$E(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \cdot \frac{1}{\exp(hc/k\lambda T) - 1}$$

where c is the velocity of light, h is Planck's Constant and k is Boltzmann's constant.

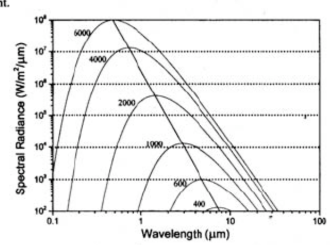


Fig. 3.9 Thermal emission (W/m²/μ) as a function of wavelength λ for a body at temperature T(K).

The intensity of the radiation increases with increasing temperature:

$I = \sigma\, \varepsilon(T^4 - T_0^{\,4})$

For most accessible temperatures, the radiation is in the infrared region.

$\sigma = 5.67 \times 10^{-8}$ J s^{-1} m^{-2} K^{-4}
Stefan-Boltzmann constant

Use an infrared light detector (discussed later in the class), measure the light intensity, infer the temperature.

Advantages: Non-contact, quick, thermal contact not a problem

Infrared Photometry

$I = \sigma\, \varepsilon(T^4 - T_0^{\,4})$

ε is the emissivity - a number between 0 and 1 which defines how close to a "black body" (perfect emitter) the material is. No material is perfect, and surface changes result in changes to the emissivity.

The "grey body" approximation sets ε as a constant for all wavelengths.

Accurate measurements of ε are difficult, and are likely to change. Thus accuracy of infrared photometry is limited by the knowledge of the emissivity.

Ratio Pyrometry

Measure the infrared intensity at two different wavelengths, take the ratio.

$$E(\lambda_1) = \frac{2\pi c^2 h}{\lambda_1^5} \frac{\epsilon(\lambda_1)}{exp(hc/k_B \lambda_1 T) - 1}$$

$$E(\lambda_2) = \frac{2\pi c^2 h}{\lambda_2^5} \frac{\epsilon(\lambda_2)}{exp(hc/k_B \lambda_2 T) - 1}$$

$$E(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \cdot \frac{1}{\exp(hc/k\lambda T) - 1}$$

where c is the velocity of light, h is Planck's Constant and k is Boltzmann's constant.

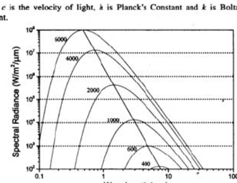


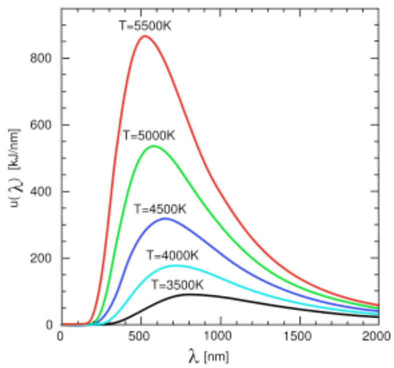
Fig. 3.9 Thermal emission (W/m²/µ) as a function of wavelength λ for a body at temperature T(K).

As long as ε doesn't vary significantly with wavelength, the ratio has a simple dependence on temperature. Measuring at two narrow wavelengths difficult.

$$R = \frac{E(\lambda_1)}{E(\lambda_2)} = \left(\frac{\lambda_2}{\lambda_1}\right)^5 \frac{\epsilon(\lambda_1)}{\epsilon(\lambda_2)} \frac{exp(hc/k_B \lambda_1 T) - 1}{exp(hc/k_B \lambda_2 T) - 1}$$

Pyrometry

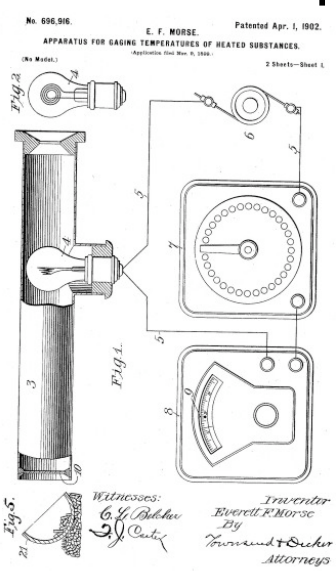
For still higher temperatures, the thermal emission will be in the visible regime.



Measuring the colour of the light, or more precisely the spectrum, will allow the temperature to be known.

One simple way to measure temperature is to compare two spectra - Disappearing filament optical pyrometer.

Disappearing Filament Optical Pyrometer



Look at background image while looking at a tungsten filament. Put power into the filament until it appears to glow the same colour as the background. Using the known properties of the filament, its temperature can be found, and the temperature of the background object is the same.

Measurement & Uncertainties

Anytime you make a measurement, you should quote an uncertainty on that measurement. This uncertainty tells the reader how confident you are in the number and takes into account two effects:

Statistical uncertainty: due to the random nature of some processes, we expect there to be variation in the measured values. For example: nuclear decay is a perfectly random event, so counting the number of decays in a given time will have some variation.

Statistical uncertainties happen whenever randomness is inherent:

- Nuclear decay
- quantum processes
- sampling of a larger ensemble

Measurement and Uncertainties

Systematic Uncertainties:

"Systematic Uncertainty: This is the degree to which a measured value differs from the 'true' value because of errors inherent in the measurement. This may be due to an incorrect scale, a wrong calibration or an erroneous assumption. In instrumentation, changes in the original calibration of an instrument over time, or if the instrument is used under abnormal conditions are major sources of systematic error. Systematic errors are generally not statistical in nature and may be corrected by measurement of a standard."

From textbook

Measurement and Uncertainties

These definitions are rather narrow, and exclude lots of other errors:

•Limited precision of a measurement device

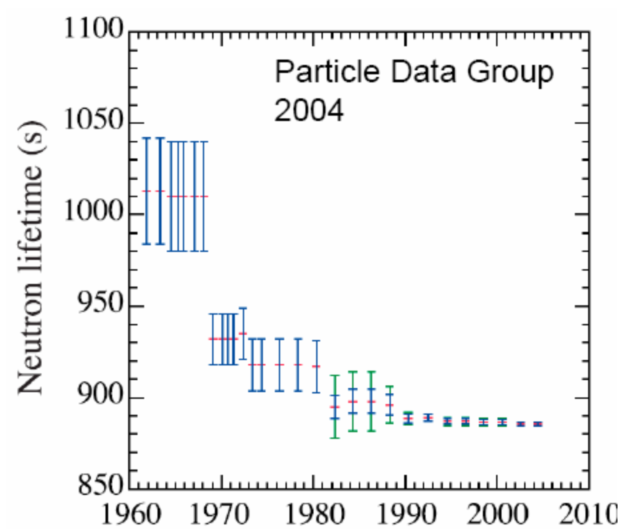
•Uncontrolled variation of extraneous variables (eg. biology)

•Variation in amplifier output which affects measured values

•Difficulty in making a measurement

These fluctuations may or may not be strictly “random” or statistical in nature. Often we will use statistics to study these effects - which may or may not be strictly true. Much of this course focuses on designing instruments or experiments which minimize these effects.

Example of Uncertainties



Uncertainties

Physics 252 (or other statistics class) dealt with the random uncertainties present in all measurements, and harnessed the power of statistics to deal with them.

- Much of this is reviewed in chapter 1 of Sayer & Mansingh.

Physics 352 builds on this. How can we use physics, instrumentation and electronics to reduce and understand these uncertainties? We will still need to understand statistics, since this is the way these random fluctuations are characterized, but we will go beyond that to study why the fluctuations occur…

Next few lectures: **NOISE**