Temperature Measurements

What is Temperature ?

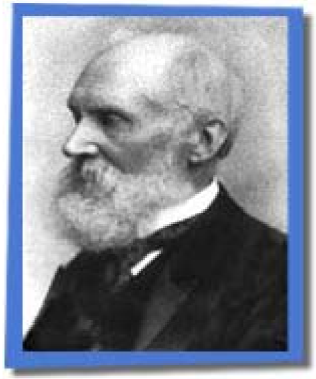
• ***Temperature:*** A measure proportional to the average translational kinetic energy associated with the disordered microscopic motion of atoms and molecules.

• The flow of heat is from a high temperature region toward a lower temperature region.

• When a high temperature object is placed in contact with a low temperature object, then energy will flow from the high temperature object to the lower temperature object, and they will approach an equilibrium temperature.

Kelvin Temperature Scale

• In the early 1800's William Thomson (Lord Kelvin), developed a universal thermodynamic scale based upon the coefficient of expansion of an ideal gas. Kelvin established the concept of absolute zero, and his scale remains the standard for modern thermometry.



• Temperature, measured in Kelvin degrees, is directly proportional to the average kinetic energy of the molecules in a substance. So, when molecules of a substance have a small average kinetic energy, then the temperature of the substance is low.

Kelvin Temperature Scale

- At a low temperature gas molecules travel, on average, at slower speeds than they travel at high temperature.

- Thus, at a low temperature the molecules have, on average, less kinetic energy than they do at a high temperature.

- Kelvin is the only true "natural" temperature scale … everything else is simply a "conversion"

The conversion equations for the four modern temperature scales are:

Celsius	$°C = 5/9\,(°F - 32)$	$°F = 9/5°\,C + 32$	Fahrenheit
Kelvin	$k = °C + 273.15$	$°R = °F + 459.67$	Rankine

Kelvin Temperature Scale

• On the **Kelvin temperature scale,** absolute zero corresponds to a condition below which temperatures do not exist.

•At absolute zero, or 0 ^{o}K, molecular motion ceases, This value corresponds to a temperature of −273.15° on the Celsius temperature scale.

• The Kelvin degree is the same size as the Celsius degree; hence the two reference temperatures for Celsius, the freezing point of water (0°C), and the boiling point of water (100°C), correspond to 273.15K and 373.15K, respectively.

Reference Temperatures

- Must rely upon temperatures established by physical phenomena which are consistently observed in nature.

- The International Temperature Scale (ITS) is based on such observed phenomena, establishes seventeen fixed points and corresponding temperatures.

Reference Temperatures

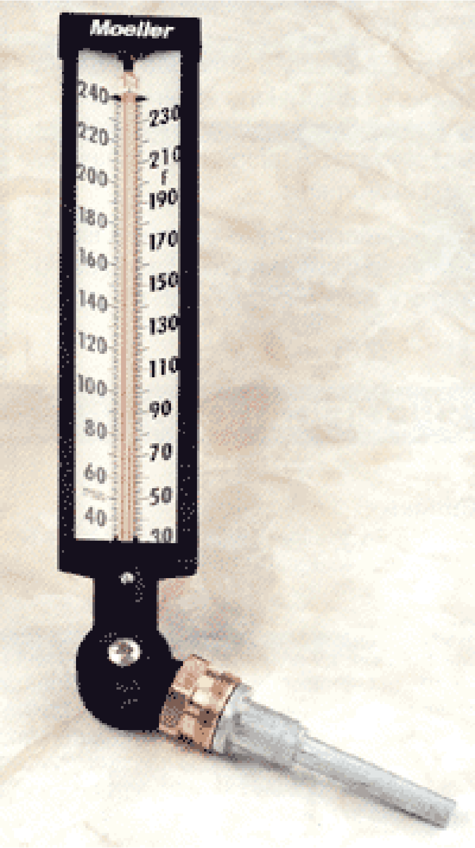
ITS-90 Fixed Points

Element		Type	Temperature K	°C
(H_2)	Hydrogen	Triple Point	13.8033 K	-259.3467° C
(Ne)	Neon	Triple Point	24.5561 K	-248.5939 ° C
(0_2)	Oxygen	Triple Point	54.3584 K	-218.7916° C
(Ar)	Argon	Triple Point	83.8058 K	-189.3442° C
(Hg)	Mercury	Triple Point	234.315 K	-38.8344° C
(H_2O)	Water	Triple Point	273.16 K	+0.01° C
(Ga)	Gallium	Melting Point	302.9146 K	29.7646° C
(In)	Indium	Freezing Point	429.7485 K	156.5985° C
(Sn)	Tin	Freezing Point	505.078 K	231.928° C
(Zn)	Zinc	Freezing Point	692.677 K	419.527° C
(Al)	Aluminum	Freezing Point	933.473 K	660.323° C
(Ag)	Silver	Freezing Point	1234.93 K	961.78° C
(Au)	Gold	Freezing Point	1337.33 K	1064.18° C

Temperature Measurements

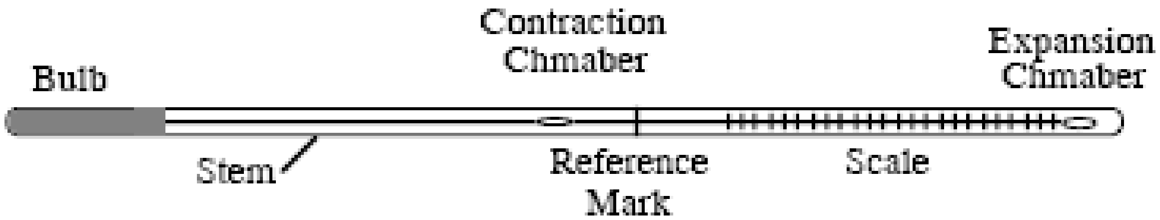
- Liquid bulb thermometers
- Gas bulb thermometers
- bimetal indicators
- RTD: resistance temperature detectors (Platinum wire)
- thermocouples
- thermistors
- IC sensors
- Optical sensors
  . Pyrometers
  . Infrared detectors/cameras
  . liquid crystals

Liquid Bulb Thermometers



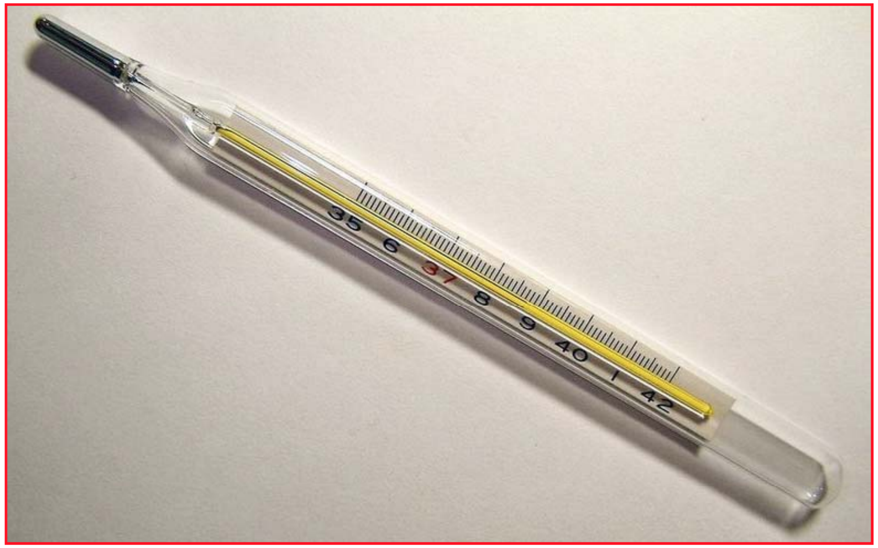
A thermometer is a device used to measure temperature.

1592 - Galileo Galilei builds a thermometer using the contraction of air to draw water up a tube



Liquid Bulb Thermometers

- Most common device
- Thermometry based on thermal expansion
- Liquid-in-glass thermometers
- The manner in which a thermometer is calibrated needs to correspond to how it used. Under normal circumstances, … accuracy from ±0.2 to ±2°C.



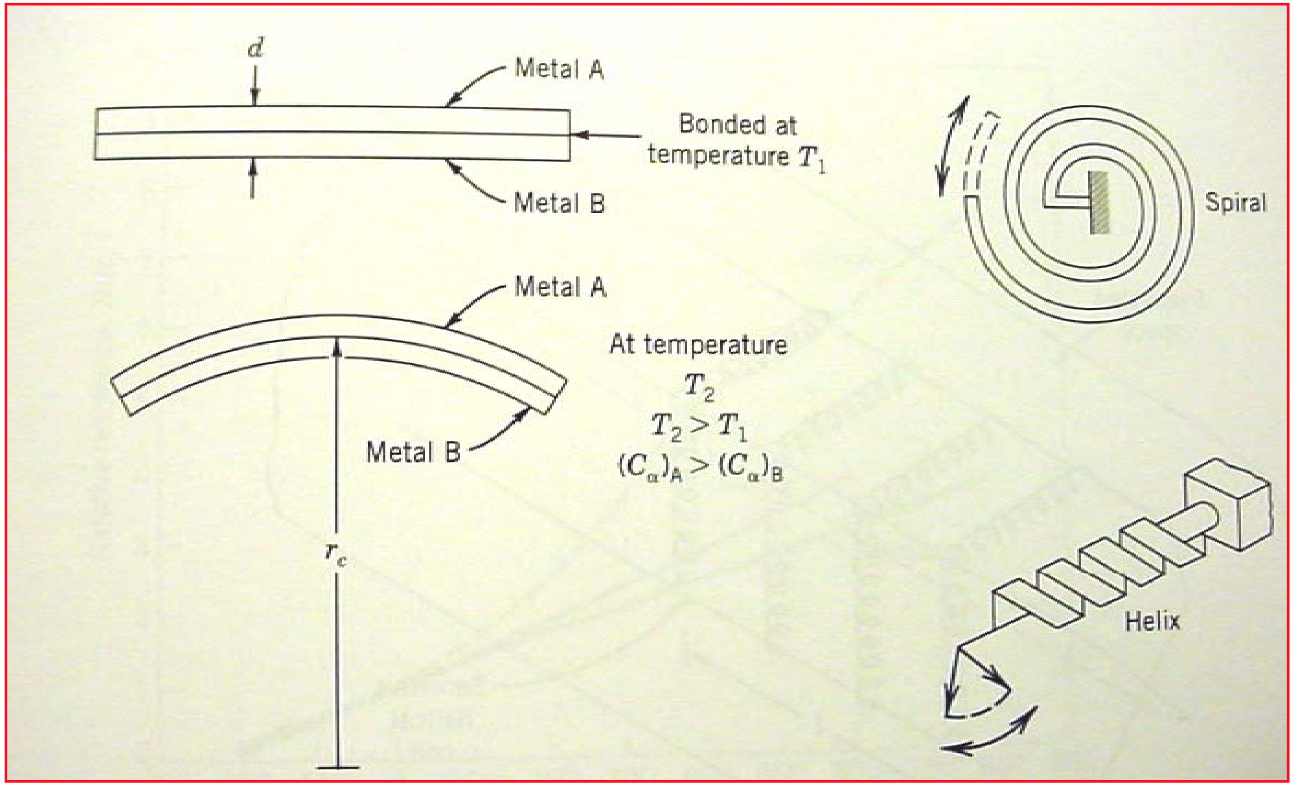
…limited Measurement Resolution and accuracy

Gas Bulb Thermometers

•**Gas bulb thermometers** measures temperature by the variation in volume or pressure of a gas. One common apparatus is a constant volume thermometer. It consists of a bulb connected by a capillary tube to a manometer.

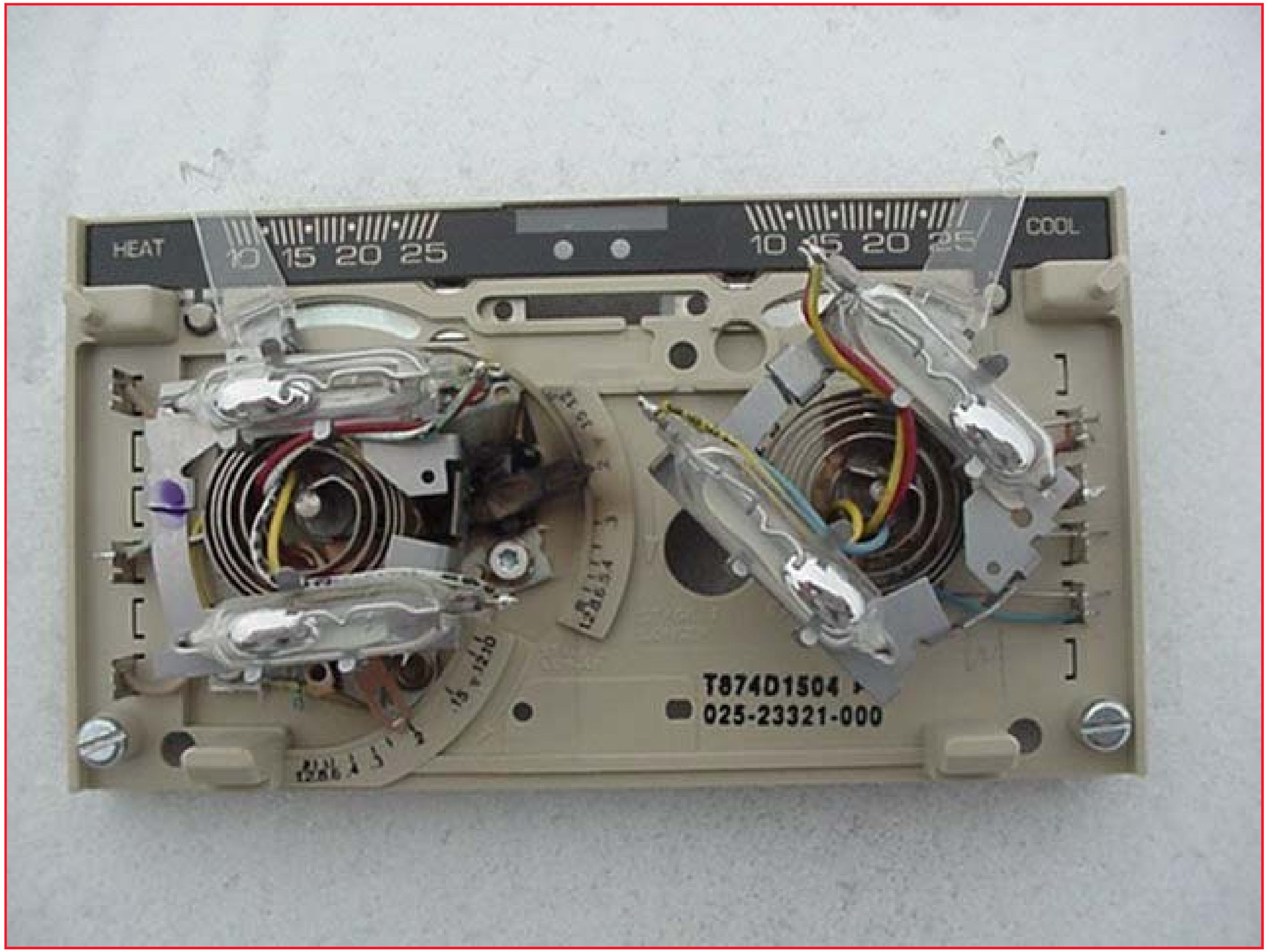
Bi-Metallic Thermometers

If you take two metals with different thermal expansion coefficients and bond them together, they will bend in one direction if the temperature rises above the temperature at which the boding was done and in the direction if temperature drops.



- Devices Can be used to indirectly Drive an Electronic Indicator

Bi-Metallic Thermometer Example



RTD's or Resistance Temperature Detectors

• The same year that Seebeck made discovery about thermoelectricity, Humphrey Davy discovered that metal resistivity had a consistent temperature dependence.

Davy

Siemens

• Fifty years later, William Siemens proffered use of platinum as element in a resistance thermometer.

• Platinum is well suited for resistance thermometry because it can Withstand high temperatures while maintaining excellent material stability.

• As a noble metal, Platinum shows limited susceptibility to contamination.

RTD's or Resistance Temperature Detectors

RTD's are stable and have a fairly wide temperature range, but are not inexpensive as thermocouples since they require the use of electric current to make measurements, RTD's are subject to inaccuracies from self-heating.

An RTD capitalizes on the fact that the electrical resistance of a material changes as its temperature changes.

RTD's rely on the resistance change in a metal. The resistance will rise more or less linearly with temperature.

Traditionally, RTD's use a length of conductor (platinum, nickel iron or copper) wound around an insulator.

RTD's are used to measure temperatures from -196° to 482° C

RTD's or Resistance Temperature Detectors

The RTD is a more linear device than the thermocouple, but it still requires curve-fitting. The Callendar-Van Dusen equation has been used for years to approximate the RTD curve.[11, 13]

$$R_T = R_0 + R_0\alpha\left[T - \delta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) - \beta\left(\frac{T}{100} - 1\right)\left(\frac{T^3}{100}\right)\right]$$

Where:

R_T = resistance at temperature T

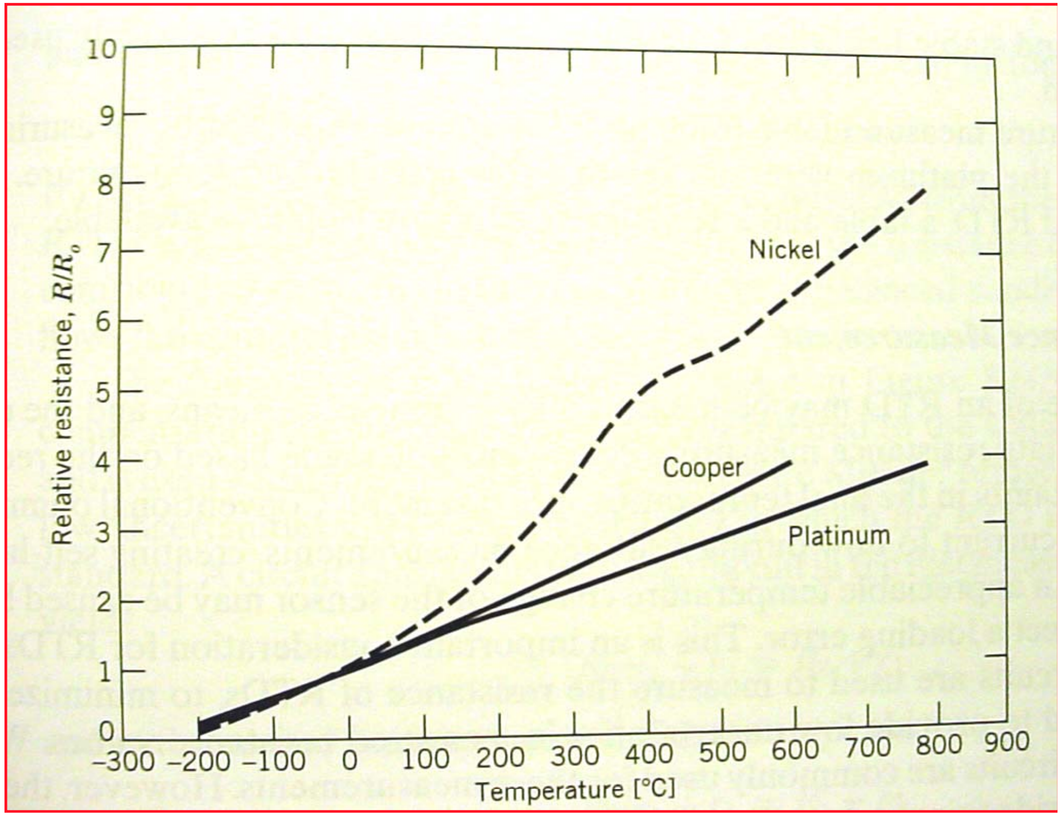
R_0 = resistance at T = 0° C

α = temperature coefficient at T = 0° C (typically + 0.00392Ω/Ω/° C)

δ = 1.49 (typical value for .00392 platinum)

β = 0 T > 0

0.11 (typical) T < 0



RTD's or Resistance Temperature Detectors

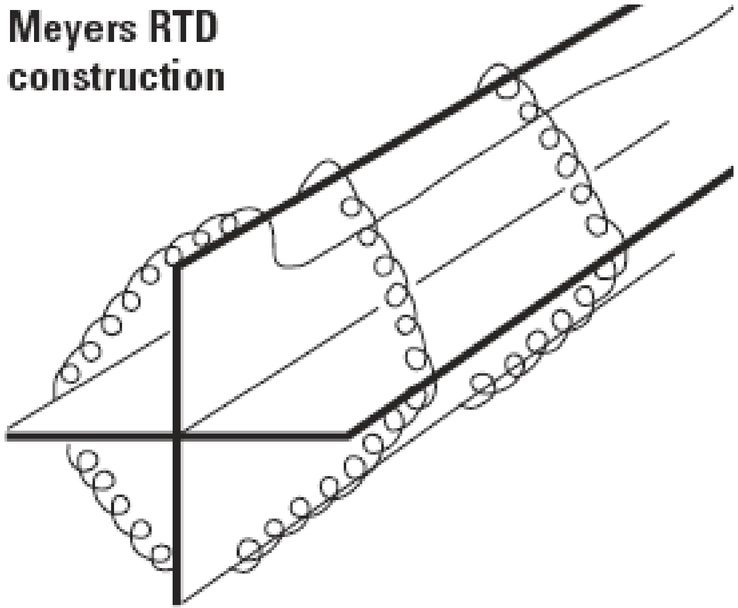
• Resistance of a small wire is used to detect temperature.

• Factors other than temperature that effect resistance must be minimized. Primary effect is strain.

• The classical RTD construction using platinum was proposed by C.H. Meyer in 1932

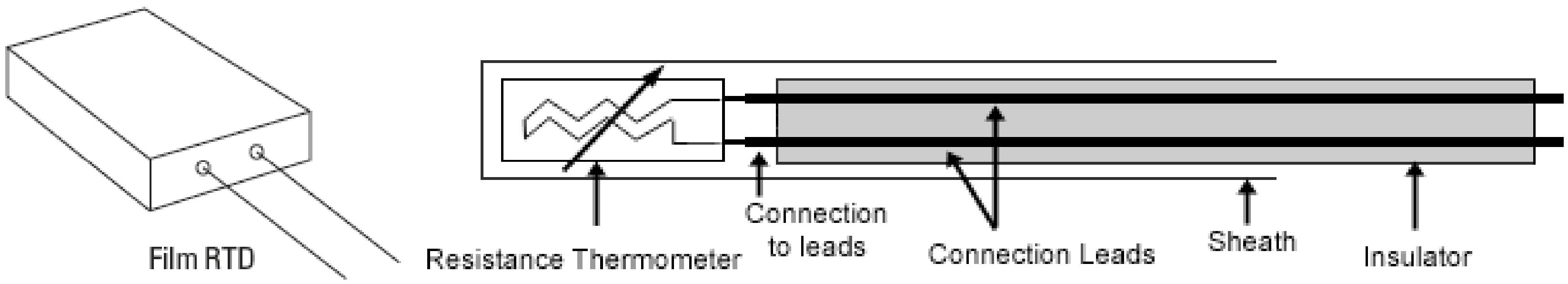
• Helical coil of platinum wound on a crossed mica web and mounted inside a glass tube.

• Minimized strain on the wire while maximizing resistance



RTD's or Resistance Temperature Detectors

• Film RTD offers substantial reduction in assembly time and has advantage of high element resistance for a given physical size.



• Small device size means fast response to changes in temperature.

• Film RTD's are less stable than wire-wound, but are more popular because of decided advantages in size, production cost and ruggedness.

Thermistors

A thermistor is an electrical resistor used to measure temperature. A thermistor designed such that its resistance varies with temperature.

Thermistors tend to be more accurate than RTD's and thermocouples, but they have a much more limited temperature range because of their marked non-linearity.

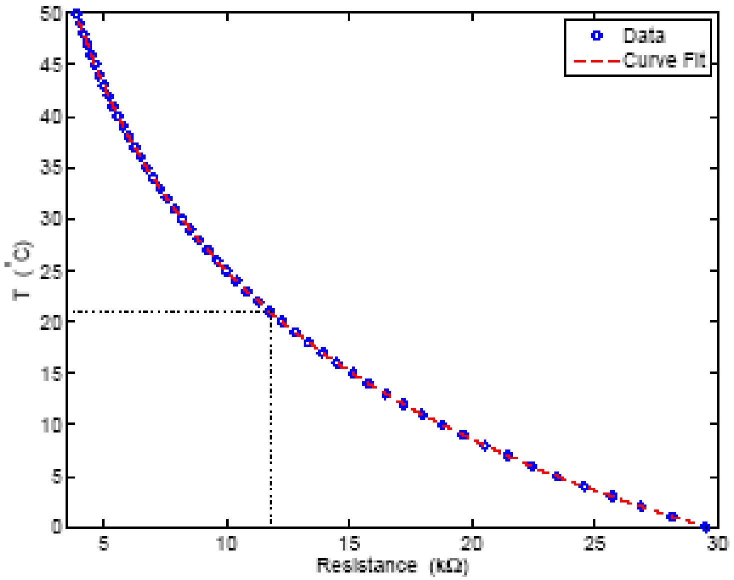
A Thermistor capitalizes on the fact that the electrical resistance of a material changes as its temperature changes. Thermistors rely on the resistance change in a ceramic semiconductor, with the resistance dropping non-linearly with a temperature rise.

Thermistors

Measure resistance, e.g., with a multimeter
Convert resistance to temperature with calibration equation

Calibration uses the Steinhart-Hart equation

$$T = \frac{1}{c_1 + c_2 \ln R + c_3 (\ln R)^3}$$



Thermistors

Advantages

• Sensor output is directly related to absolute temperature – no reference junction needed.

• Relatively easy to measure resistance

Disadvantages

• Possible self-heating error

e.g. Repeated measurements in rapid succession can cause thermistor to heat up

• More expensive than thermocouples: $20/each versus $1/each per junction

• More difficult to apply for rapid transients: slow response and self-heating

Advantages	Disadvantages
High Output	Non Linear
	Limited Temperature Range
Two-wire ohms measurement	Fragile
	Current Source Required
	Self-heating

Thermistors

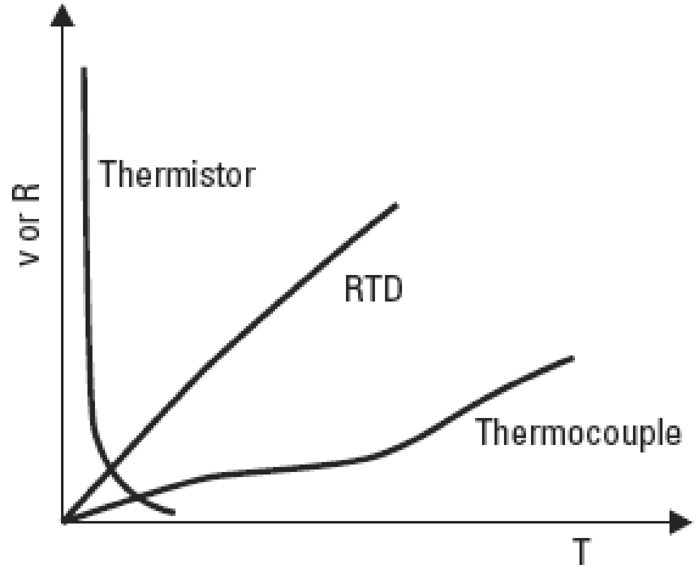
Thermistors usually are made of a semiconductor and have the following properties:

•Much larger *dR/dT* than RTD's

•Fast Response

•Inconsistent, must be calibrated indivic

•Can change over time



• Like RTD, thermistor is also a temperature-sensitive resistor.
--- thermocouple is the most versatile temperature transducer
--- RTD is most stable,
--- Thermistor is most sensitive.

--- Of three major categories of sensors, thermistor exhibits by far largest parameter change with temperature.

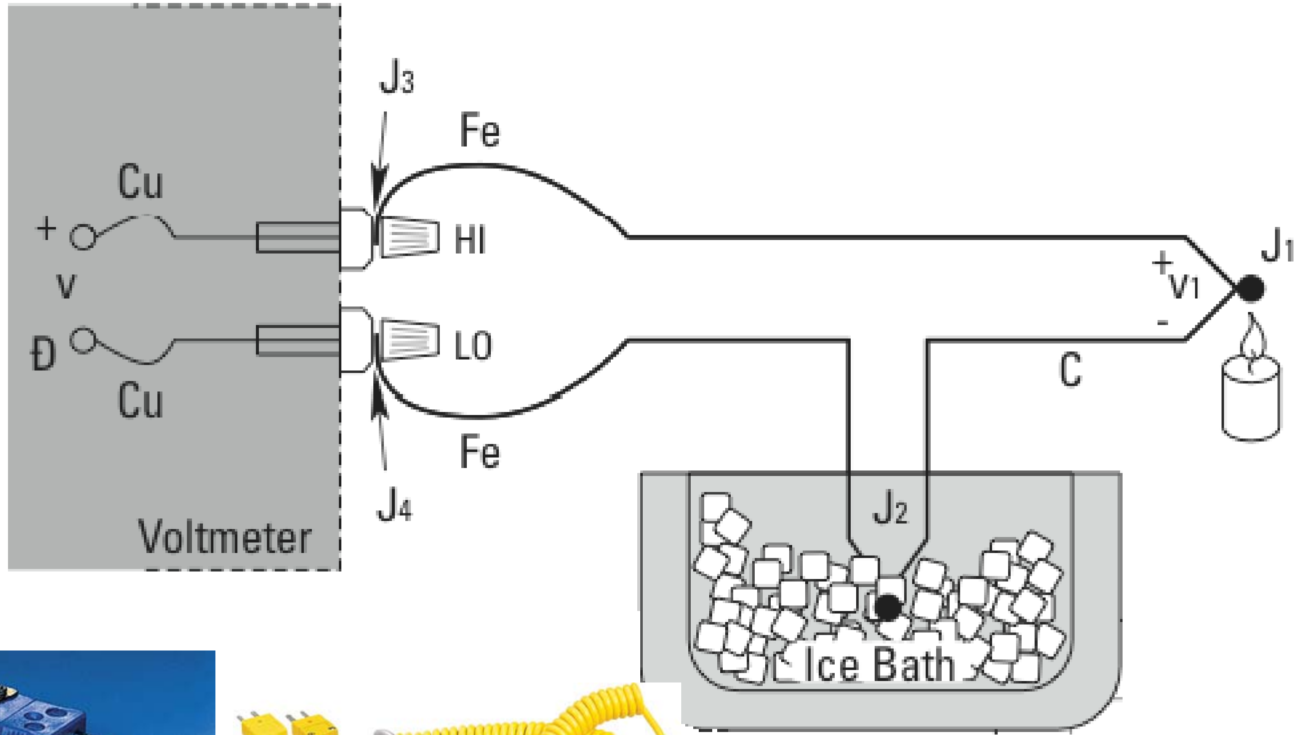
IC Sensors

The newest type of temperature sensor on the market is the integrated circuit (IC) temperature transducer. IC sensors can be designed to produce either voltage or current output and are extremely linear.

IC sensors are a very effective way to produce an analog voltage proportional to temperature.

They have a limited temperature range and are used to measure temperatures from -45° to 150° C

Thermocouples



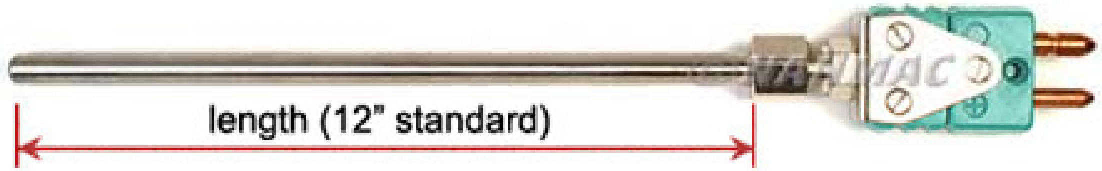
Thermocouples

The most commonly used device for temperature measurements, with the possible exception of thermometer, is the thermocouple.

Thermocouples operate on the principle that a voltage is generated by two dissimilar metals in contact with each other when a temperature variation exists through the metals.

Thermocouples are active measurement devices since there is no power input to thermocouples

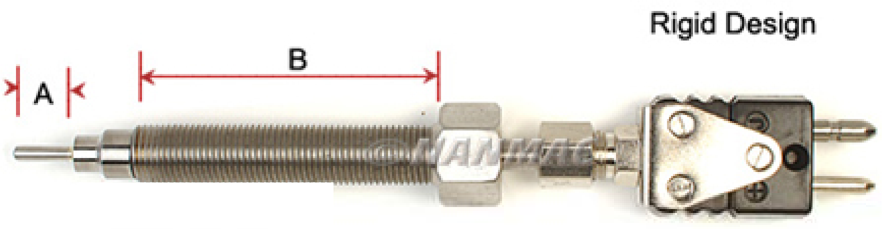
Temperature difference generates voltage

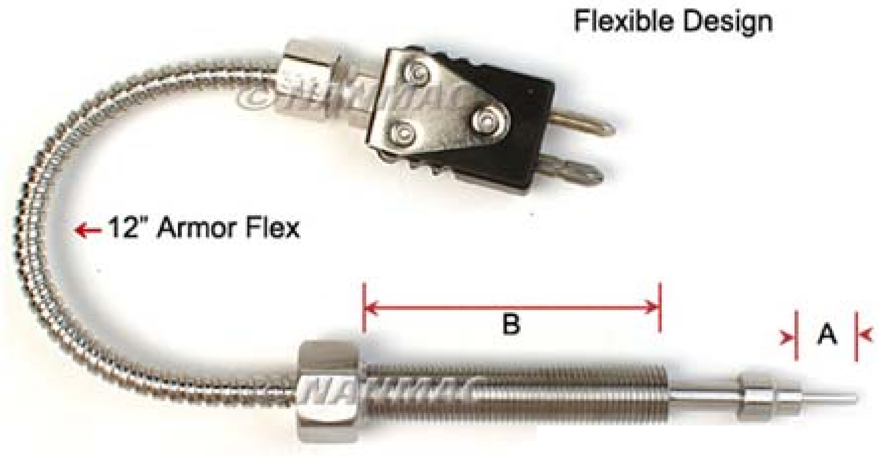


Thermocouples

The thermocouple effect (the « Seebeck » effect) was discovered in 1821, when showing that a new voltage is generated when the junctions of different metals are heated to different temperatures.

A decade later, Peltier showed that this effect was reversible: thermal effects were observed when small, externally imposed currents were directed through the junctions of different thermocouple wires.





Thermocouples

Thermocouples can be used over a wide range of temperatures, from liquid helium (-270°C) to high temperature furnaces (2200°C).

Different alloys are necessary for the extremes in temperatures.

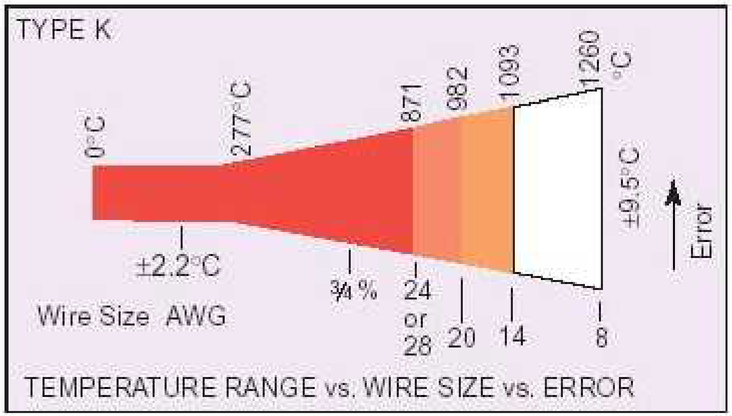
Many of the thermocouple combinations give a nearly linear output in a wide range of temperatures. The number of potential combinations is virtually infinite.

A few examples are given in the Table below:

Combination	Maximum Temperature (°C)	Seebeck coefficient Sensibility ($\mu V/^oC$)
Chromel-Alumel (type K)	1250	40
Chromel-Constantan (type E)	870	60
Iron-Constantan (type J)	750	50
Copper-Constantan (type T)	370	40
0.6 Rhodium+0.4 Iridium-Tridium	2100	5

How to Select Thermocouple?

- Junction protection: sheath or not.
- Tip size: big or small
- Thermocouple type (T, J, K, E, S, R):
  - –Temperature range (cryogenic or high temperature)
  - –Corrosion (noble metal is more inert to chemical attack)
- Termination: wire or connector
- Cost



AWG	DIA, MILS	DIA, mm
8	128	3.3
10	102	2.6
12	81	2.1
14	64	1.6
16	51	1.3
18	40	1
20	32	0.8
22	25	0.6
24	20	0.5
26	16	0.4
28	13	0.3

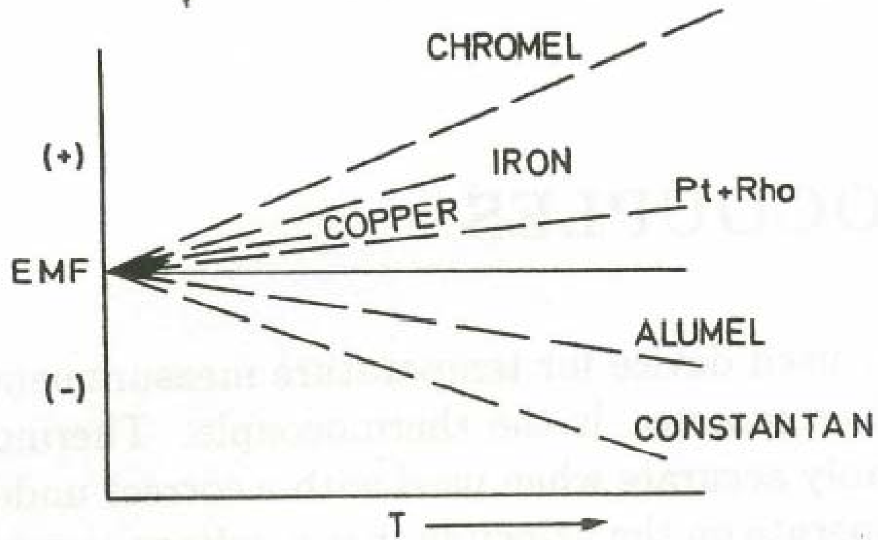
Operation Principles of Thermocouples

Metals used for thermocouples can be classified in terms of thermoelectricpolarity.

A « positive » material is one on which the EMF increases with temperature along its length. Materials which are more greatly « positive » than others have a higher EMF versus temperature slope.

As an example, an iron-palladium thermocouple, the cold end of the iron will be positive with respect to the cold end of the palladium.

Figure shows the variation of EMF with temperature for several common materials. All of the slopes for materials in the figure are given relative to pure platinum.

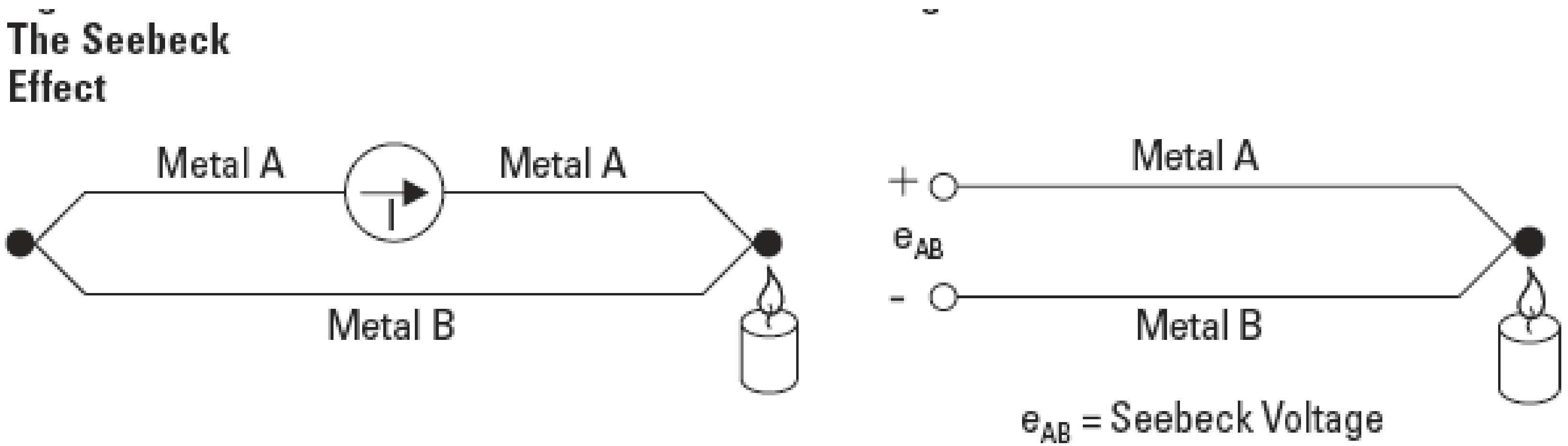


Electromotive Force

The **emf** represents energy per unit charge (**voltage**)

Thermocouples: Physical Measurement Principals

• If this circuit is broken at the center, net open circuit voltage (Seebeck voltage) is a function of the junction temperature and this varies with the composition of the two metals.

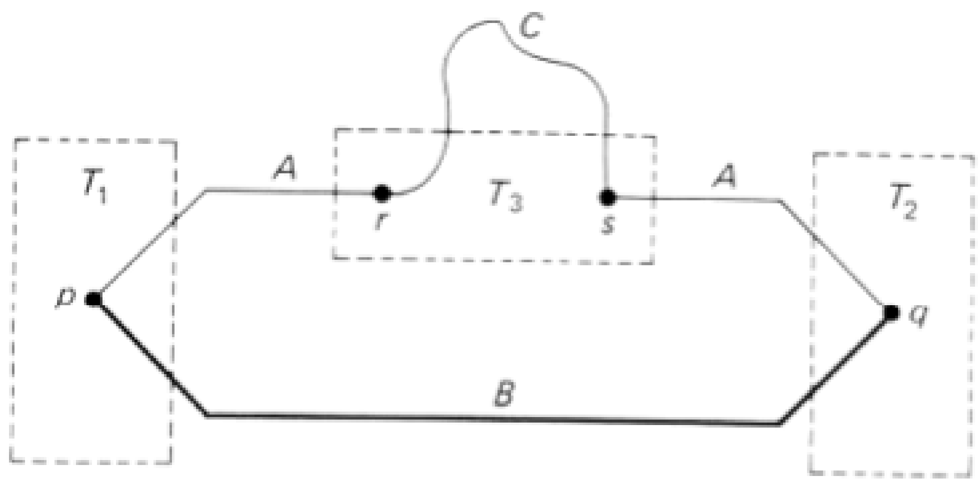


• All dissimilar metals exhibit this “Seebeck effect”.

For small changes in temperature the Seebeck voltage is linearly proportional to temperature: $e_{AB} = \alpha T$ *(°K)*

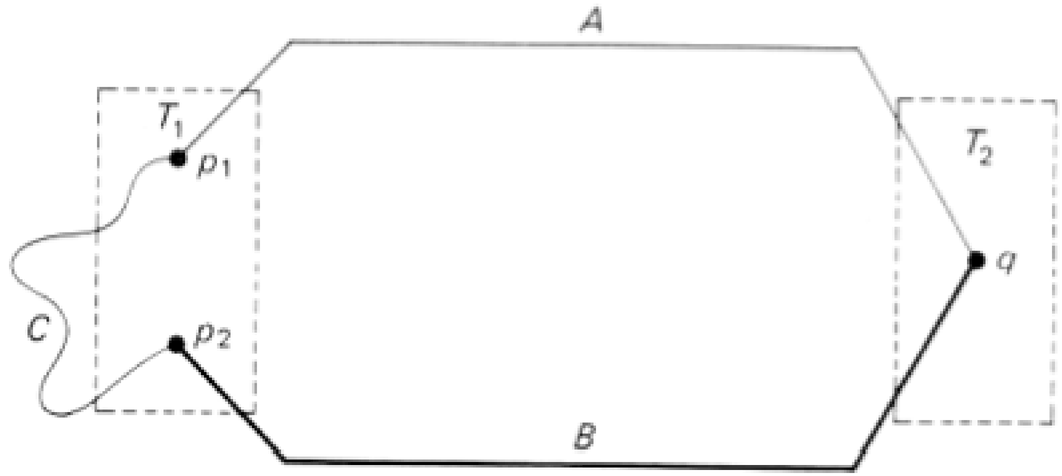
Thermocouples: Physical Measurement Principals

Law of Intermediate Materials: If you break your thermocouple and add something of another material, it will have no effect as long as both ends of the new material are at the same temperature.



Thermocouples: Physical Measurement Principals

Law of Intermediate Temperatures: If you get emf_1 when the two temperatures are T_1 and T_2, and you get emf_2 when you have T_2 and T_3, you will get $emf_1 + emf_2$ when the temperatures are T_1 and T_3.



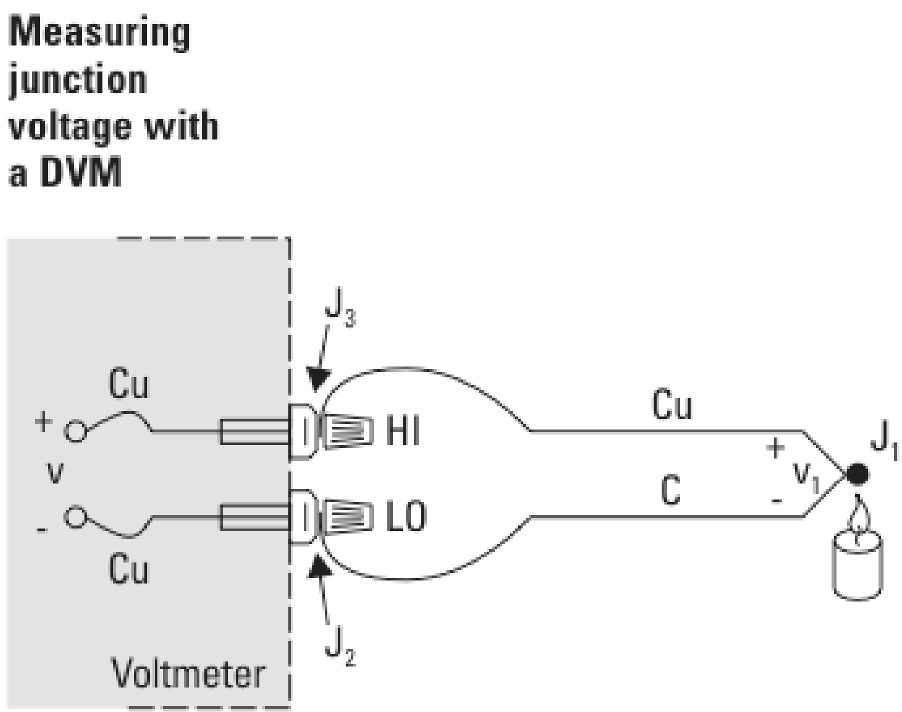
Sensing The Thermocouple Voltage

- The reason we call the induced potential *emf (electro-motive force)* rather than *voltage* is that output only exists for an open circuit.

- We can't measure the Seebeck voltage directly because one must first connect a *voltmeter* to the thermocouple, and the voltmeter leads, themselves, create a new thermoelectric circuit.

Sensing The Thermocouple Voltage

• As an example … connect a voltmeter to the ends of a *copper-constantan* (*Type T* … a type of *Thermocouple*)



• Want voltmeter to read only V_1

• By connecting voltmeter, we have created two more metallic junctions: J_2 and J_3.

• Since J_3 is a copper-to-copper junction, it creates no thermal *emf*. *(V_3= 0)*

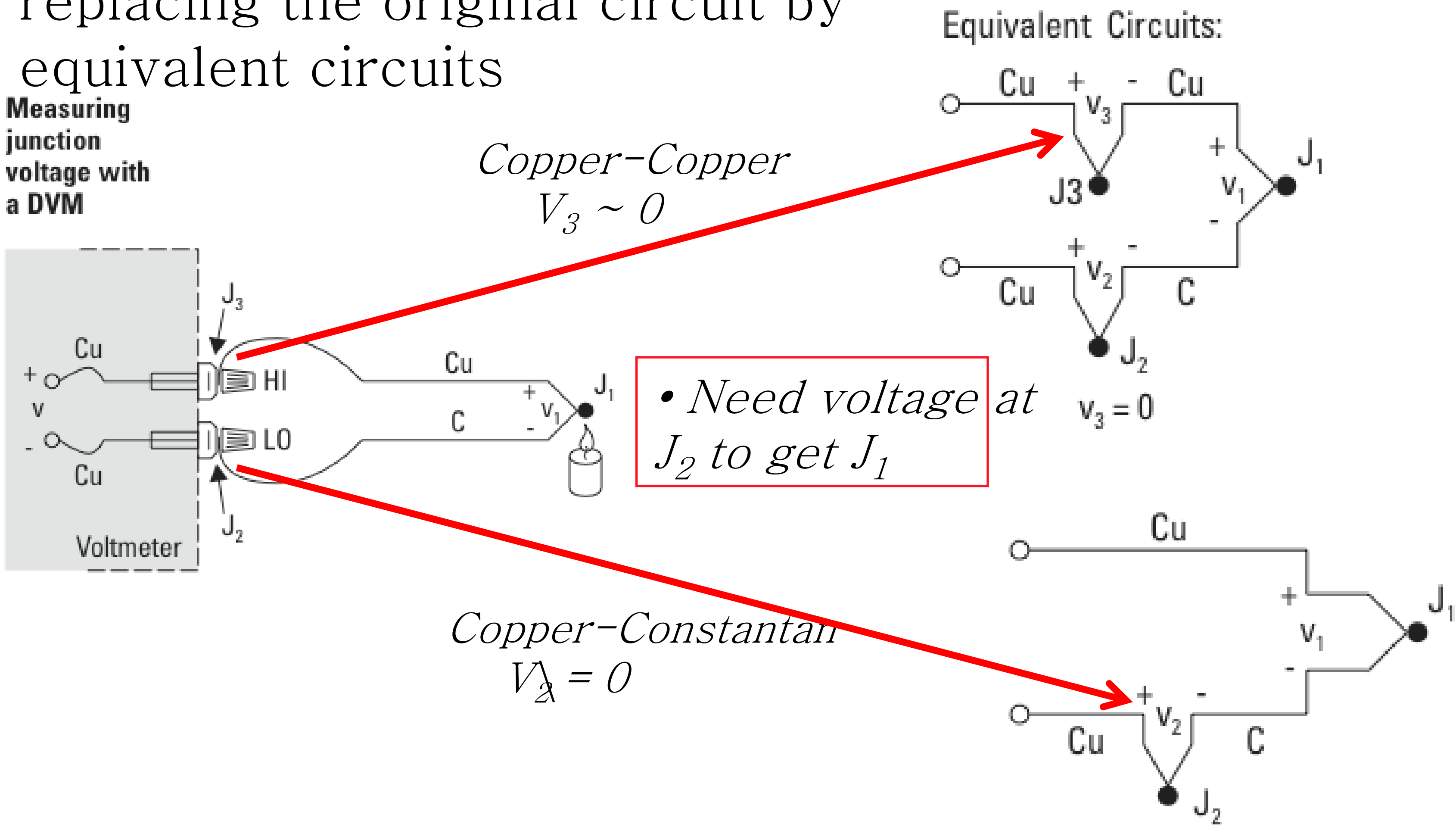
• But J_2 is a copper-to constantan junction that will add an *emf*. *(V_2)* opposing to V_1.

• The resulting voltmeter reading V is proportional to the temperature difference between J_1 and J_2.

• We can't find temperature at J_1 without first finding temperature of J_2.

Sensing The Thermocouple Voltage

- We can draw this concept by replacing the original circuit by equivalent circuits



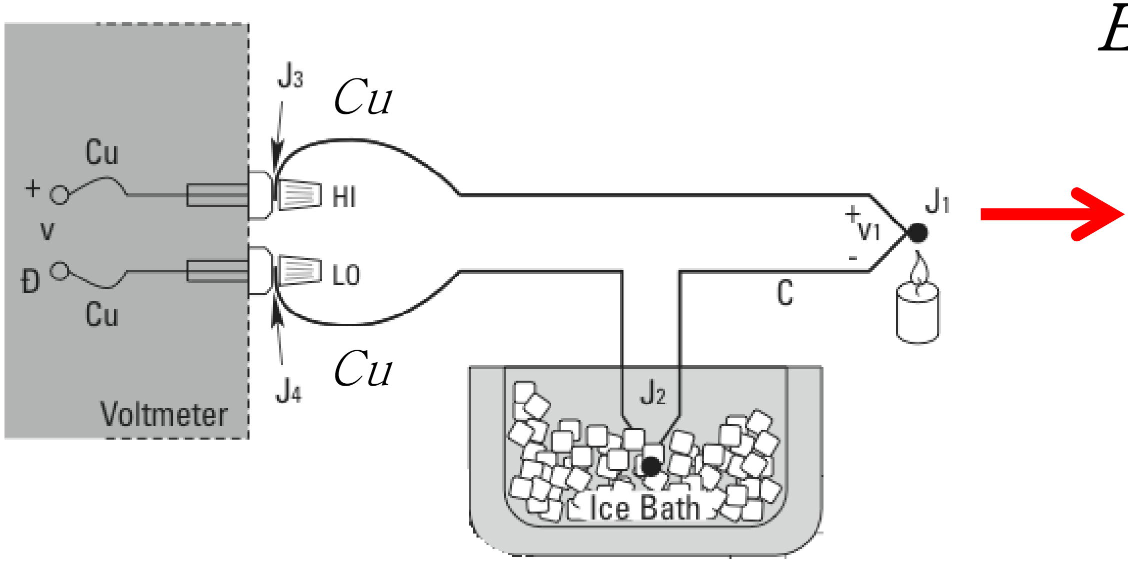
Copper–Copper
$V_3 \sim 0$

- *Need voltage at J_2 to get J_1*

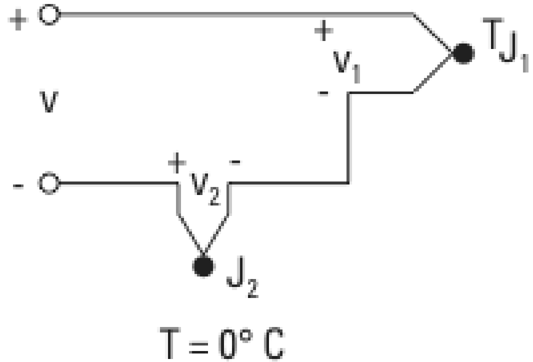
Copper–Constantan
$V_2 = 0$

Sensing The Thermocouple Voltage

• One way to determine the temperature J_2 is to physically put the junction into an ice bath, forcing its temperature to be 0° C and establishing J_2 as a Reference Junction with a known temperature.



Equivalent circuit



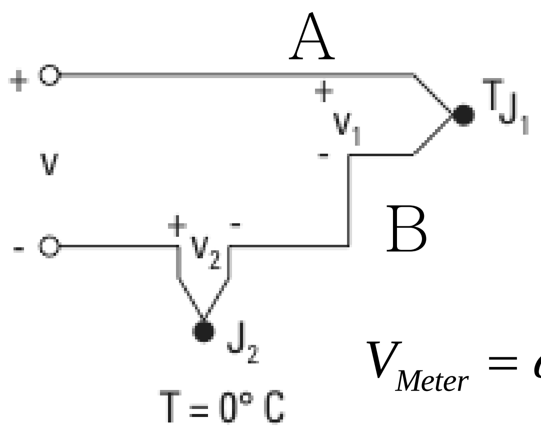
• Wire from J_2 *to* J_3 is copper, no thermal *emf at* J_4

Sensing The Thermocouple Voltage

- Since both voltmeter terminal junctions are now copper-copper, they create no thermal *emf* and the reading *V* on the voltmeter is proportional to the temperature difference between J_1 and J_2.

Equivalent circuit

$$e_{AB} = \alpha T \rightarrow V_{Meter} = V_1 - V_2 \cong \alpha\left(T_{J_1} - T_{J_2}\right)$$



- But the temperature at J_2 is 0^{o} C (273.15 ^{o}K)

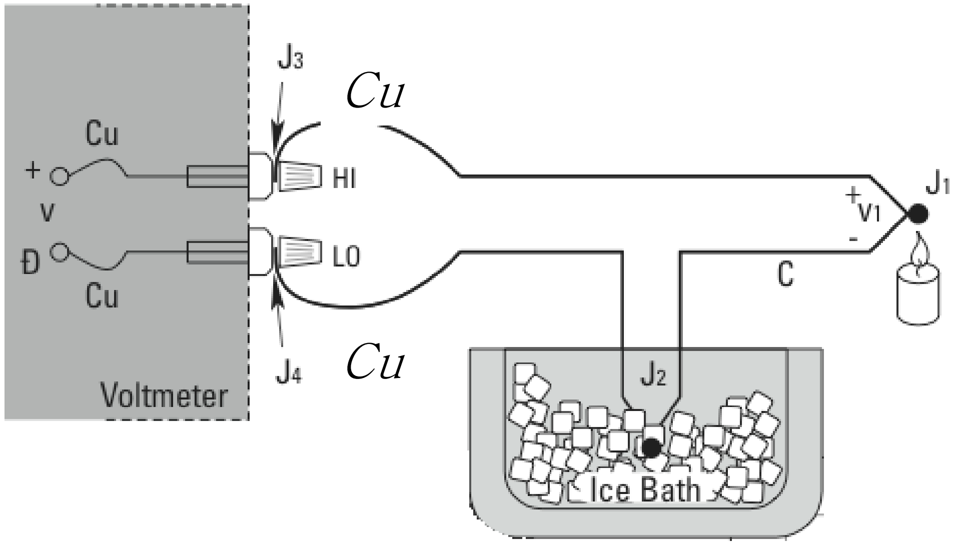
$$V_{Meter} = \alpha\left(T_{J_1} - T_{J_2}\right) = \alpha\left(\left[T_{J_1\,(^oC)} + 273.15^{o}K\right] - 273.15^{o}K\right)$$

$$\rightarrow \boxed{V_{Meter} = \alpha \cdot T_{J_1\,(^oC)}}$$

- *Meter reading is proportional to temperature at J_1 in deg. C.*

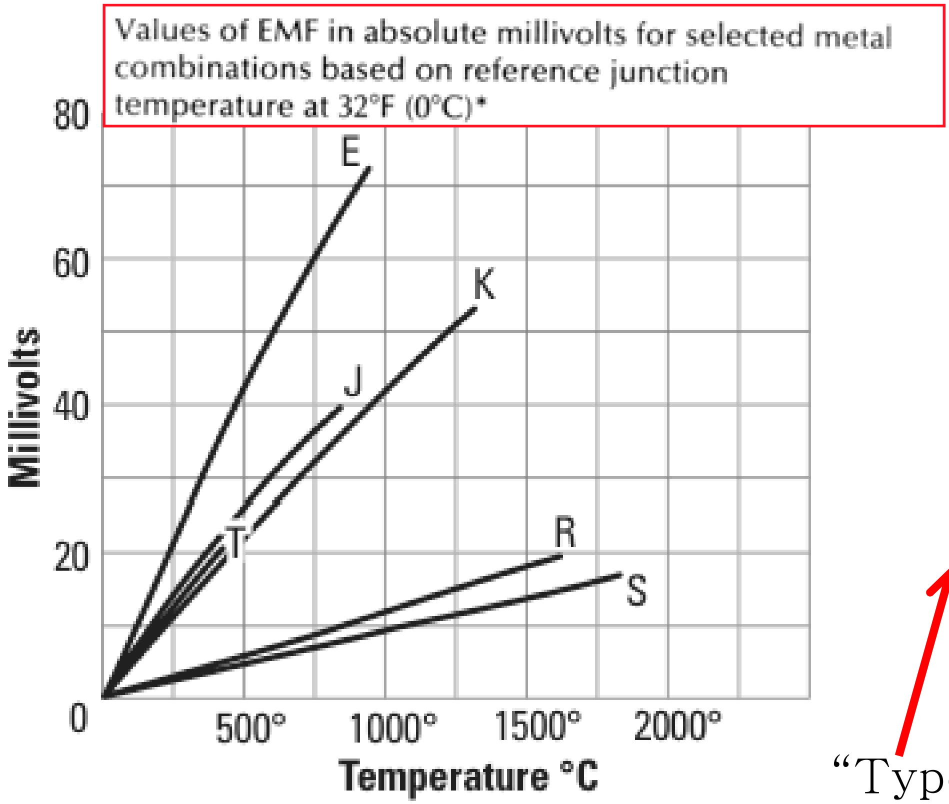
Sensing The Thermocouple Voltage

- In other words … Thermocouples can't measure a single temperature, but can only tell us the difference in temperature between two points.
- If we can put one of those points at a known temperature, we then have to look at the type of thermocouple…



Sensing The Thermocouple Voltage

- Ice Point method is very accurate because the temperature can be precisely controlled.
- If the Thermocouple is linear than we can calculate the temperature at J_1 DIRECTLY.
- *Otherwise .* Ice point is used by National Institute of Standards and Technology (NIST) as fundamental reference point for thermocouple tables, We can now look at NIST tables and directly convert from sensed voltage Temperature at J_1.



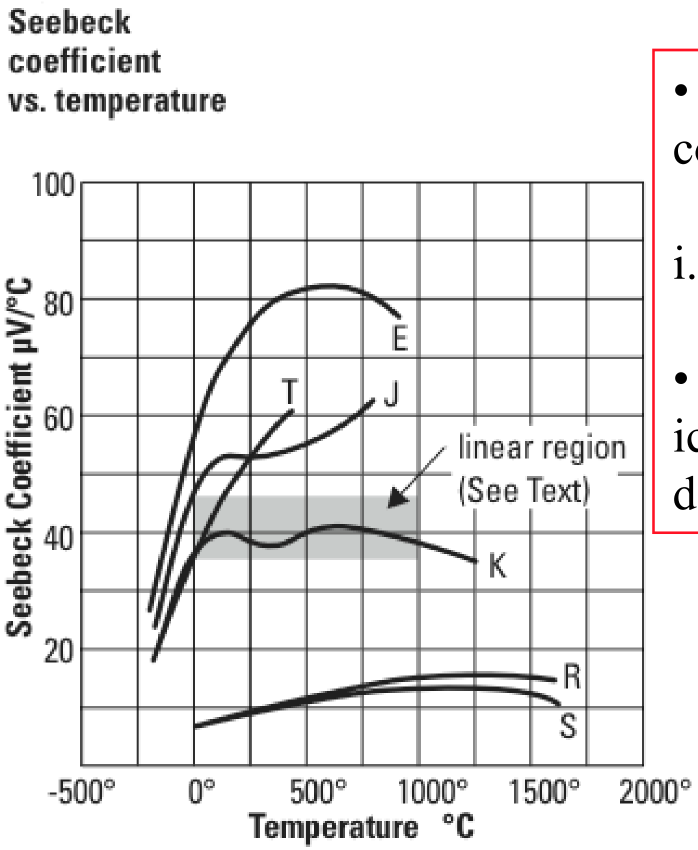
Type	Metals		
	+		-
E	Chromel	vs.	Constantan
J	Iron	vs.	Constantan
K	Chromel	vs.	Alumel
R	Platinum	vs.	Platinum 13% Rhodium
S	Platinum	vs.	Platinum 10% Rhodium
T	Copper	vs.	Constantan

“Type” Designation

Sensing The Thermocouple Voltage

• Unfortunately … THE OUTPUT OF THERMOCOUPLES IS NOT LINEAR

• The slope of the output curve (Seebeck coefficient) plotted on the previous page is plotted here … A horizontal line indicates a constant α, in other words, a linear device … Obviously these devices are NOT linear



• Notice that slope of the K thermocouple approaches constant over a temperature range from 0° C to 1000° C.

i.e. temperature display involves only a scale factor.

• Consequently, type K can be used with an external ice point reference to obtain a moderately accurate direct readout of temperature.

Sensing The Thermocouple Voltage

Type	Wire: Positive	Wire: Negative	Expected Bias Error[b]
S	Platinum	Platinum/ 10% rhodium	±1.5°C or 0.25%
R	Platinum	Platinum/ 13% rhodium	±1.5°C
B	Platinum/ 30% rhodium	Platinum/ 6% rhodium	±0.5%
T	Copper	Constantan	±1.0°C or 0.75%
J	Iron	Constantan	±2.2°C or 0.75%
K	Chromel	Alumel	±2.2°C or 0.75%
E	Chromel	Constantan	±1.7°C or 0.5%

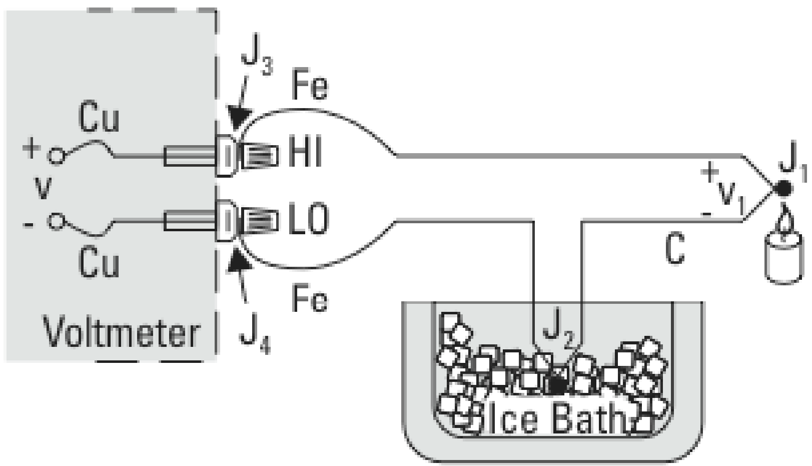
What we just analyzed

Thermocouple With Dissimilar Meter Leads

• The copper-constantan thermocouple considered earlier is a unique example because copper wire is same metal as **voltmeter terminals**.

• Look at an iron-constantan (Type J) thermocouple instead of Copper-constantan.

• Iron wire increases the number of dissimilar metal junctions in circuit, as both voltmeter terminals become Cu-Fe thermocouple junctions.



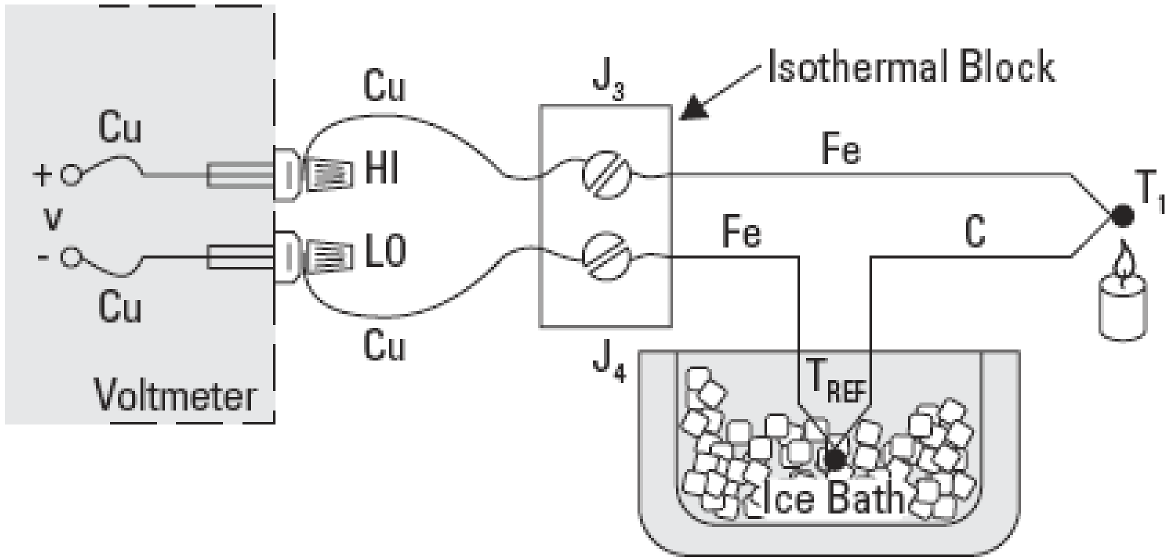
• Circuit provides accurate measurements as long as voltmeter terminals(J_3 & J_4) act at same temperature

Thermocouple With Dissimilar Meter Leads

• If both front panel terminals are not at same temperature, Voltage error will result.

• For more precise measurement, copper voltmeter leads are extended so copper-to-iron junctions are made on a *temperature regulated* (isothermal) terminal block

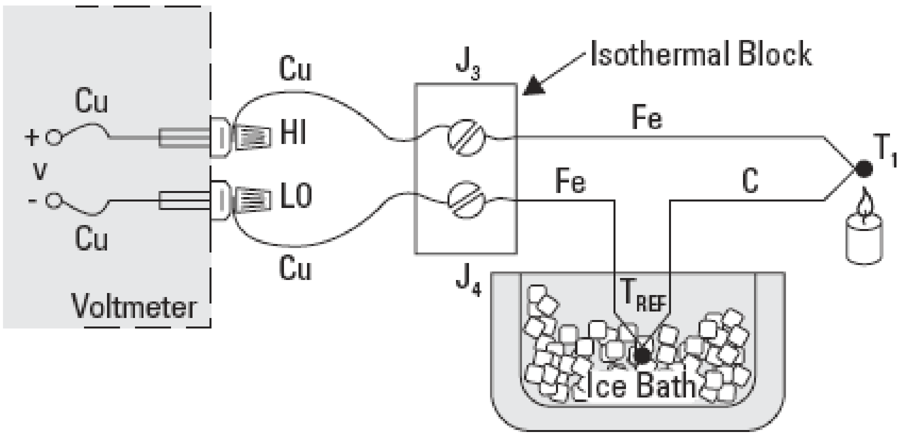
Removing junctions from DVM terminals



Thermocouple With Dissimilar Meter Leads

• Isothermal block is an electrical insulator but a good heat conductor
and serves to keep J_3 and J_4 at same temperature.

• Block temperature is not important because both Cu-Fe junctions are at the same temperature. Thus ….



$$V_{Meter} = \alpha\left[T_{J_1} - T_{Ref}\right]$$

$$ice\ bath \rightarrow V_{Meter} = \alpha\left[T_{J_1\,(^oC)}\right]$$

For linear Thermocouple region

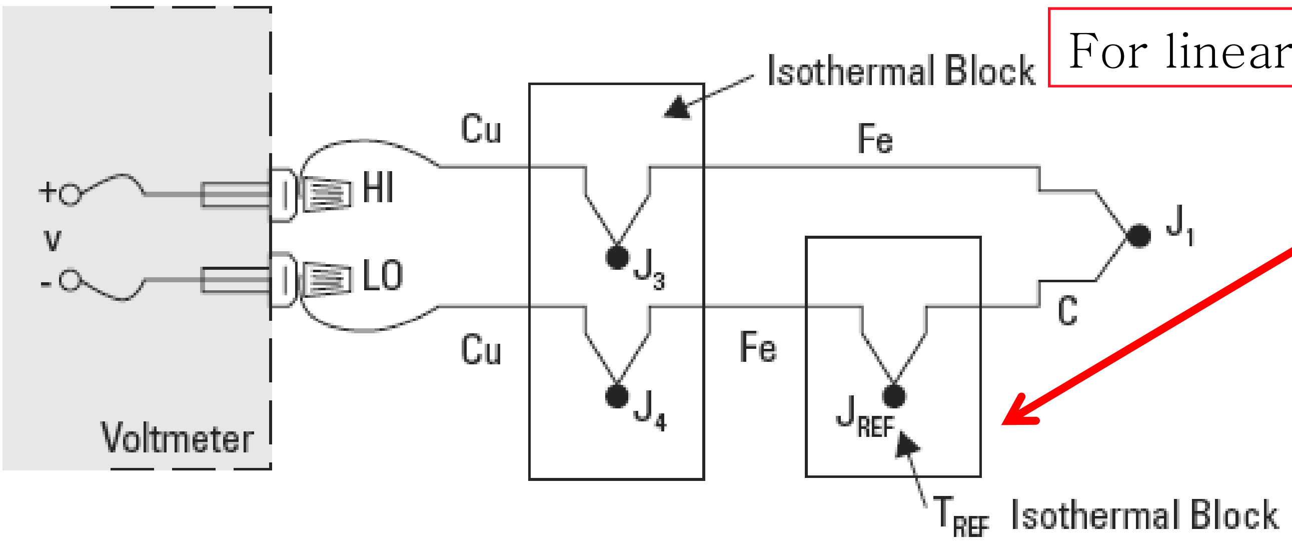
Thermocouple With Dissimilar Meter Leads

• Obviously an Ice bath is impractical for most thermocouple applications

• Replace the *ice bath* with another *isothermal block* ···

$$V_{Meter} = \alpha\left[T_{J_1} - T_{Ref}\right]$$

For linear TC region

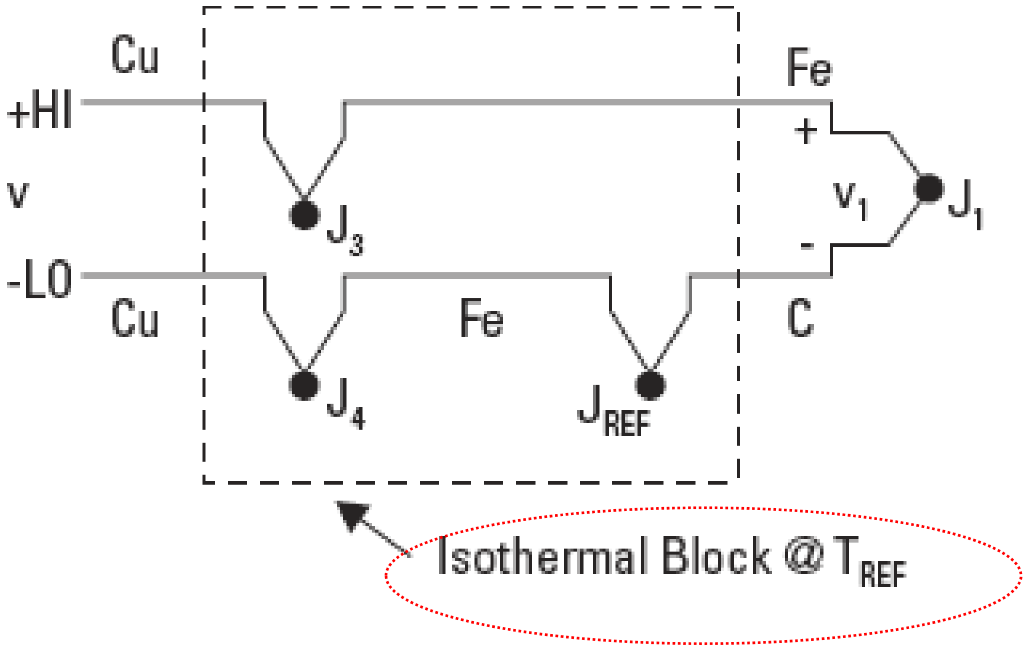


Thermocouple With Dissimilar Meter Leads

• A more convenient arrangement with less connections that Achieves the same result is ….

$$V_{Meter} = \alpha\left[T_{J_1} - T_{Ref}\right]$$

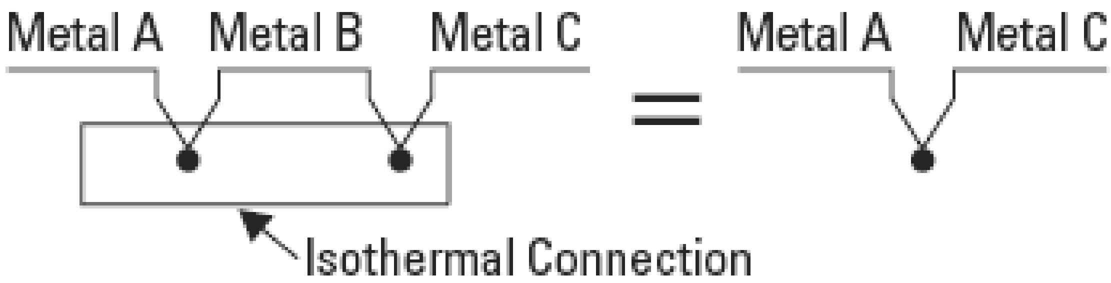
For linear TC region



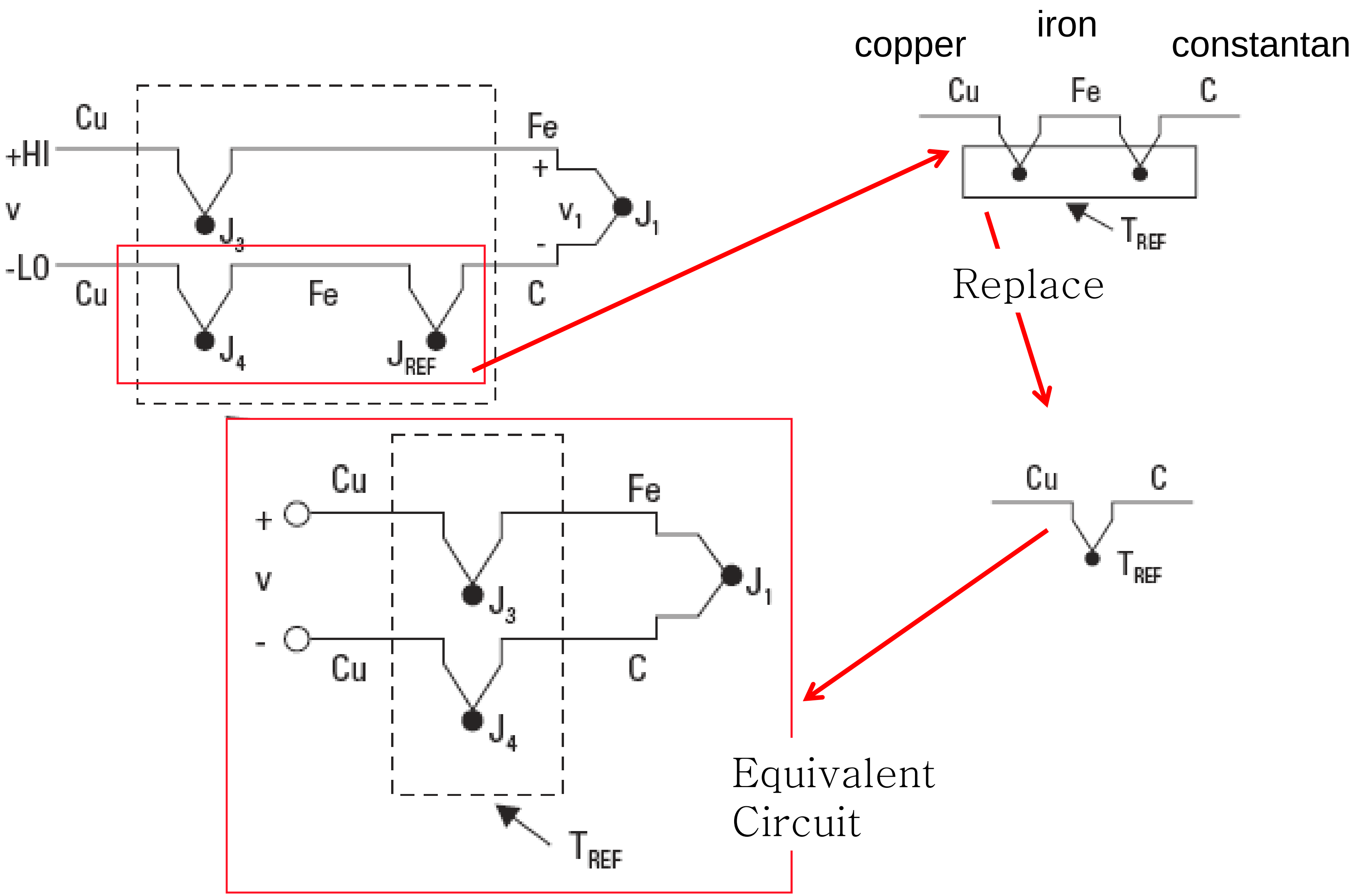
Thermocouple With Dissimilar Meter Leads

- Now use law of intermediate materials to eliminate extra junction.

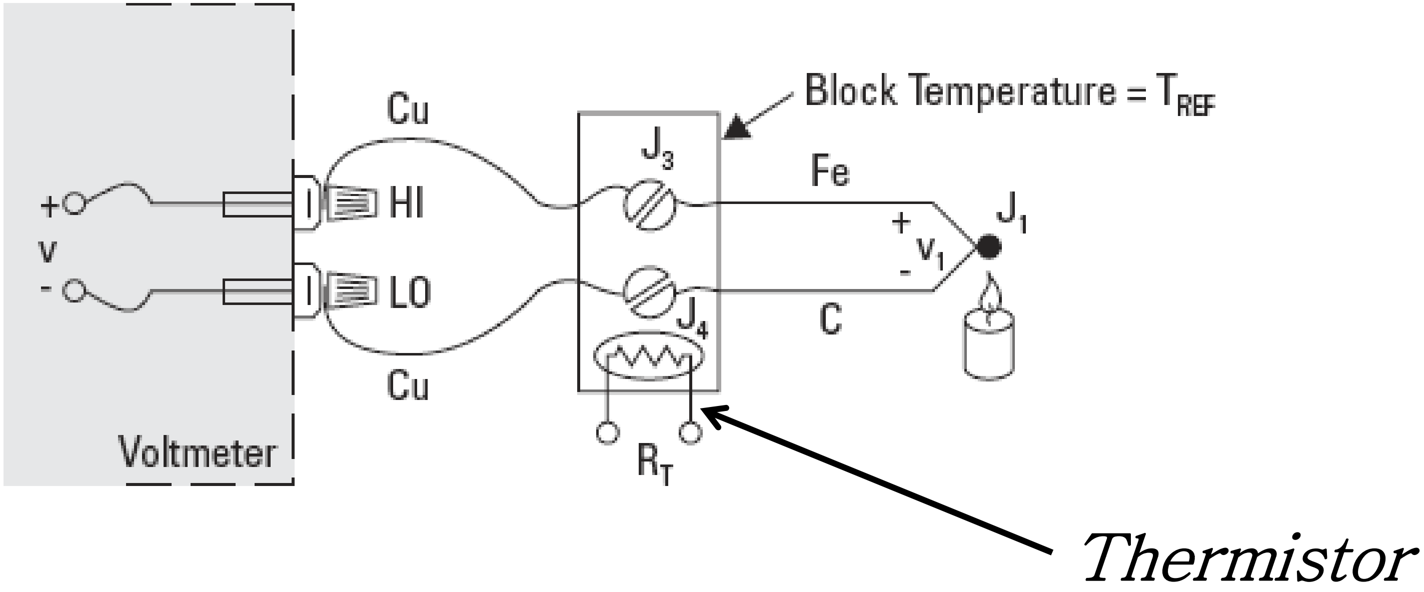
> Law of Intermediate Materials: If you break your thermocouple and add something of another material, it will have no effect as long as both ends of the new material are at the same temperature.



Thermocouple With Dissimilar Meter Leads

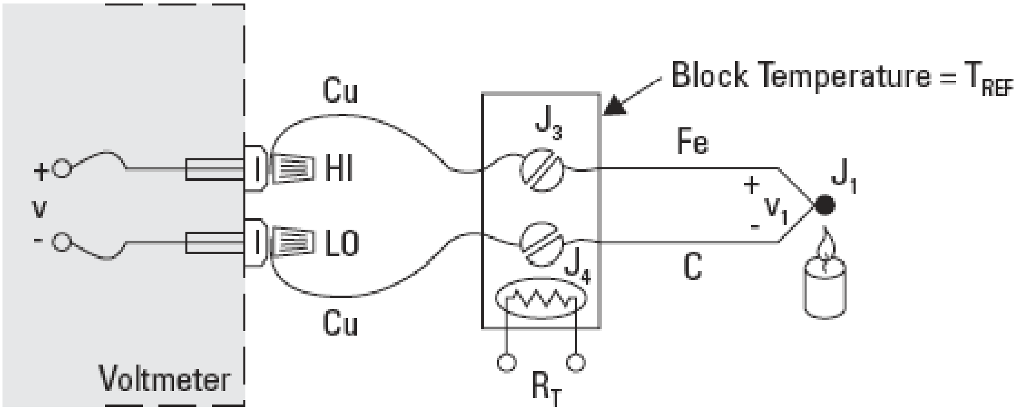


Thermocouple With Dissimilar Meter Leads



• Next Step is to directly measure the temperature of isothermal block *(reference junction)* and use that reading to compute the unknown temperature, T_{J_1}

Thermocouple With Dissimilar Meter Leads



• Thermistor resistance function of temperature provides way to measure absolute temperature of reference junction.

1. Measure R_T (Thermistor resistance) to sense T_{REF} and convert T_{REF} to its equivalent reference junction voltage, V_{REF}

2. Measure V and add V_{REF} to find V_1
and convert V_1 to temperature T_{J1} …. Using table lookup data.

Thermocouple With Dissimilar Meter Leads

- Stored as polynomial fit coefficients ..

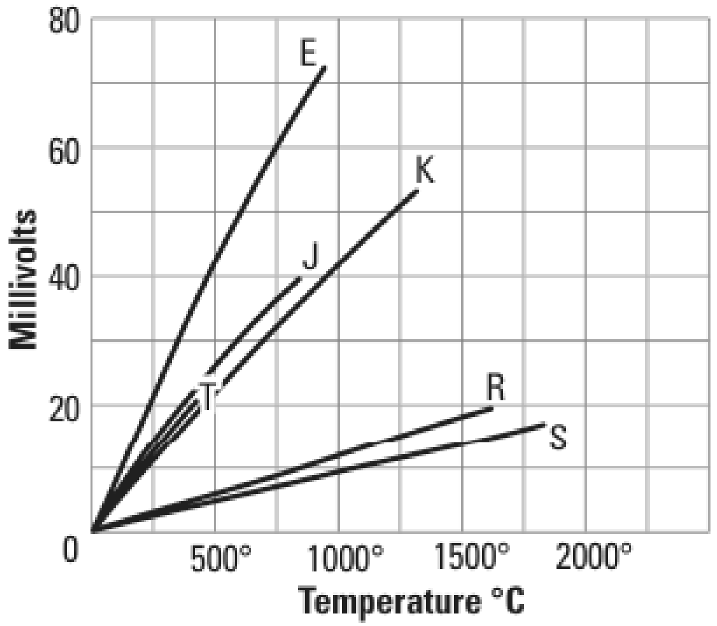
$$V(T) = \sum_{0}^{n} a_n T^n$$

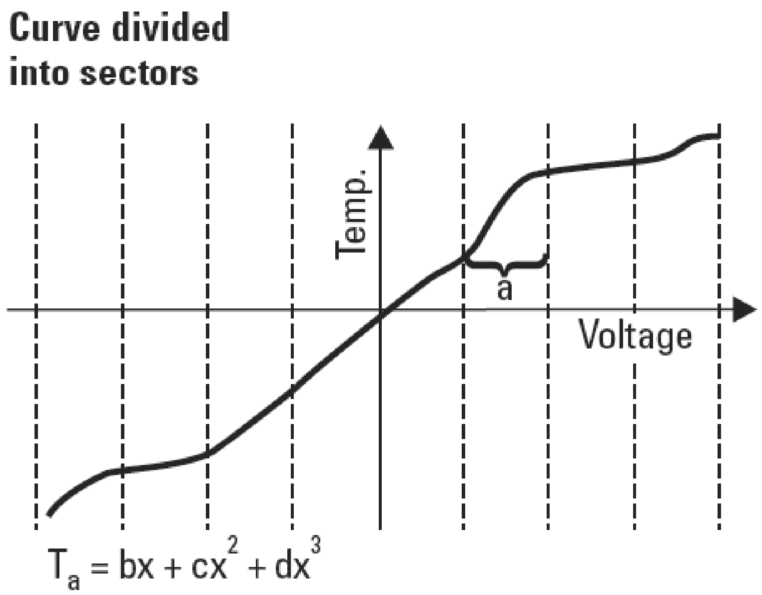
Given reference junction Temperature, compute Equivalent EMF

$$T(V) = \sum_{0}^{n} b_n V^n$$

Given Sensed Voltage Compute Temperature

- Curves divided into sectors and then curve fit with very high order polynomial





NIST Type-J Thermocouple Calibration Data

****

- This section contains coefficients for type J thermocouples for the two subranges of temperature listed below. The coefficients are in units of *deg. C* and *mV* and are listed in the order of constant term up to the highest order.

Temperature Range (deg. C)

-210.000 to 760.000

760.000 to 1200.000

****

type: J

temperature units: deg. C *emf units: mV*

$$V(T) = \sum_{0}^{n} a_n T^n$$

Temperature to Voltage

Temperature range: **-210.000**, **760.000**, fit order: 8

0.000000000000E+00
0.503811878150E-01
0.304758369300E-04
-0.856810657200E-07
0.132281952950E-09
-0.170529583370E-12
0.209480906970E-15
-0.125383953360E-18
0.156317256970E-22

Temperature range: **760.000**, **1200.000**, fit order: 5

0.296456256810E+03
-0.149761277860E+01
0.317871039240E-02
-0.318476867010E-05
0.157208190040E-08
-0.306913690560E-12

NIST Type-J Thermocouple Calibration Data

****

• Section contains coefficients of approximate inverse functions for type J thermocouples for the subranges of temperature and voltage listed below.
The range of errors of the approximate inverse function for each subrange is also given.
The coefficients are in units of *deg. C and mV* and are listed in the order of constant term up to the highest order.

Temperature range (deg. C)	Voltage range (mV)	Error range (deg. C)
-210. to 0.	-8.095 to 0.000	-0.05 to 0.03
0. to 760.	0.000 to 42.919	-0.04 to 0.04
760. to 1200	42.919 to 69.553	-0.04 to 0.03

Voltage to Temperature

$$T(V) = \sum_{0}^{n} b_n V^n$$

Temp	***-210-0.0***	***0.0-760***	***760-1200***
mVolts	***-8.095-0.0***	***0.00-42.919***	***42.919-69.553***
	0.0000000E+00	0.000000E+00	-3.11358187E+03
	1.9528268E+01	1.978425E+01	3.00543684E+02
	-1.2286185E+00	-2.001204E-01	-9.94773230E+00
	-1.0752178E+00	1.036969E-02	1.70276630E-01
	-5.9086933E-01	-2.549687E-04	-1.43033468E-03
	-1.7256713E-01	3.585153E-06	4.73886084E-06
	-2.8131513E-02	-5.344285E-08	0.00000000E+00
	-2.3963370E-03	5.099890E-10	0.00000000E+00
	-8.3823321E-05	0.000000E+00	0.00000000E+00
Error Range:	-0.05 0.03	-0.04 0.04	-0.04 0.03

Fit Order: 8

Example

Say we hook a *J* type thermocouple to a volt meter and read *0.507 mV*. An independent temperature measurement at the connection to the volt meter tells us that the temperature there is *20°C*. What is the temperature at the thermocouple junction?

1) …. First use $V(T) = \sum_{n}^{n} a_n T^n$ for reference junction

Temperature range: -210.000, 760.000, fit order: 8
0.000000000000E+00
0.503811878150E-01
0.304758369300E-04
-0.856810657200E-07
0.132281952950E-09
-0.170529583370E-12
0.209480906970E-15
-0.125383953360E-18
0.156317256970E-22

At **20°C**, the voltage from the table curve fit is 1.01915 mV

So our voltage relative to 0°C is the measured voltage plus the 20° value:
$V_1 = V + V_{ref} = 0.507 + 1.01915 = 1.52615$ mV

Example

So our voltage relative to 0°C is the measured voltage plus the 20° value:
$V_1 = V + V_{ref} = 0.507 + 1.01915 = 1.52615$ mV

Temp	***-210-0.0***	***0.0-760***	***760-1200***
mVolts	***-8.095-0.0***	***0.00-42.919***	***42.919-69.553***
	0.0000000E+00	0.000000E+00	-3.11358187E+03
	1.9528268E+01	1.978425E+01	3.00543684E+02
	-1.2286185E+00	-2.001204E-01	-9.94773230E+00
	-1.0752178E+00	1.036969E-02	1.70276630E-01
	-5.9086933E-01	-2.549687E-04	-1.43033468E-03
	-1.7256713E-01	3.585153E-06	4.73886084E-06
	-2.8131513E-02	-5.344285E-08	0.00000000E+00
	-2.3963370E-03	5.099890E-10	0.00000000E+00
	-8.3823321E-05	0.000000E+00	0.00000000E+00
Error	-0.05	-0.04	-0.04
Range:	0.03	0.04	0.03

2) Convert V_1 to temperature T_{J1} using look up tables

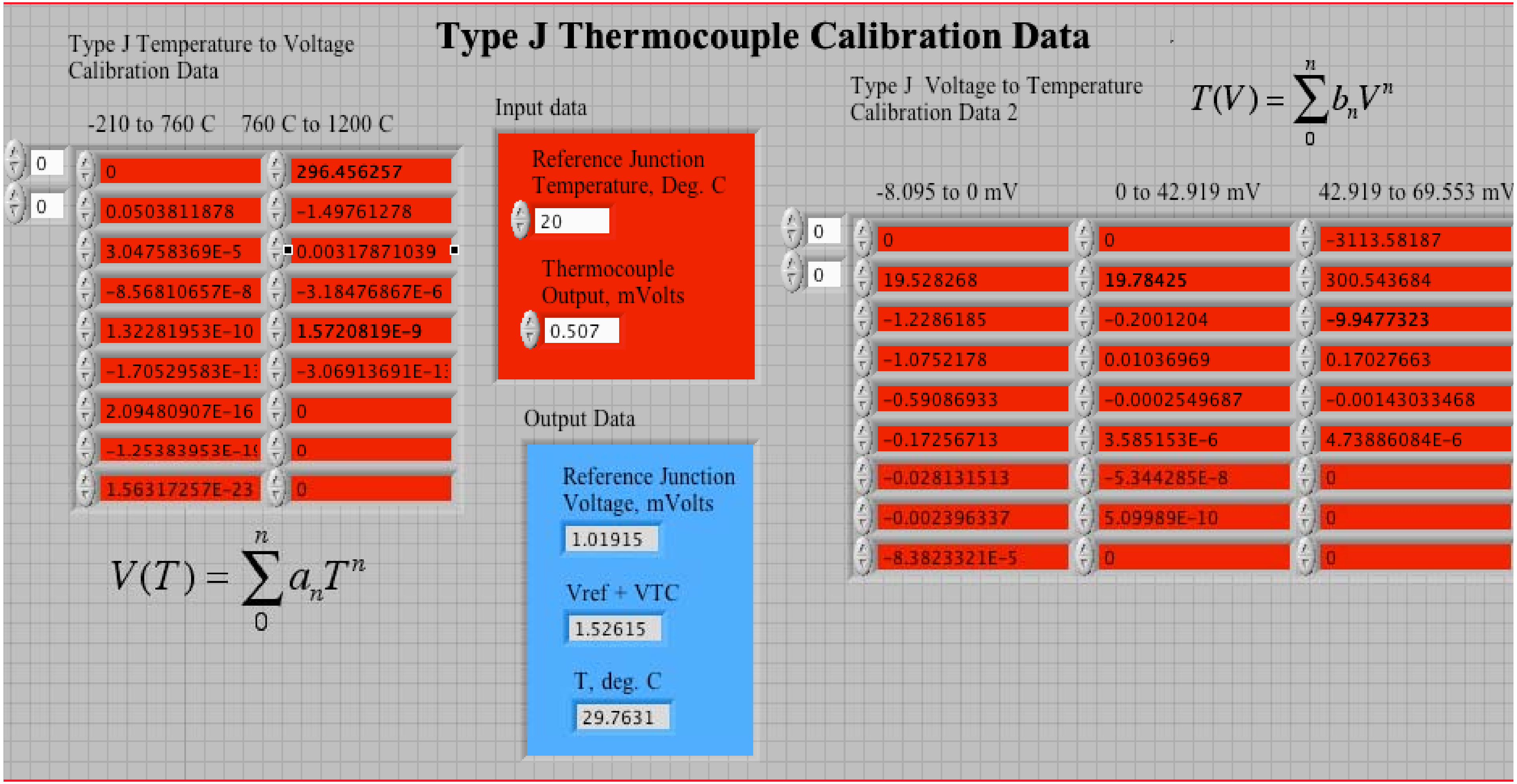
$$T(V) = \sum_{0}^{n} b_n V^n$$

This corresponds to:

$$\boxed{T_{J1} = 29.7631°C}$$

Example

An example program written in Labview:



NIST Calibration Data

http://www.temperatures.com/tctables.html

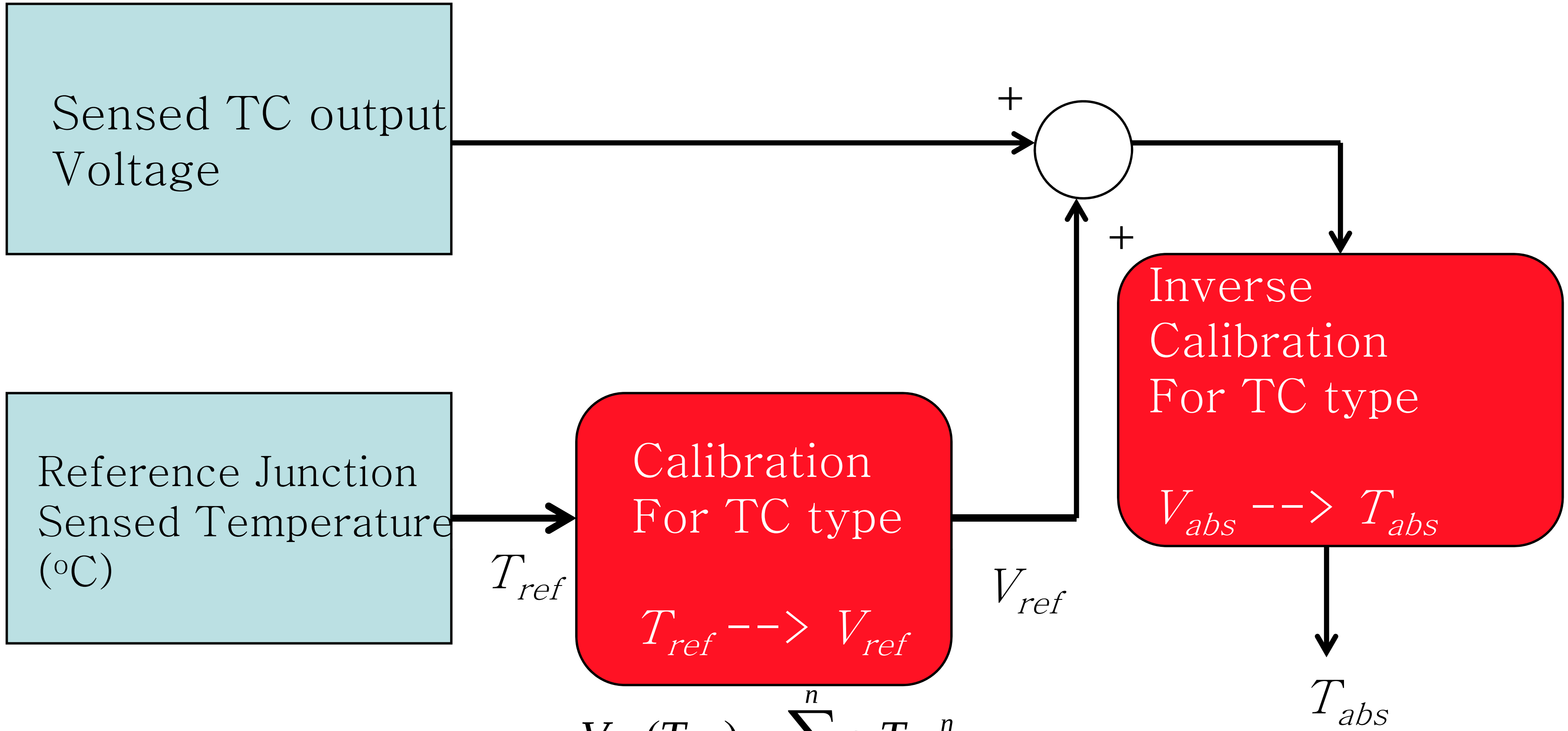
Direct download links from the NIST data base files(Degrees Celcius, only) (Note that these files have the extension *.tab, but are in ASCII format and can be renamed easily to *.txt or *.asc):

All Thermocouple Types in ASCII or text format (NIST WEB file) (131K)
Type B Thermocouple(19K)
Type E Thermocouple(14K)
Type J Thermocouple(16K)
Type K Thermocouple(18K)
Type N Thermocouple(17K)
Type R Thermocouple(20K)
Type S Thermocouple(20K)
Type T Thermocouple(9K)

Generalized Procedure

1) Measure the thermocouple voltage V_{TC}
2) Measure the temperature at the location where the TC is connected to the meter (the reference temperature, T_{ref})
3) Using a table or a polynomial, find the voltage generated by the junction at the meter at T_{ref}, call it V_{ref}.
4) Add the two voltages $V_{abs} = E_{TC} + V_{ref}$.
5) Find the temperature that corresponds to V_{abs} from tables or a polynomial.
6) Be sure to use the table data that corresponds to your TC type

Generalized Procedure



$$V_{ref}(T_{ref}) = \sum_{0}^{n} a_n T_{ref}{}^{n}$$

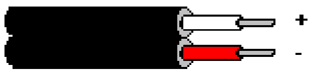
$$T_{abs}(V_{abs}) = \sum_{0}^{n} b_n V_{abs}{}^{n}$$

Thermocouple Color Codes:

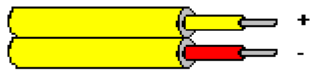
Thermocouple wiring is color coded by thermocouple types. Different countries utilize different color coding. Jacket coloring is sometimes a colored stripe instead of a solid color as shown.

United States ASTM:

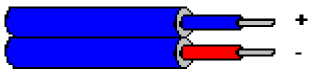
J



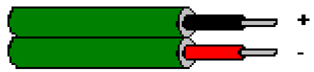
K



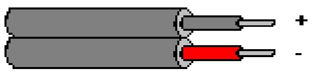
T



R/S

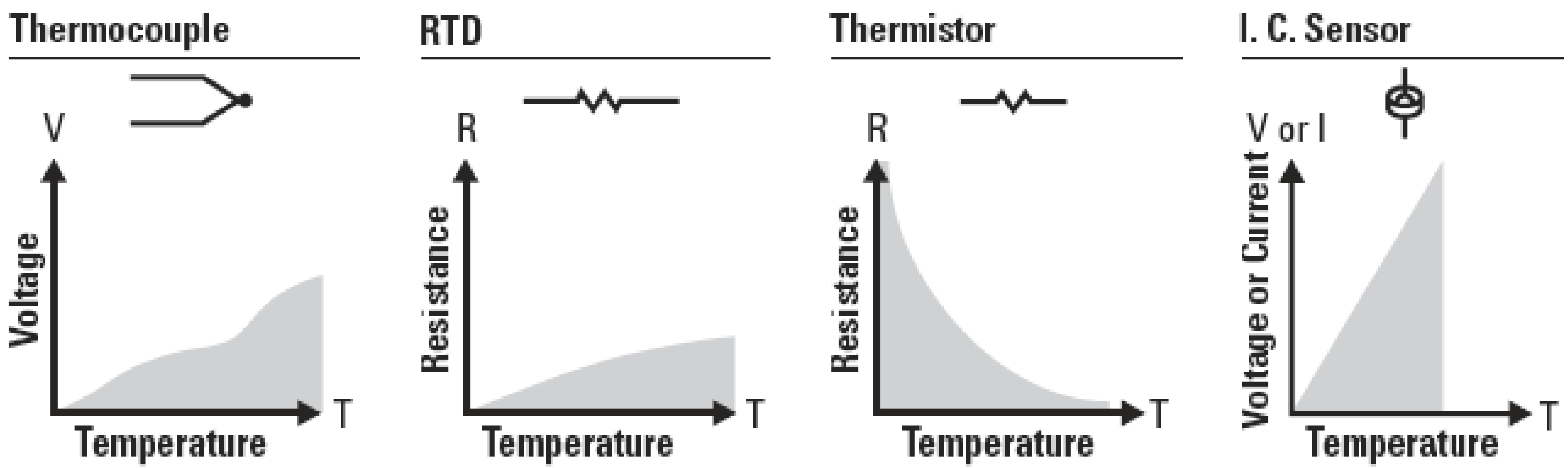


B

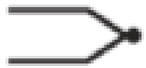


Temperature Sensors

• Converts Kinetic Energy of molecular motion into electrically Sensible output .. Either current or voltage … best for accuracy For Scientific or engineering measurements



Temperature Sensors

	Thermocouple	RTD	Thermistor	I. C. Sensor
				
Advantages	• Self-powered • Simple • Rugged • Inexpensive • Wide variety of physical forms • Wide temperature range	• Most stable • Most accurate • More linear than thermocouple	• High output • Fast • Two-wire ohms measurement	• Most linear • Highest output • Inexpensive
Disadvantages	• Non-linear • Low voltage • Reference required • Least stable • Least sensitive	• Expensive • Slow • Current source required • Small resistance change • Four-wire measurement	• Non-linear • Limited temperature range • Fragile • Current source required • Self-heating	• $T < 250°$ C • Power supply required • Slow • Self-heating • Limited configurations

Temperature Versus Heat

• Often the concepts of heat and temperature are thought to be the same, but they are not.

• Temperature is a number that is related to the average kinetic energy of the molecules of a substance. If temperature is measured in Kelvin degrees, then this number is directly proportional to the average kinetic energy of the molecules.

• Heat is a measurement of the total energy in a substance. That total energy is made up of not only of the *kinetic energies* of the molecules of the substance, but total energy is also made up of the *potential energies* of the molecules.

Temperature Versus Heat

- When heat, (i. e., energy), goes into a substance one of two things can happen:

1. The substance can experience a raise in temperature. That is, the heat can be used to speed up the molecules of the substance.

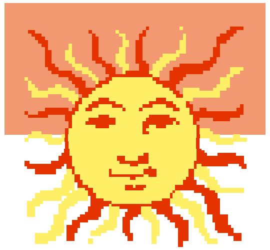
2. The substance can change state. For example, if the substance is ice, it can melt into water. This change does not cause a raise in temperature. The moment before melting the average kinetic energy of the ice molecules is the same as the average kinetic energy of the water molecules a moment after melting. Although heat is absorbed by this change of state, the absorbed energy is not used to speed up the molecules. The energy is used to change the bonding between the molecules.

There are three mechanisms by which thermal energy is transported.

1. Convection 2. Conduction 3. Radiation

Convection is the transfer of heat by the actual movement of the warmed matter. Heat leaves the coffee cup as the currents of steam and air rise. Convection is the transfer of heat energy in a <u>gas</u> or <u>liquid</u> by movement of currents. The heat moves with the fluid

Conduction is the transfer of energy through matter from particle to particle. It is the transfer and distribution of heat energy from atom to atom within a substance. For example, a spoon in a cup of hot soup becomes warmer because the heat from the soup is conducted along the spoon. Conduction is most effective in solids-but it can happen in fluids.



Radiation: Electromagnetic waves that directly transport ENERGY through space. Sunlight is a form of radiation that is radiated through space to our planet without the aid of fluids or solids. The sun transfers heat through 93 million miles of space. Because there are no solids (like a huge spoon) touching the sun and our planet, conduction is not responsible for bringing heat to Earth. Since there are no fluids (like air and water) in space, convection is not responsible for transferring the heat. Thus, radiation brings heat to our planet.

Gas Temperature Measurements

When measuring the temperature of a gas, a thermocouple or any immersed device, can indicate only its own temperature. In general, this will not be equal to the gas temperature.

It is the responsibility of the investigator to determine the difference which exists, and to correct for it, or to design the probe such that the difference is acceptably small.

For temperature measurements, a steady state difference between thermocouple and gas temperature is commonly called an « error » but actually represents the balancing of four well defined phenomena.

- Heat transfer to or from the probe by radiation
- Heat transfer by conduction
- Conversion of kinetic energy to thermal energy in the boundary layer around the thermocouple
- Heat transfer from the boundary layer to the junction by convection

Surface Temperature Measurements

A. Optical Methods

A number of optical techniques have been developed over the last decades in order to determine surface temperature distributions.

All techniques discussed in this section rely on a visual effect produced by temperature changes; they proved to be extremely efficient, especially in the case of complex geometries.

They provide both qualitative and quantitative information on the thermal field.

Surface Temperature Measurements

A. <u>Optical Methods</u>

<u>Temperature Sensitive Paint</u>

Temperature sensitive paints are a technique by which a surface coating changes color as the temperature changes over a given range.

The lines of color change represent the isotherms.

These paints usually contain metallic salts which liberate a number of substances at specific temperatures; as a result, the color change is irreversible.

Their operating domain ranges from room temperature to about 1900K and these paints can undergo multiple color changes for different temperatures.

The local value of temperature can be estimated within a few degrees K.

They can unfortunately also be sensitive to pressure, chemical products, atmospheric contaminants and high humidity.

This technique has been and is still widely used in the gas turbine industry for the location of “hot spots” in combustion chambers and blades.

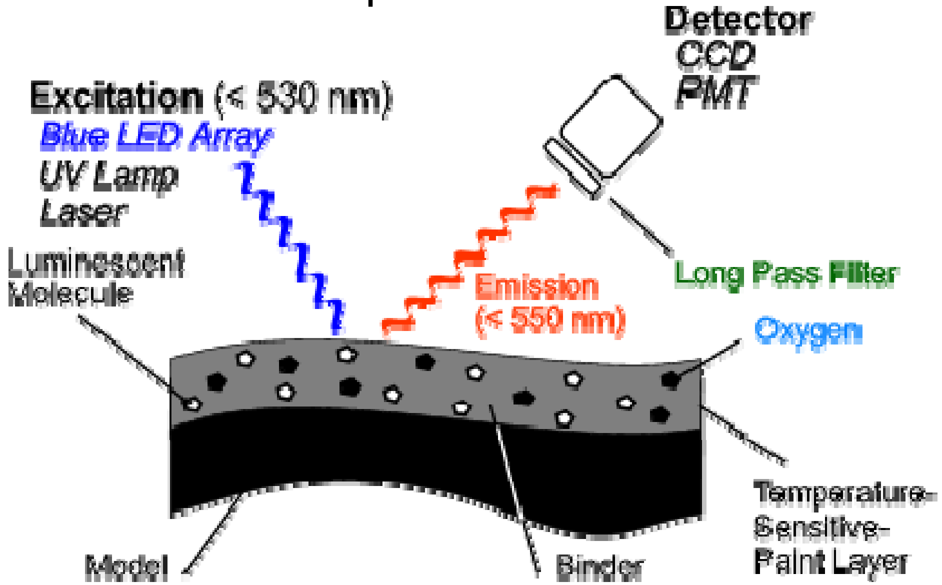
Surface Temperature Measurements

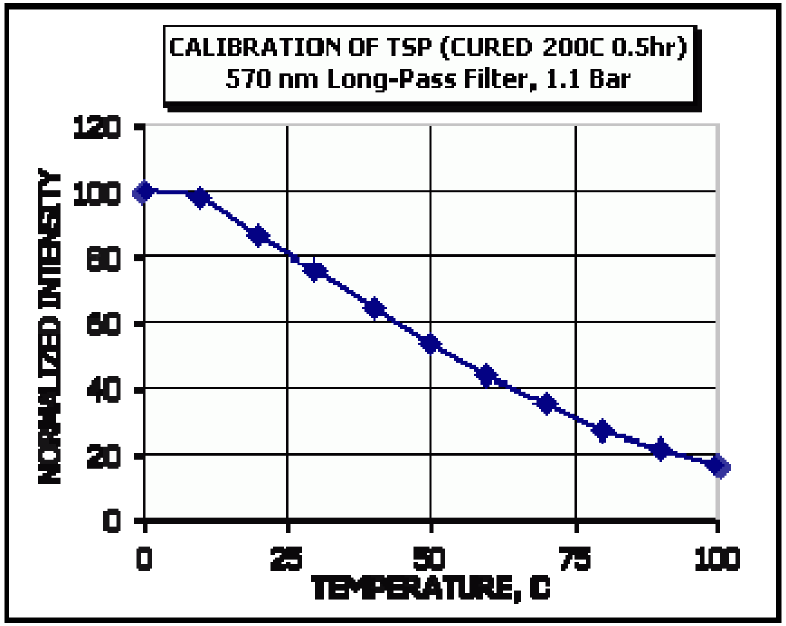
A. Optical Methods

Temperature Sensitive Paint

Temperature-Sensitive Paint (TSP) is a surface coating that utilizes luminescence to measure surface temperature. The coating is applied with common spray-painting techniques. The cured paint is illuminated with a short-wavelength (< 530 nm) source, and the surface image is observed through a long-pass (> 550 nm) optical filter.

Variations in intensity represent variations in temperature on the surface; areas darken as the temperature increases.

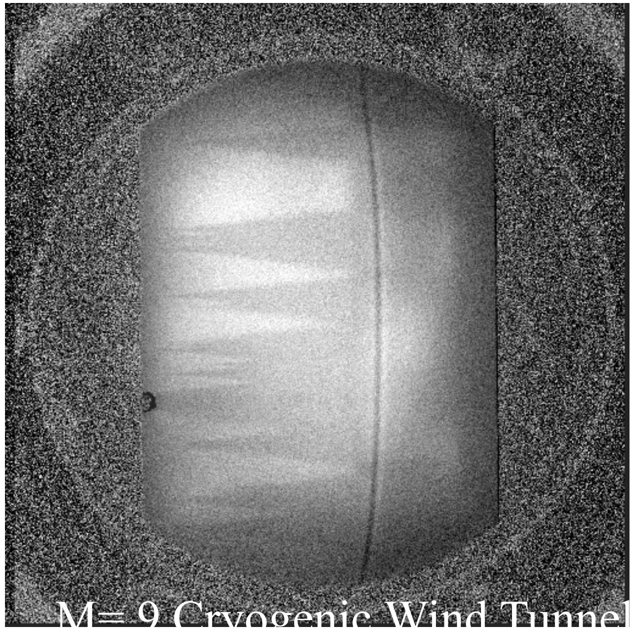




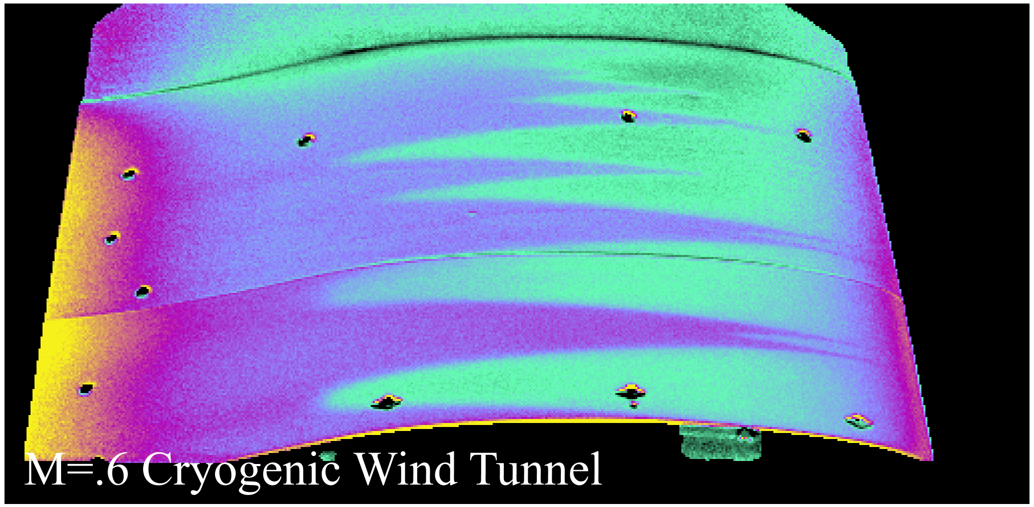
Temperature Sensitive Paint

Laminar to Turbulent BL Transition

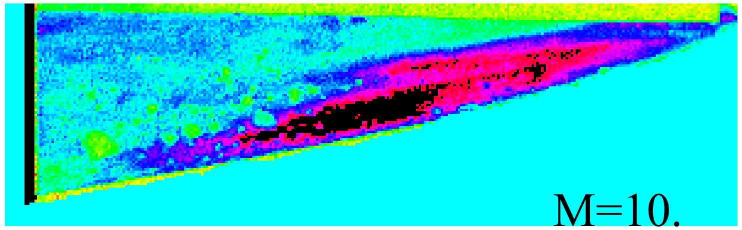
M=.1



M=.9 Cryogenic Wind Tunnel



M=.6 Cryogenic Wind Tunnel



M=10.

The best of diatomic gases for use in a cryogenic wind tunnel are nitrogen, carbon monoxide and air, offering tunnel sizes in the order of 25% to **30%** of that of normal temperature air.

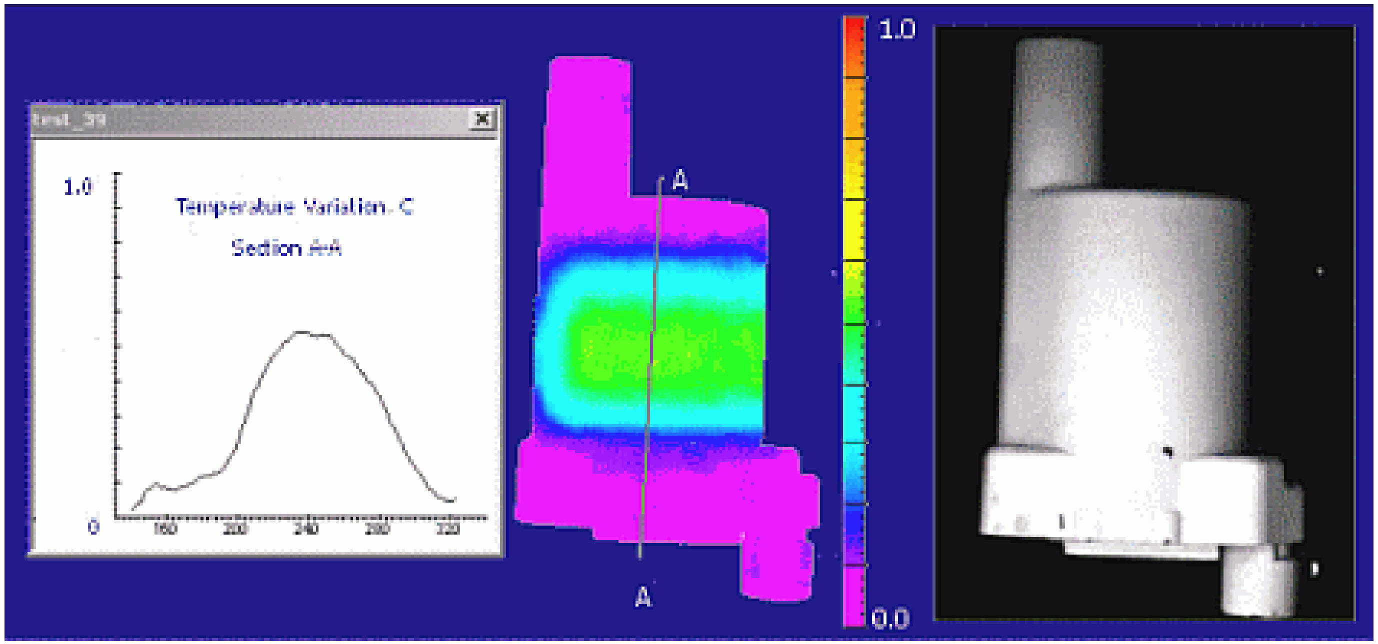
Find more about cryogenic Wind tunnels:

http://ftp.rta.nato.int/public//PubFullText/AGARD/R/AGARD-R-812/AGARDR812.pdf

A reference on PSP/TSP: **http://www.innssi.com/References.htm**

Development and Analysis of Data Processing Methods Applied to Luminescent Coating Systems in Aerodynamics, author Vladimir S. Fonov, Ph.D., 2003

Ex: Temperature-field variation on surface of ignition coil obtained with TSP



Surface Temperature Measurements

A. Optical Methods

Phase Change Coatings

These coatings are made of materials having calibrated melting points suspended in an inert (not chemically active) volatile liquid.

They are sprayed or painted on the surface of interest and produce an opaque film.

When heating, the film melts at the phase change temperature and becomes transparent. The process is irreversible; when cooling, the film solidifies but remains transparent.

The operating domain of these temperature detectors ranges between ambient and 1650K

Surface Temperature Measurements

A. Optical Methods

Phase Change Coatings

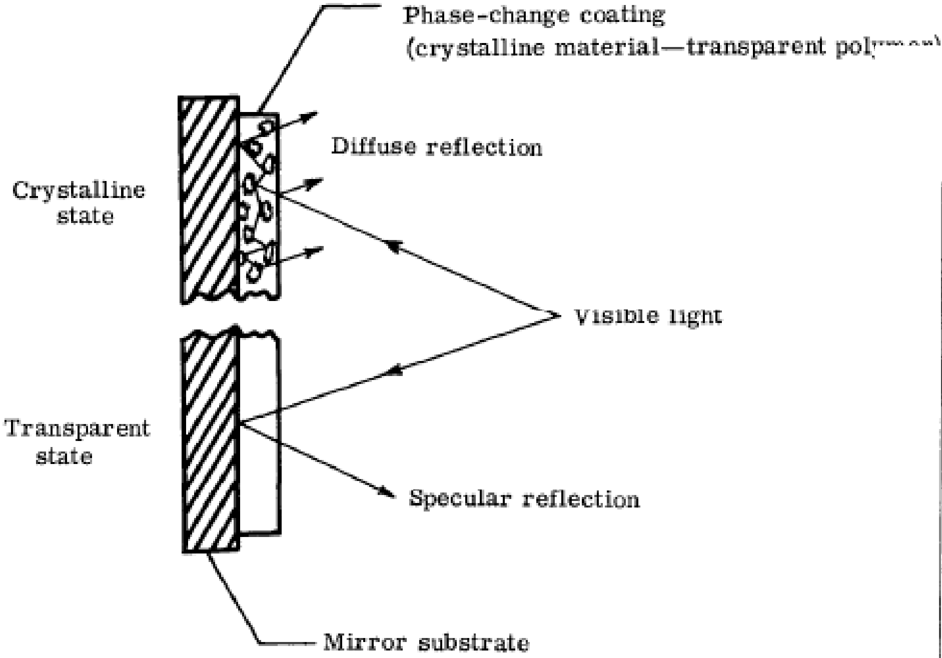


Figure 1.- Schematic of model phase-change coating system.

TABLE I.- PHYSICAL PROPERTIES OF CRYSTALLINE MATERIALS USED IN THERMAL CONTROL COATING STUDY

Crystalline material	Chemical structure	Refractive index, η_D	Melting or softening point, °C
Paraffin	$CH_3(CH_2)_{17-28}CH_3$	1.440 (60° C)	50 to 56
Eicosane	$CH_3(CH_2)_{18}CH_3$	1.435 (40° C)	38
Hexadecane	$CH_3(CH_2)_{14}CH_3$	1.434 (25° C)	20
Octadecanol	$CH_3(CH_2)_{17}OH$	------------	58
Hexadecanol	$CH_3(CH_2)_{15}OH$	1.428 (80° C)	47
Tetradecanol	$CH_3(CH_2)_{13}OH$	------------	37
Dodecanol	$CH_3(CH_2)_{11}OH$	------------	23
Decanol	$CH_3(CH_2)_9OH$	1.437 (25° C)	6
Octanol	$CH_3(CH_2)_7OH$	1.429 (25° C)	-16
Hexanol	$CH_3(CH_2)_5OH$	1.418 (25° C)	-52
Nonadecene	$CH_3(CH_2)_{16}CH=CH_2$	1.444 (25° C)	24
Lauric acid	$CH_3(CH_2)_{10}COOH$	1.418 (80° C)	45
Diphenyl methane	⌬ - CH_2 - ⌬	1.577 (25° C)	25

Reference:
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720018274_1972018274.pdf

Surface Temperature Measurements

A. Optical Methods

Liquid Crystals

Reinitzer in 1881 observed color changes of cholesterol esters and noted optical activity under certain conditions. He discovered the existence of two melting points.

The first is characterized by the transformation of the substance from a solid to a cloudy liquid.

The second is characterized by the change of this cloudy liquid into a transparent one.

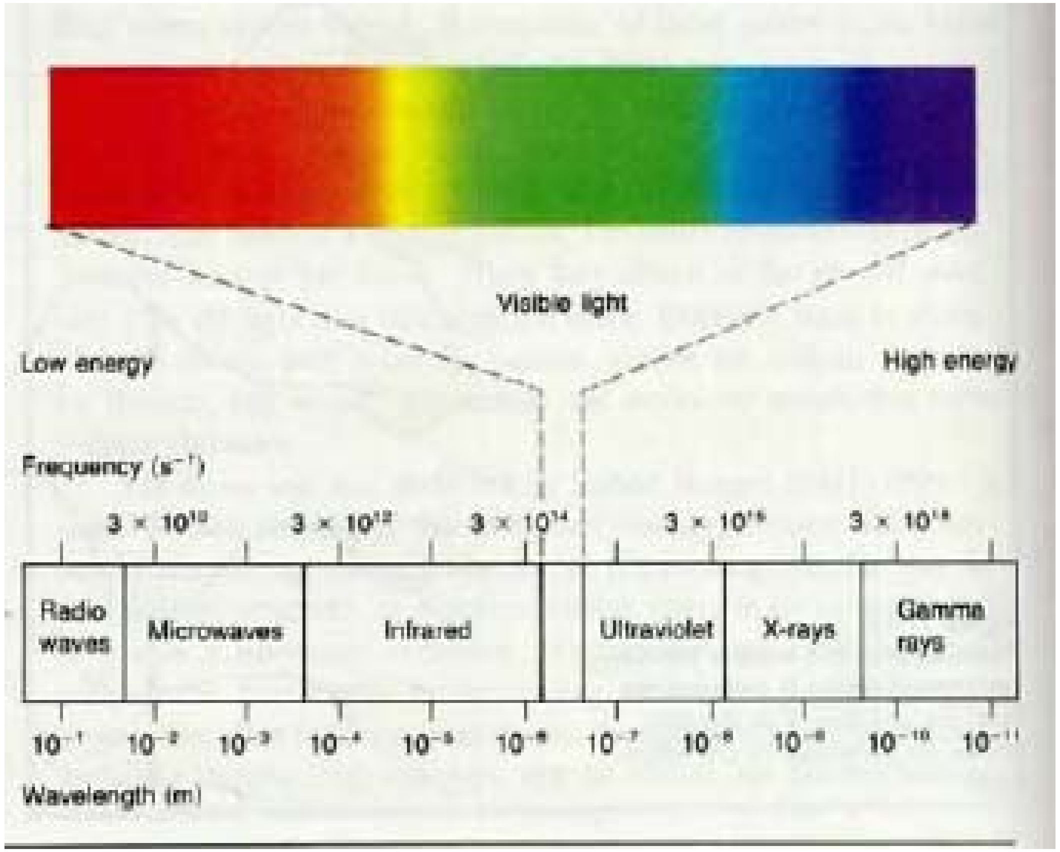
Surface Temperature Measurements

A. Optical Methods

Liquid Crystals

Mechanically these substances resemble liquids with viscosities ranging from low values to almost solid glass; optically they exhibit many of the properties of crystals.

As they are gradually heated, cholesteric liquid crystals will progressively exhibit all colors of the visible spectrum. The phenomenon is reversible and repeatable.



Surface Temperature Measurements

B. Other Methods

Surface attached resistance thermometers

Resistance thermometers function by producing a repeatable variation of electrical resistance as a function of temperature. Such devices are constructed of materials such as oxides of manganese, nickel and cobalt.

Surface attached resistance thermocouples

The temperature of a surface may be measured using thermocouples attached directly to the surface.

Surface Temperature Measurements

B. Other Methods

Surface attached resistance thermocouples

However the thermocouple wire could act as a fin for heat transfer from the solid to the gas. So the temperature at the point of attachment will be different from the measured temperature. Minimized errors may be obtained by using small diameter wires with low thermal conductivity and well insulated from the flow. Also place the wire close to the surface.

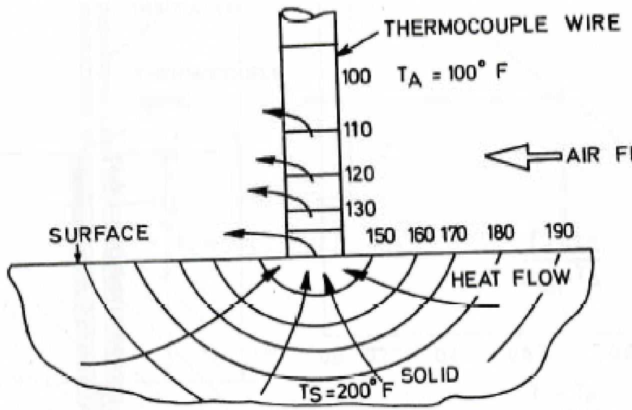


Figure 4.10: Temperature variation in a thermocouple wire attached to a surface

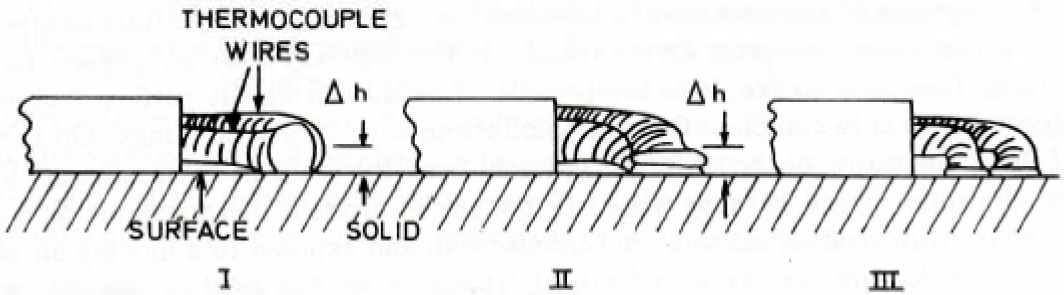


Figure 4.11: Possible configurations to attach thermocouples to a plate for surface temperature measurement

Solid Temperature Measurements

Thermocouples are often used for temperature measurements of solids. However, it is important to realize that:

-The thermocouple may not be at the same temperature as the solid

-The temperature of the solid may be altered by the presence of the thermocouple junction

The most common method for installing the thermocouple for this purpose is to drill a hole and insert the thermocouple inside.

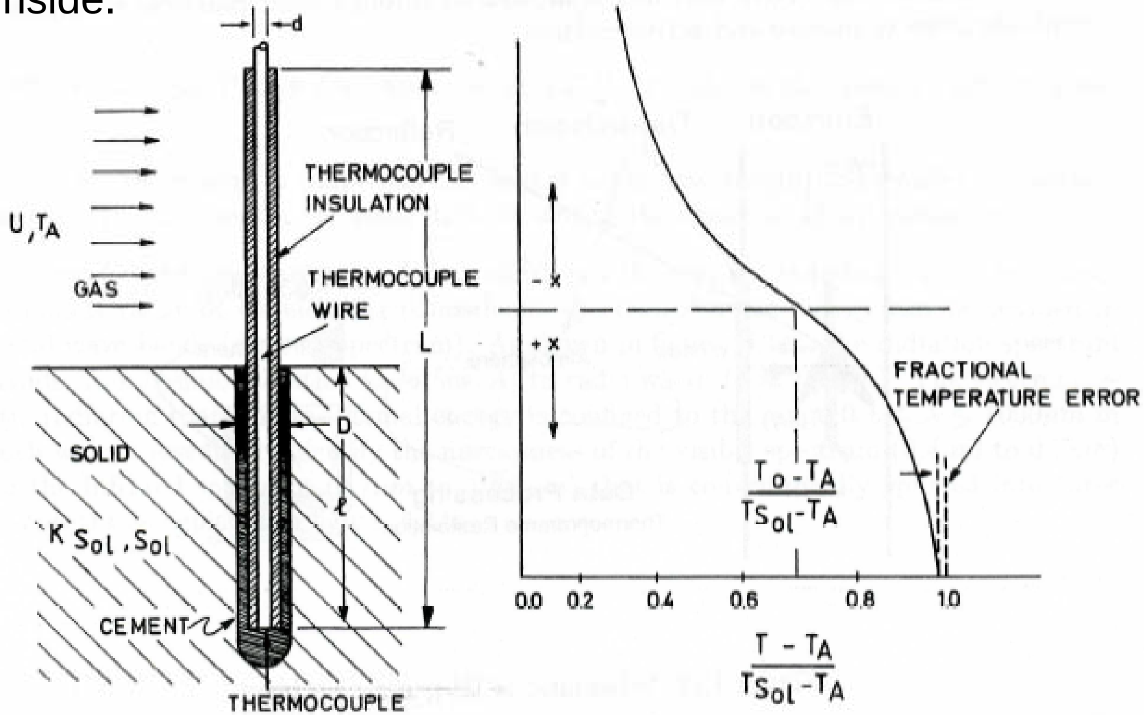


Figure 4.12: Idealized thermocouple installation for solid temperature measurements and temperature distribution