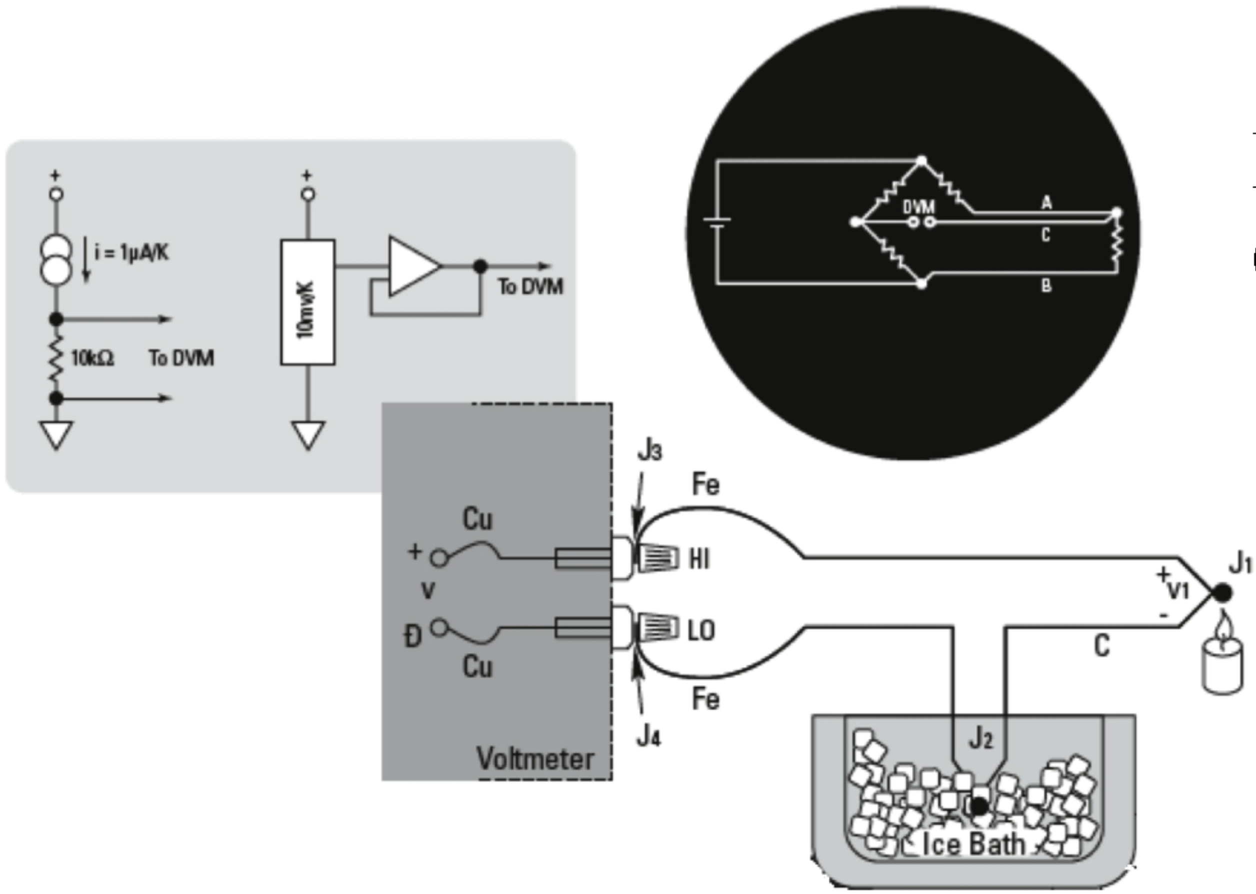
Section 6.1 : Introduction to Temperature Measurement Methods

- F&B Chapter 8

Beckwith Chapter 16



What is Temperature ? (1)

• ***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.

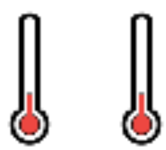
Zeroth Law of Thermodynamics …

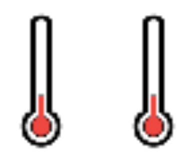
if two systems are separately in thermal equilibrium with a third, then they must also be in thermal equilibrium with each Other.

What is Temperature ? (2)

- ***Temperature:*** Temperature is not directly proportional to internal energy since temperature measures only the kinetic energy part of the internal energy, so two objects with the same temperature do not in general have the same internal energy.

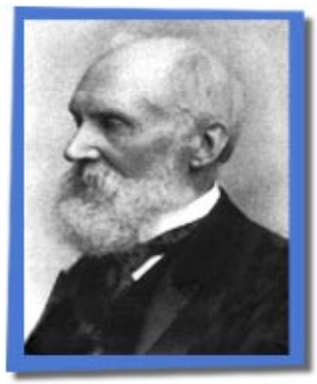
- When a high temperature object is placed in contact with a low temperature object, then energy will flow from the high temperature object to the lower temperature object, and they will approach an equilibrium temperature.





Kelvin Temperature Scale (1)

• 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 (2)

• 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:

°C = 5/9 (°F - 32) °F = 9/5° C + 32

k = °C + 273.15 °R = °F + 459.67

Kelvin Temperature Scale (3)

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

•At absolute zero, or 0 °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 (1)

- Can't build a temperature divider like we can a voltage divider, nor can one add temperatures as we would add lengths to measure distance.

- 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 (2)

ITS-90 Fixed Points

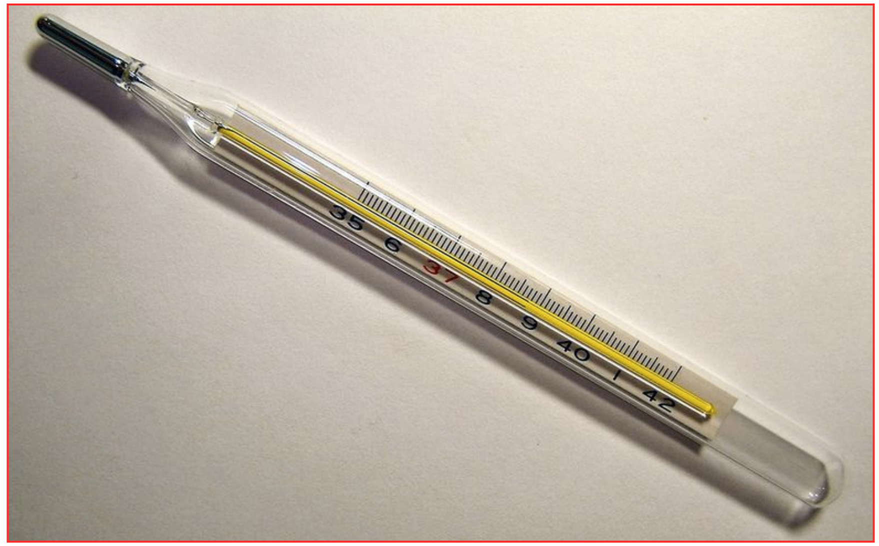
Element		Type	Temperature K	°C
(H_2)	Hydrogen	Triple Point	13.8033 K	-259.3467° C
(Ne)	Neon	Triple Point	24.5561 K	-248.5939 ° C
(O_2)	Oxygen	Triple Point	54.3584 K	-218.7916° C
(Ar)	Argon	Triple Point	83.8058 K	-189.3442° C
(Hg)	Mercury	Triple Point	234.315 K	-38.8344° C
(H_2O)	Water	Triple Point	273.16 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

Types of Temperature Sensors

- 5 Most common devices are …..

- Thermometer
- Thermocouple
- RTD (resistance temperature detector)
- Thermistor
- Integrated (semiconductor) Circuit Sensor

Fluid-Based 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.

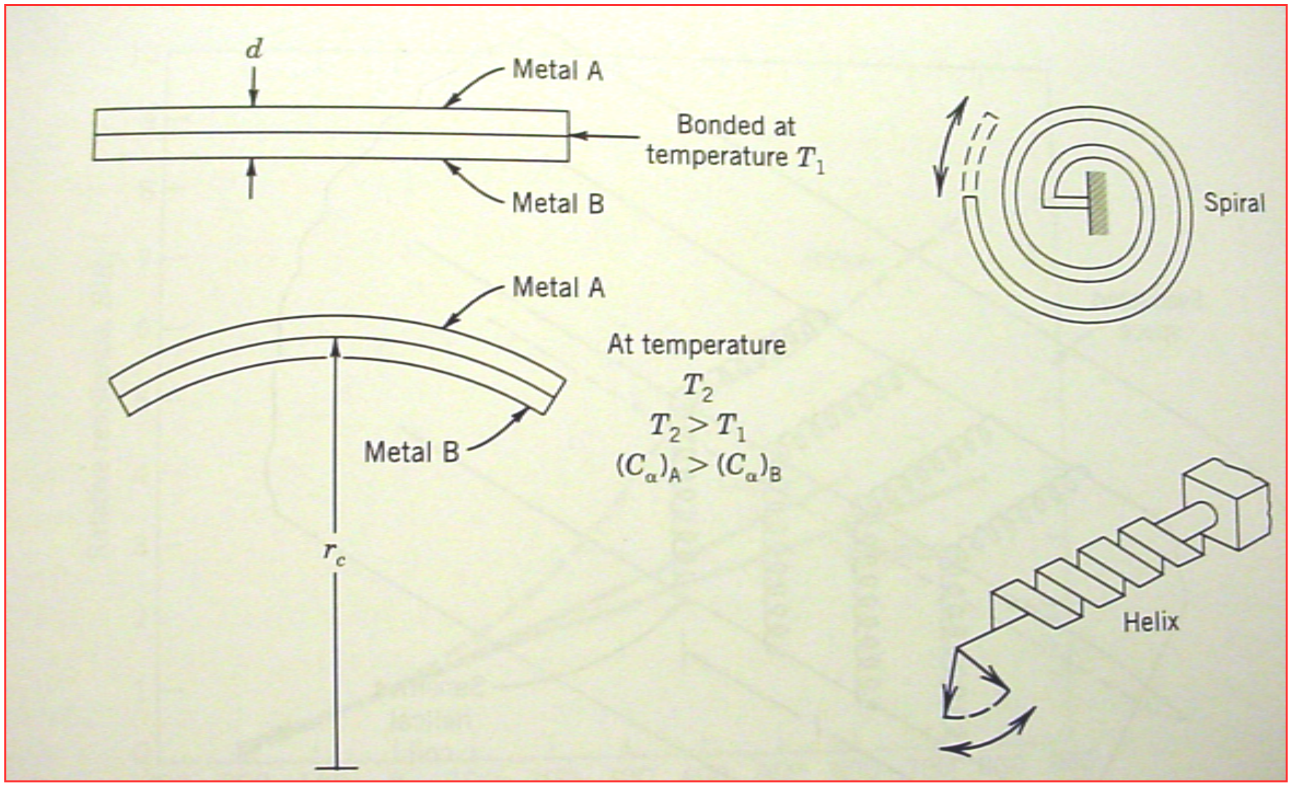
Mechanical…only…device not Electronic readout

… not true "transducers"

…limited Measurement Resolution and accuracy

Bi-Metallic Thermometers

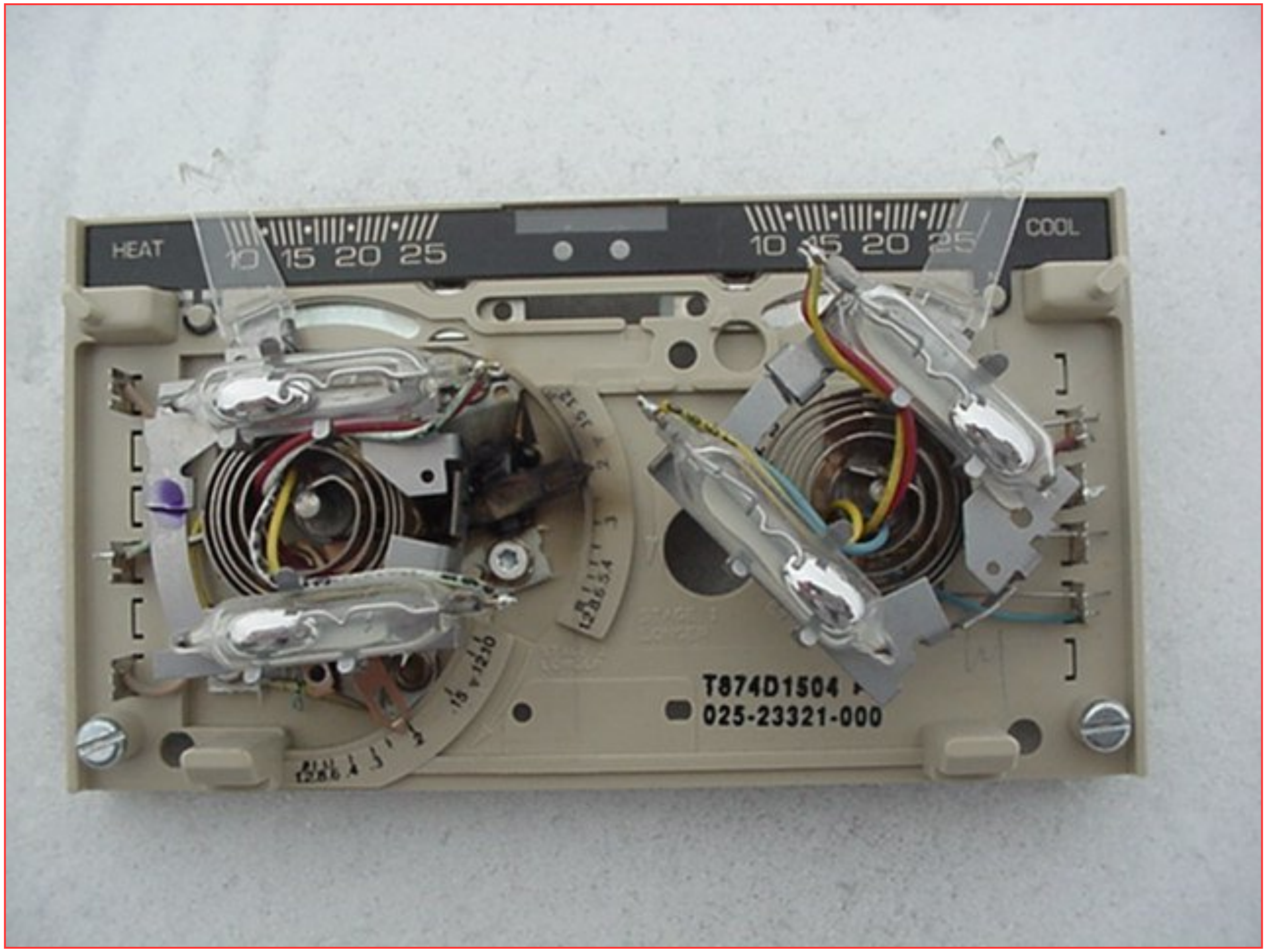
If you take two metals with different thermal expansion coefficients and bond them together, they will bend in one direction if the temperature rises above the temperature at which the boding was done and in the direction if temperature drops.



- Devices Can be used to indirectly Drive an Electronic Indicator

… not true "transducers"

Bi-Metallic Thermometer Example



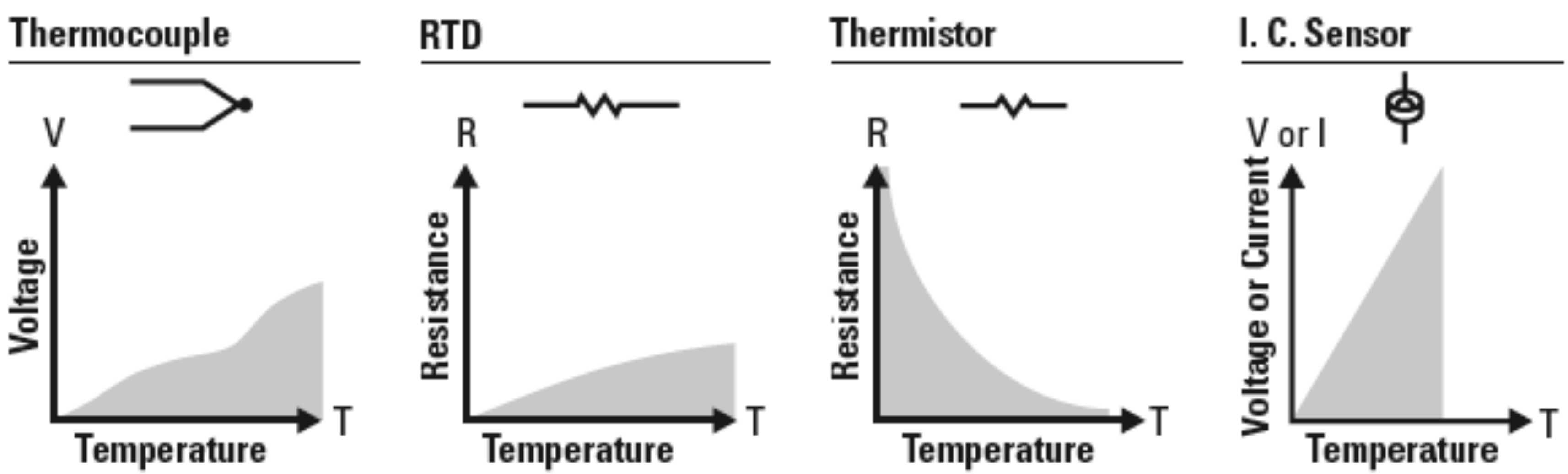
- Household Heater thermostat Indicator

… not true "transducers"

…limited Measurement Resolution and accuracy

"Transduction" Temperature Sensors (1)

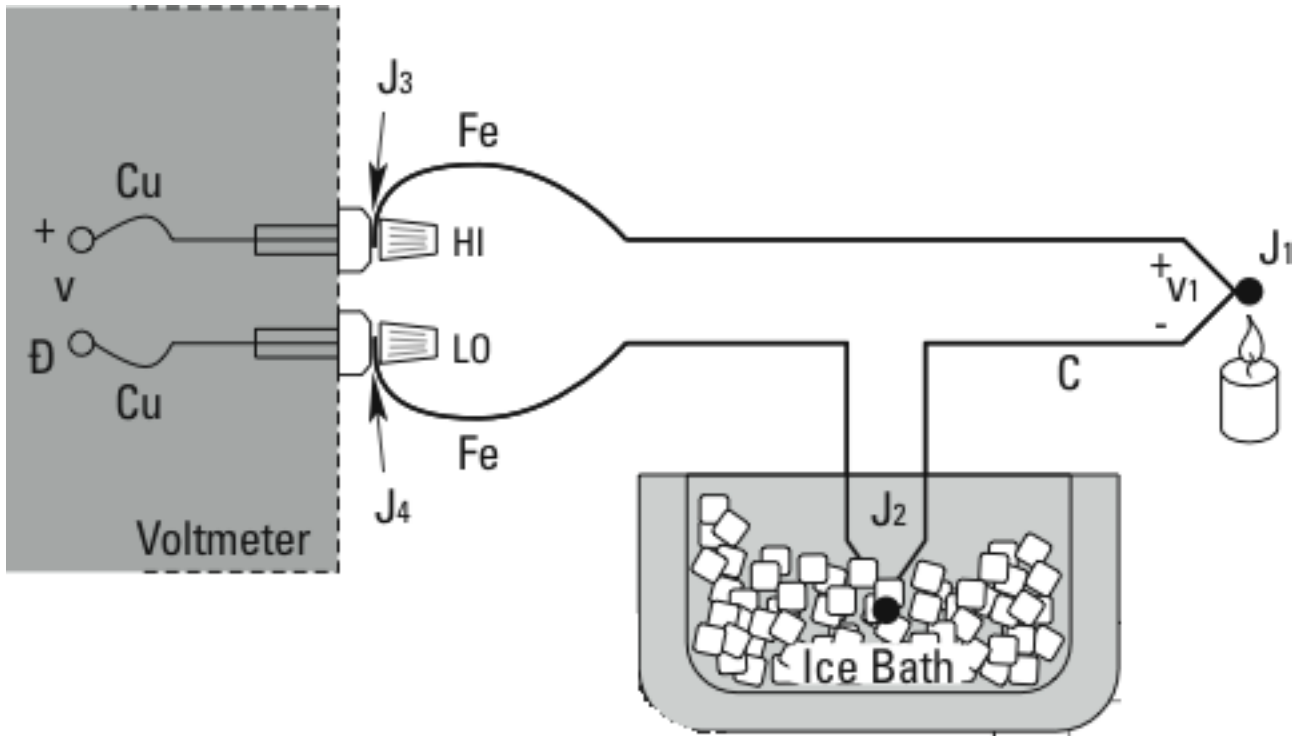
• Converts Kinetic Energy of molecular motion into electrically Sensible output .. Either current or voltage … best for accuracy For Scientific or engineering measurements



"Transduction" Temperature Sensors (2)

	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

Thermocouples



Thermocouples: Physical Measurement Principals (1)

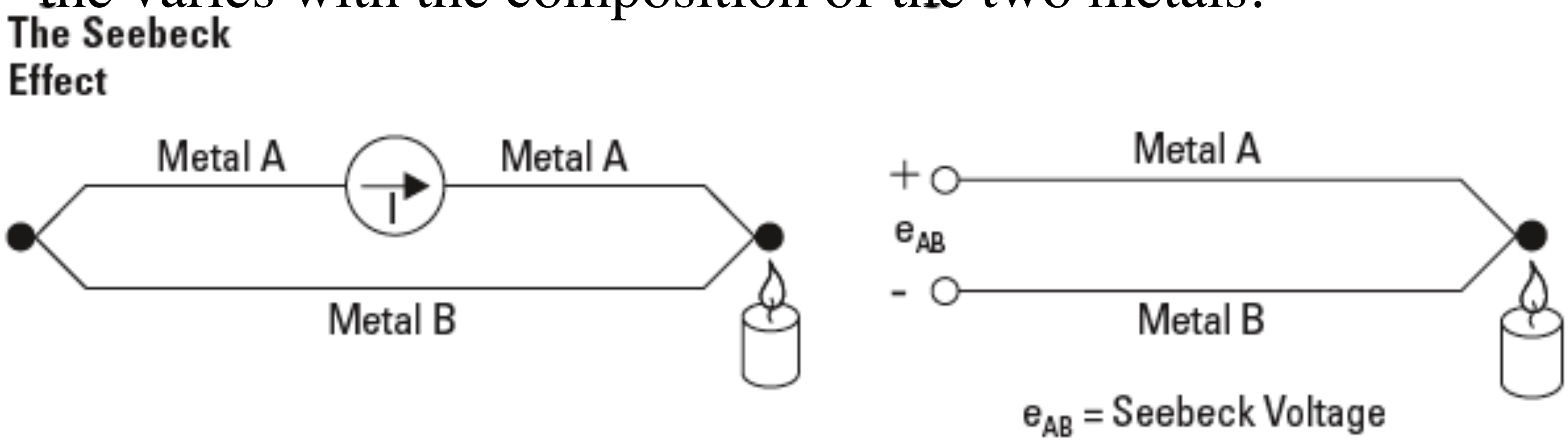
• **Seebeck Effect** … In 1821 Thomas Seebeck found that a circuit made from two dissimilar metals, with junctions at different temperatures would deflect a compass magnet.

• Seebeck believed effect was due to magnetism induced by temperature differences. However, it was later realized that electrical current induced the magnetic field that deflects the magnet.

More specifically, the temperature difference produces an electric potential (voltage) which can drive an electric current in a closed circuit. Today, this is known as the Seebeck effect.

Thermocouples: Physical Measurement Principals (2)

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



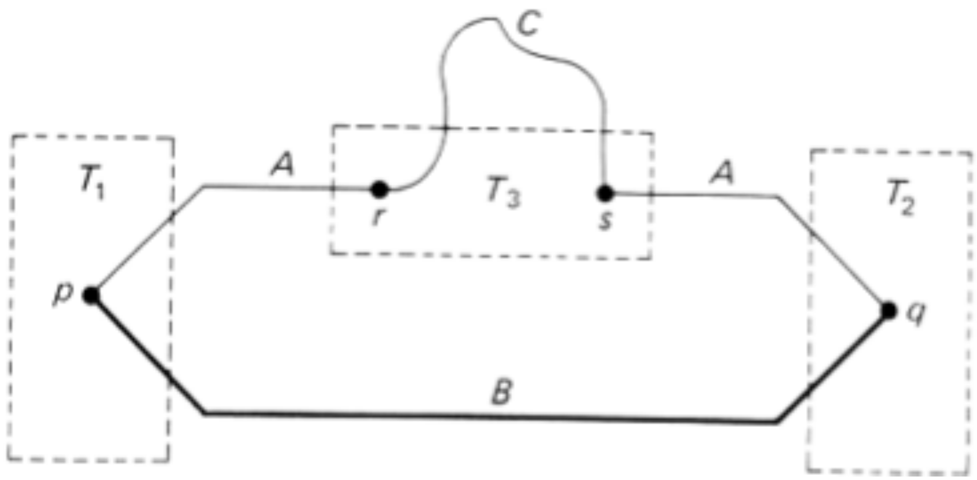
- All dissimilar metals exhibit this "Seebeck effect".

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

- *Often abbreviated at TC*

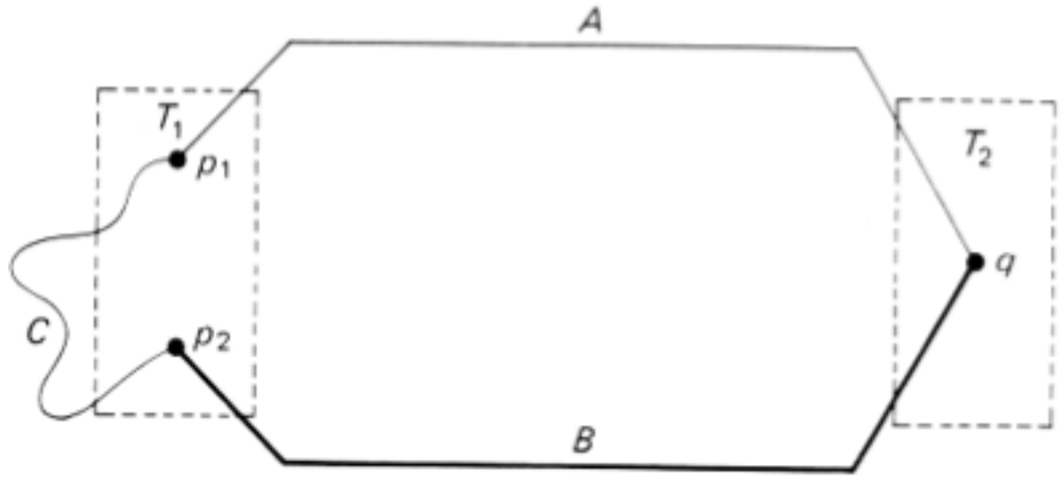
Thermocouples: Physical Measurement Principals (3)

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 (4)

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 (1)

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

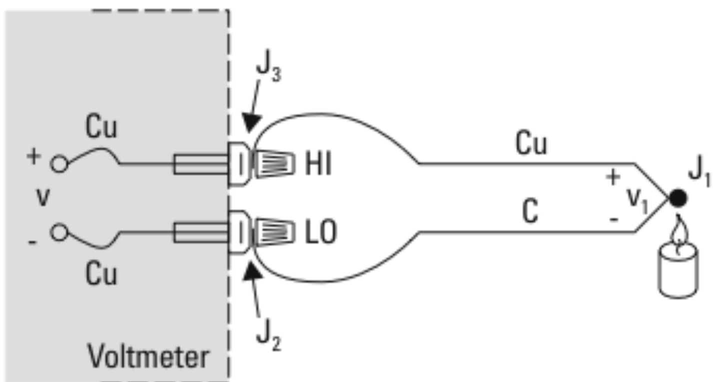
• We must be careful to measure the output of the thermocouple in such a way as to not draw current *(infinite impedance!)*, which would load the thermocouple and distort the reading.

• i.e. … 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 (2)

- As an example … connect a voltmeter to the ends of a *copper-constantan* (*Type T* … a type of *TC* … *more on this later*)

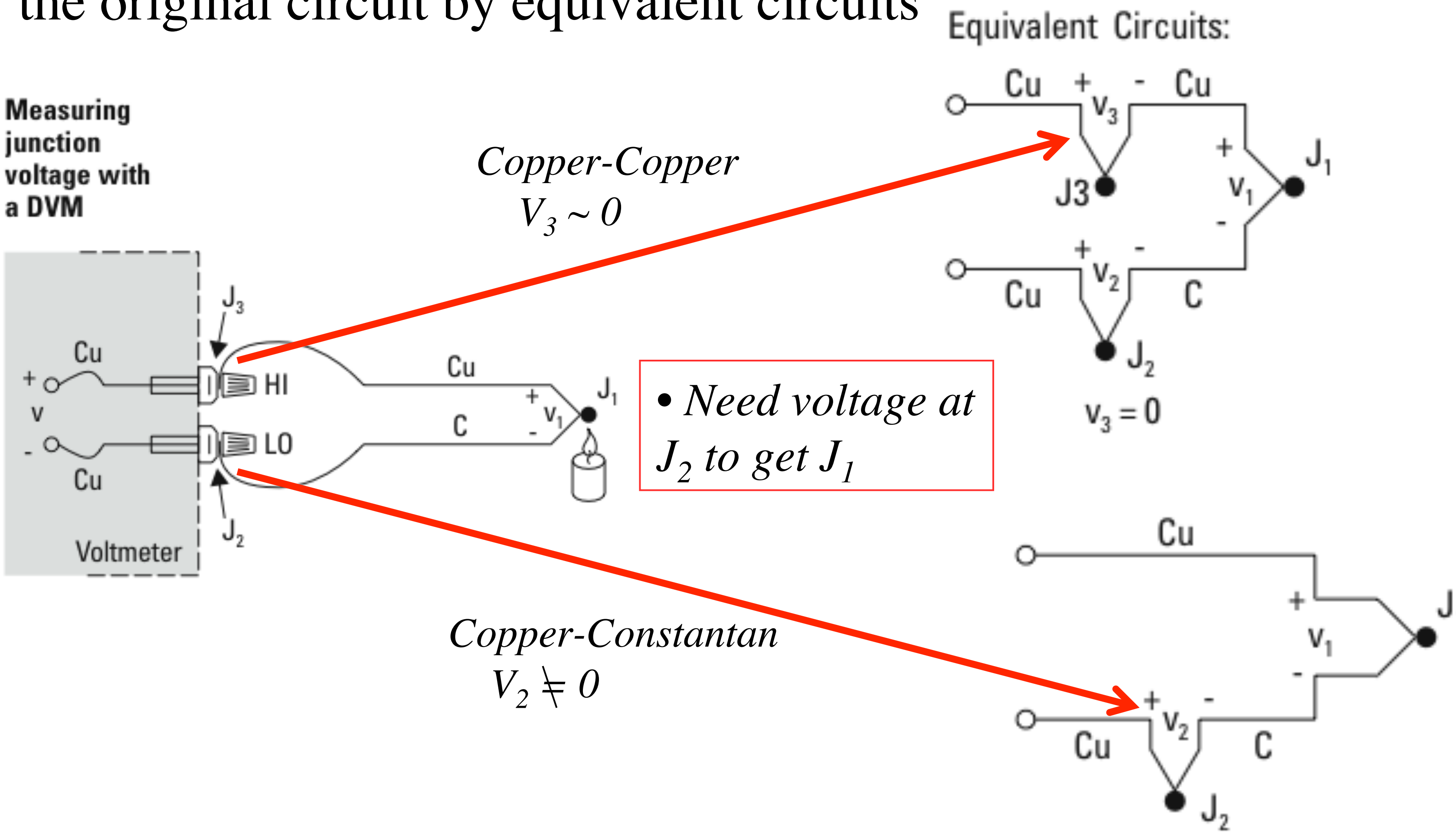
Measuring junction voltage with a DVM



- Want voltmeter to read only V_1
- By connecting voltmeter 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.
- Can't we can't find temperature at J_1 without first finding temperature of J_2.

Sensing The Thermocouple Voltage (3)

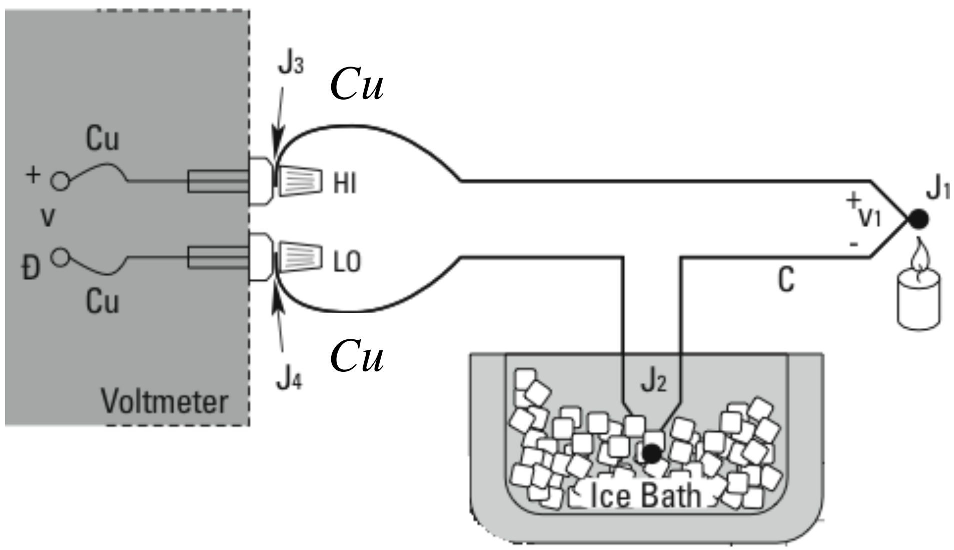
- We can draw this concept by replacing the original circuit by equivalent circuits



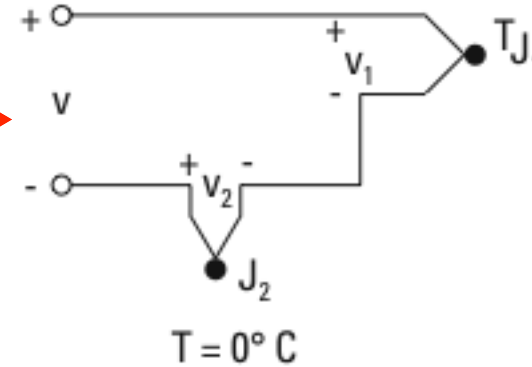
- *Need voltage at J_2 to get J_1*

Sensing The Thermocouple Voltage (4)

• 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



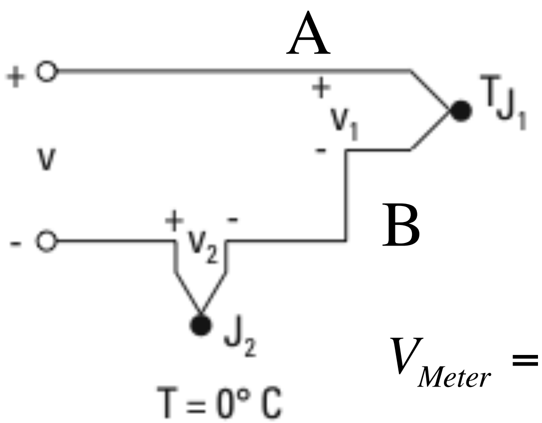
• **Wire from J_2 *to* J_3 is copper, no thermal *emf at* J_4**

Sensing The Thermocouple Voltage (5)

• 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

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



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

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

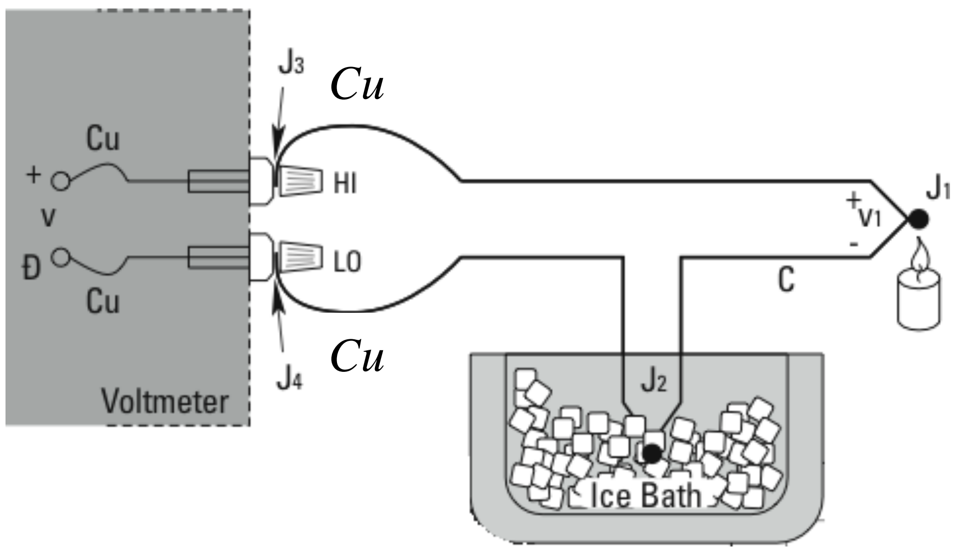
$$\rightarrow \boxed{V_{Meter} = \alpha \cdot T_{J_1\,(^\circ C)}}$$

• Meter reading is proportional to temperature at J_1 in deg. C. !

Sensing The Thermocouple Voltage (6)

- In other words … Thermocouples can't measure a single temperature, but can only tell us the difference in temperature between two points.

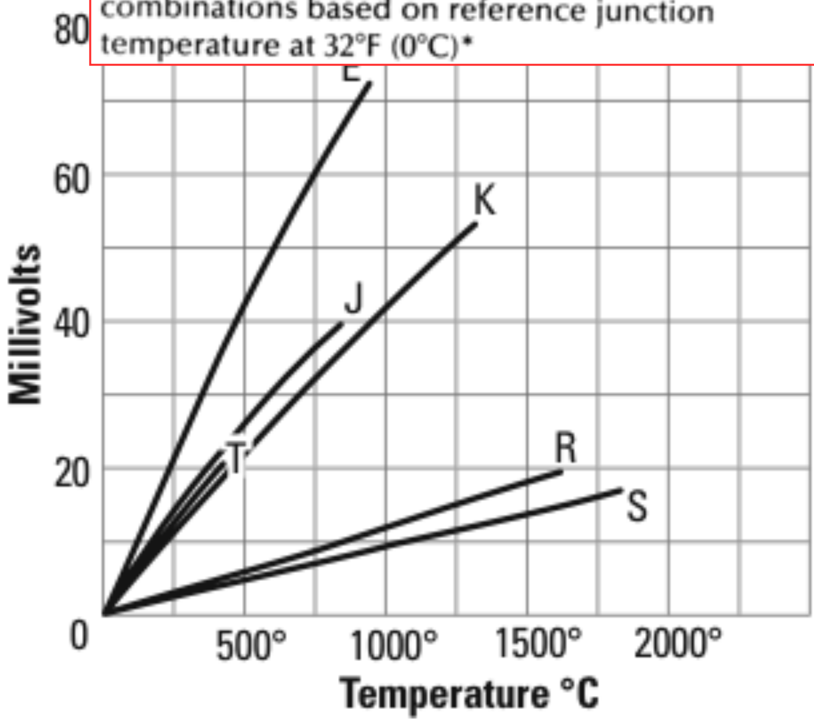
- If we can put one of those points at a known temperature, we are set …. Well … not quite!



Sensing The Thermocouple Voltage (7)

- 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, … can now look at NIST tables and directly convert from sensed voltage Temperature at J_1.

Values of EMF in absolute millivolts for selected metal combinations based on reference junction temperature at 32°F (0°C)*



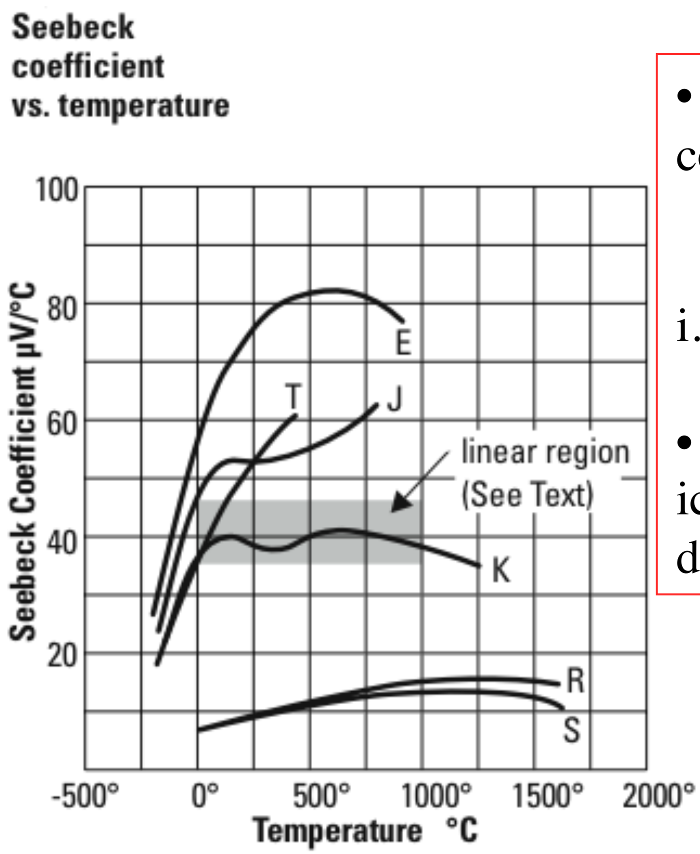
Type	Metals		
	+		-
E	Chromel	vs.	Constantan
J	Iron	vs.	Constantan
K	Chromel	vs.	Alumel
R	Platinum	vs.	Platinum 13% Rhodium
S	Platinum	vs.	Platinum 10% Rhodium
T	Copper	vs.	Constantan

"Type" Designation

Sensing The Thermocouple Voltage (8)

• 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.

Types of Thermocouple Metal Pairs

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%

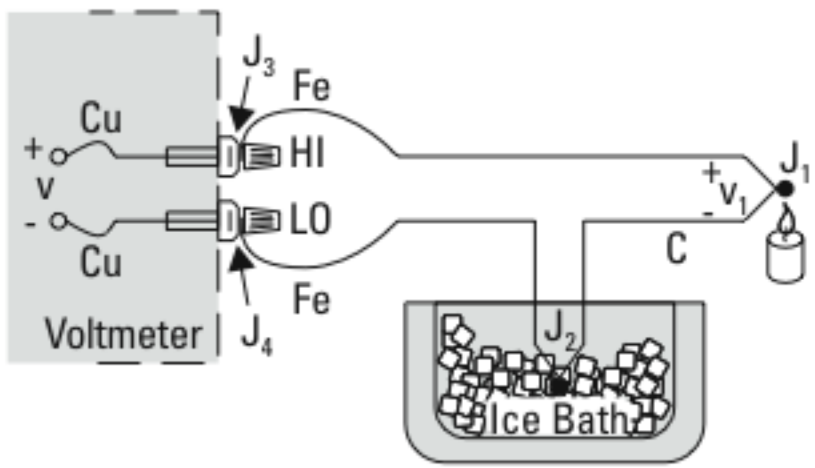
What we just analyzed

TC With Dissimilar Meter Leads (1)

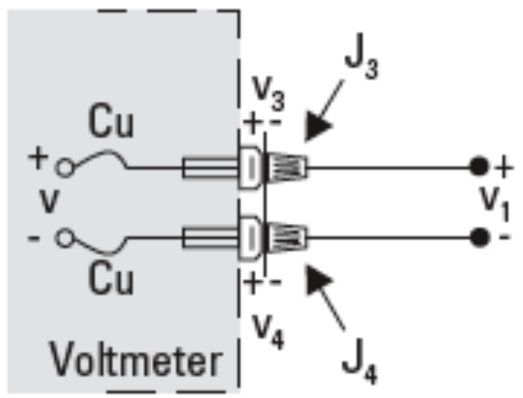
• The copper-constantan thermocouple considered earlier is a unique example because copper wire is same metal as voltmeter terminals.

• 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.



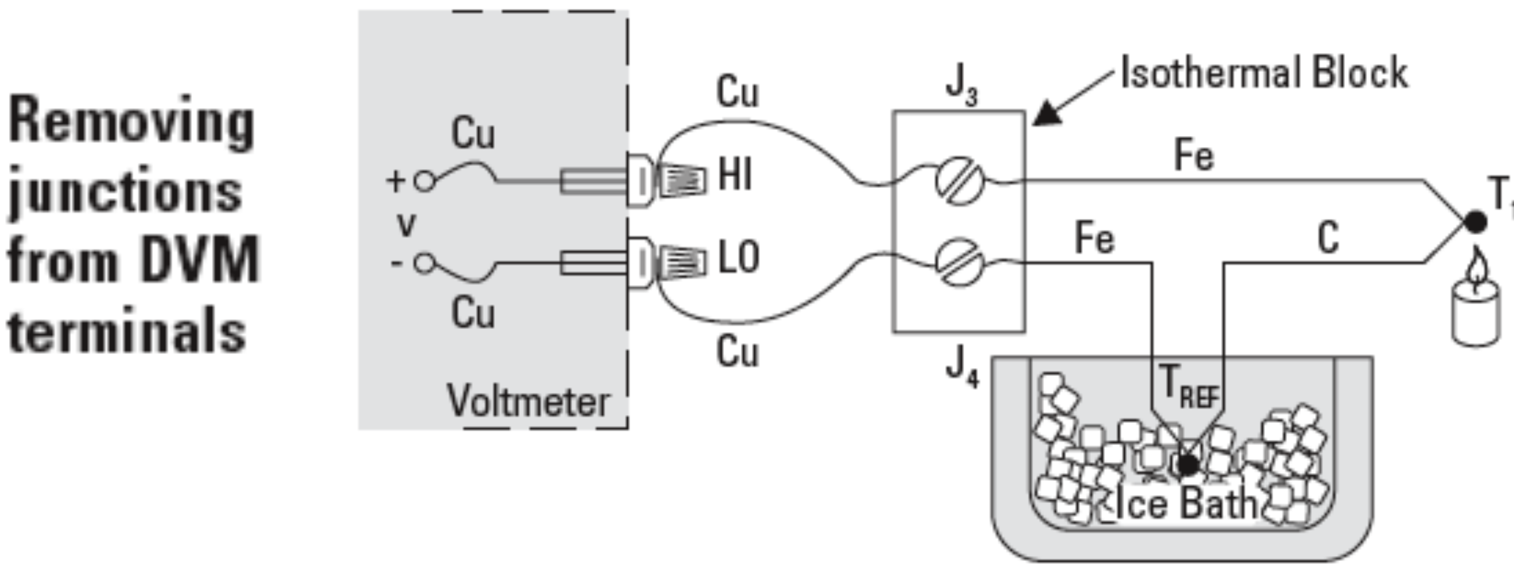
• Circuit provides accurate measurements as long as voltmeter terminals(J_3 & J_4) act in opposition, i.e. @ same temperature



TC With Dissimilar Meter Leads (2)

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

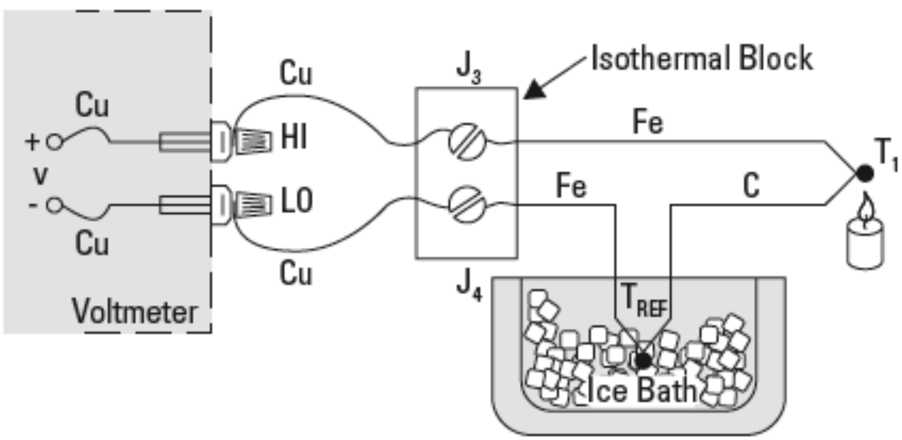
• For more precise measurement, copper voltmeter leads are extended so copper-to-iron junctions are made on a *temperature regulated* (isothermal) terminal block



TC With Dissimilar Meter Leads (3)

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

• Absolute block temperature not important because both Cu-Fe junctions act in opposition. Thus ….



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

$$ice\ bath \rightarrow V_{Meter} = \alpha\left[T_{J_{1\,(^\circ C)}}\right]$$

For linear TC region

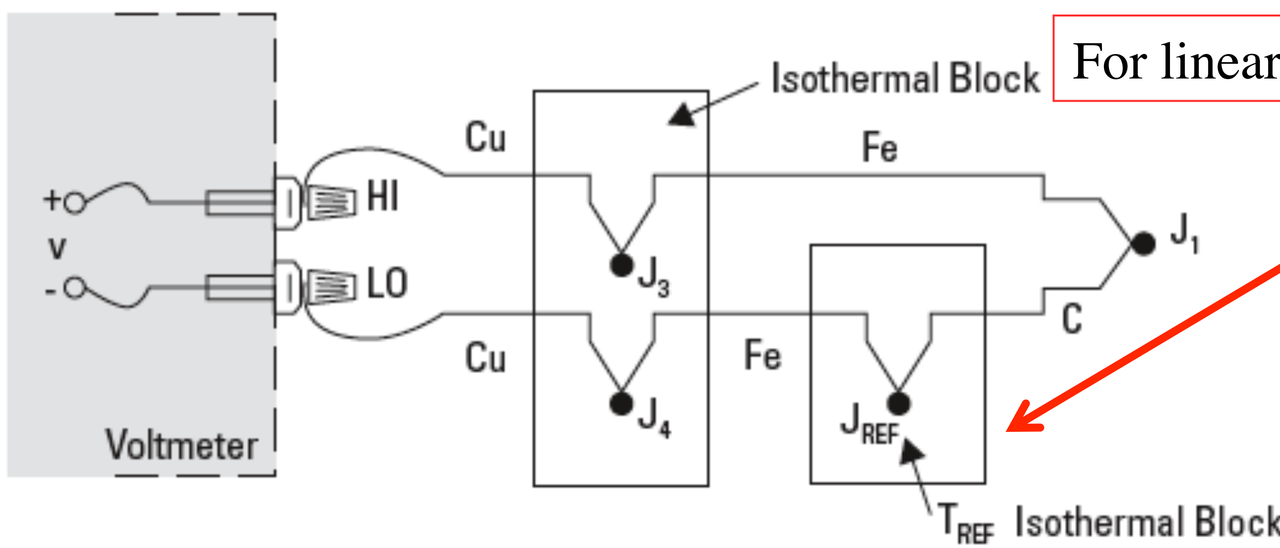
Electronic *TC* Compensation Methods (1)

- Obviously an Ice bath" is impractical for most TC application… especially for field deployments … would love to get rid of that!….

- Replace the *ice bath* with another *isothermal block* …

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

For linear TC region

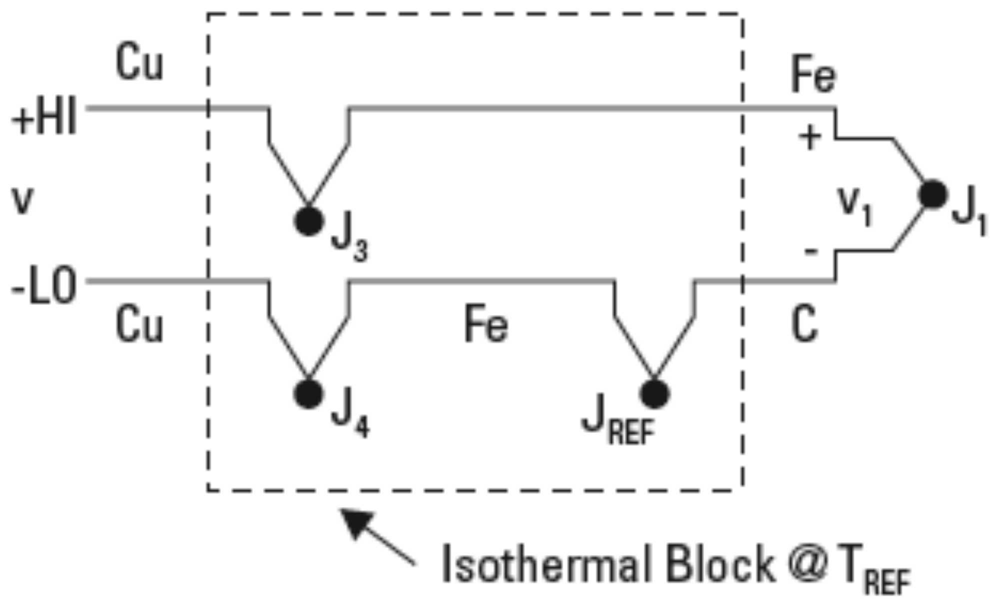


Electronic *TC* Compensation Methods (2)

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

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

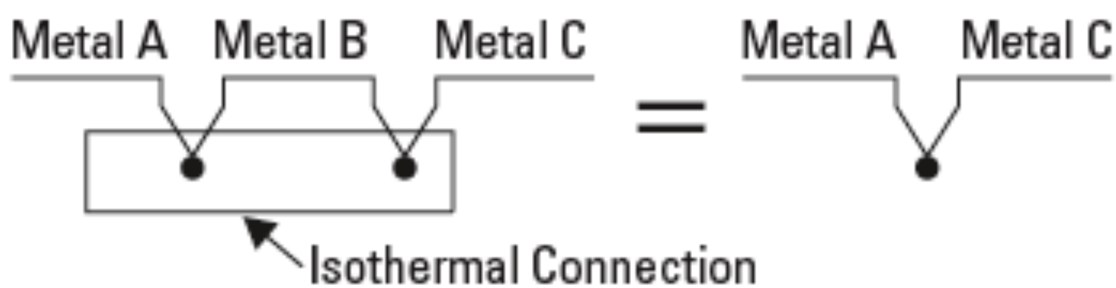
For linear TC region



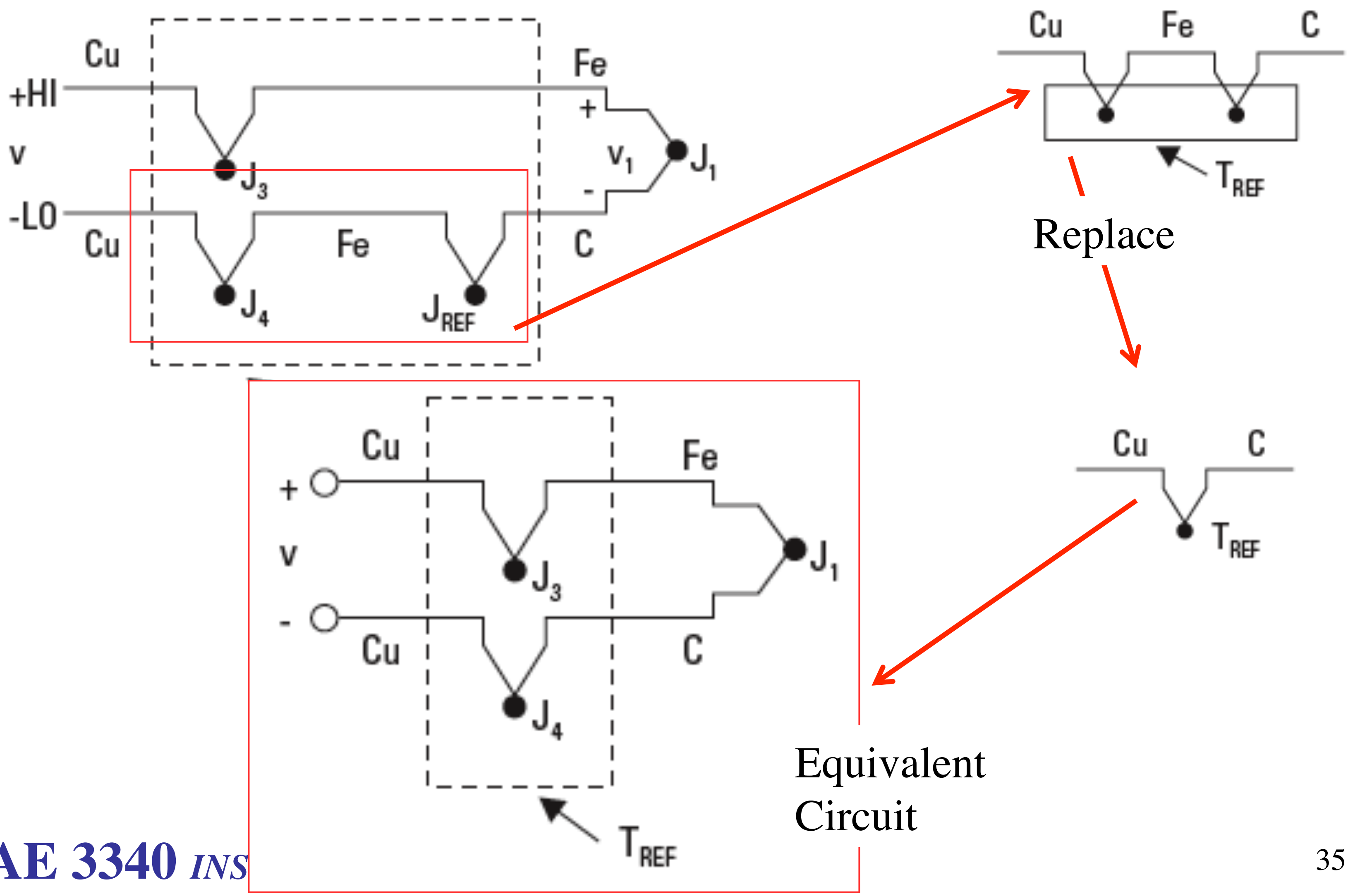
Electronic *TC* Compensation Methods (3)

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

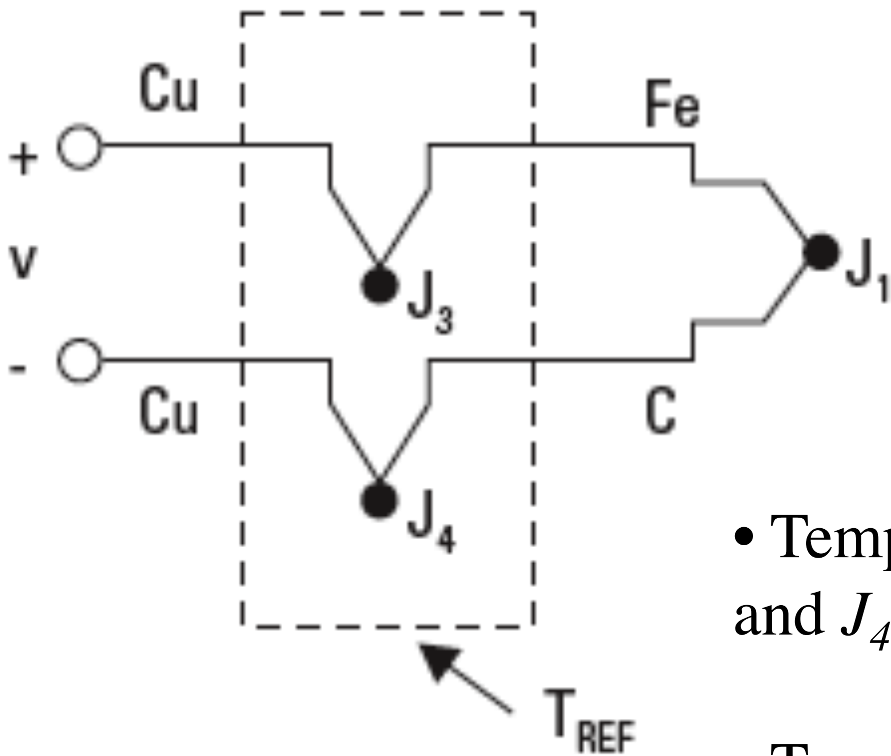
Law of Intermediate Materials: If you break your thermocouple and add something of another material, it will have no effect as long as both ends of the new material are at the same temperature.



Electronic *TC* Compensation Methods (4)



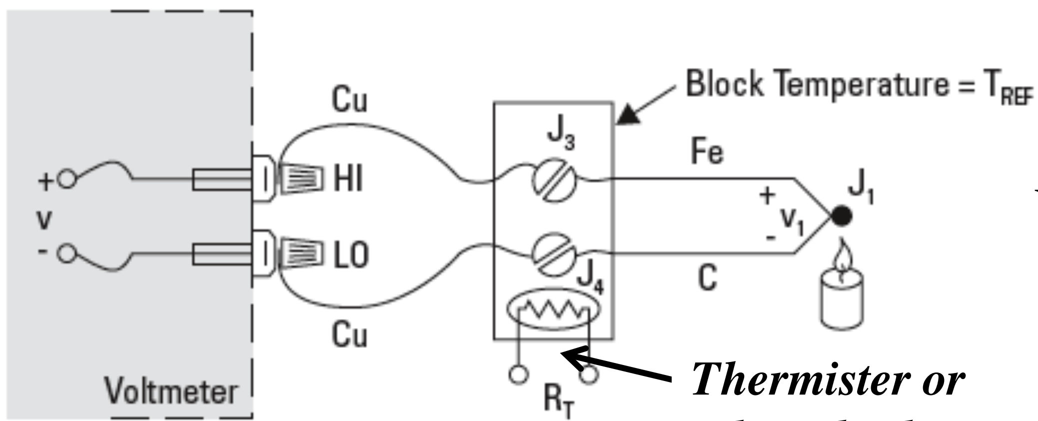
Electronic *TC* Compensation Methods (5)



• Temperature regulated Junctions J_3 and J_4 take place of the "ice bath".

• Together two junctions now become ***reference junction***.

Electronic *TC* Compensation Methods (6)



Thermister or other absolute reference sensor

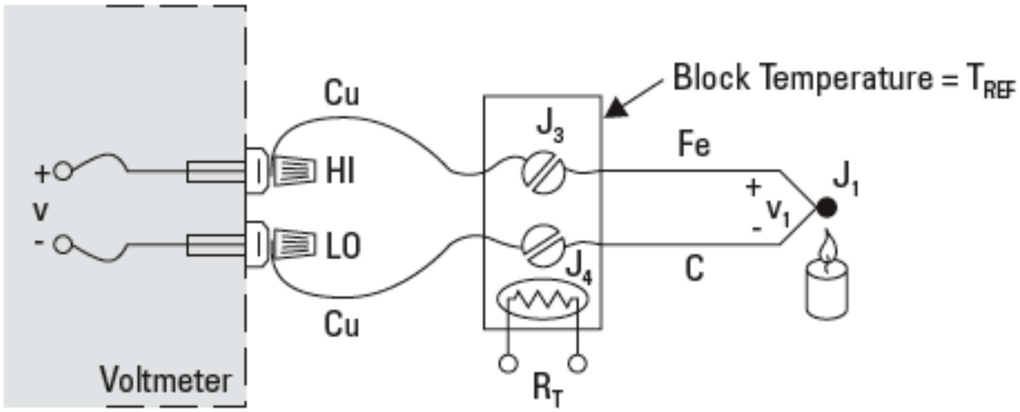
$$V_{meter} = \sum_{0}^{n} a_n \left[T_{J_1} - T_{Ref}\right]^n$$

$$V_{eq}(T_{Ref}) = \sum_{0}^{n} a_n \left(T_{Ref}\right)^n$$

- 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}

…. Ice point is used by National Institute of Standards and Technology (NIST) as fundamental reference point for thermocouple tables … if reference Temperature is other than zero deg C .. We Must add in "equivalent voltage"

Electronic *TC* Compensation Methods (7)



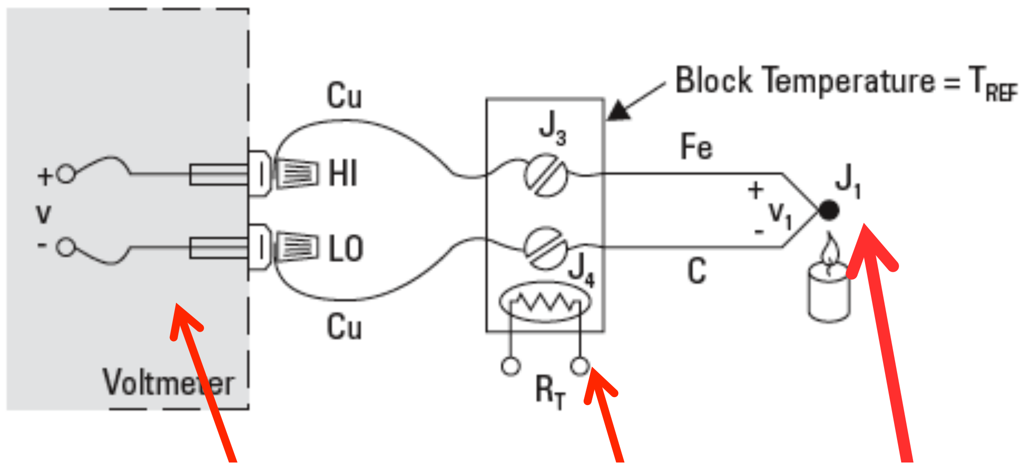
• Thermistor resistance function of temperature *(more later)*, …. provides way to measure absolute temperature of reference junction.

1. Measure T_{REF} and convert T_{REF} to its equivalent
2. reference junction voltage, V_{REF}

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

.

Electronic *TC* Compensation Methods (8)



Temperature °F (°C)	Iron vs. Constantan (J)
−300 (−184.4)	−7.519
−200 (−128.9)	−5.760
−100 (−73.7)	−3.492
0 (−17.8)	−0.885
100 (37.8)	1.942
200 (93.3)	4.906
300 (148.9)	7.947
400 (204.4)	11.023
500 (260.0)	14.108
700 (371.1)	20.253
1000 (537.8)	29.515

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

- ***Referred to as "Software compensation"***

Thermocouple Calibration Data (1)

- Stored as polynomial fit coefficients ..

Table 16.6 B.M.L …. $V_{eq}(T_{Ref}) = \sum_{0}^{n} a_n \left(T_{Ref}\right)^n$ ***Given reference junction Temperature, compute Equivalent EMF***

Table 16,7 B.M.L ….

$$T(J_1) = \sum_{0}^{n} b_n \left(V_{meter} + V_{eq}\right)^n$$

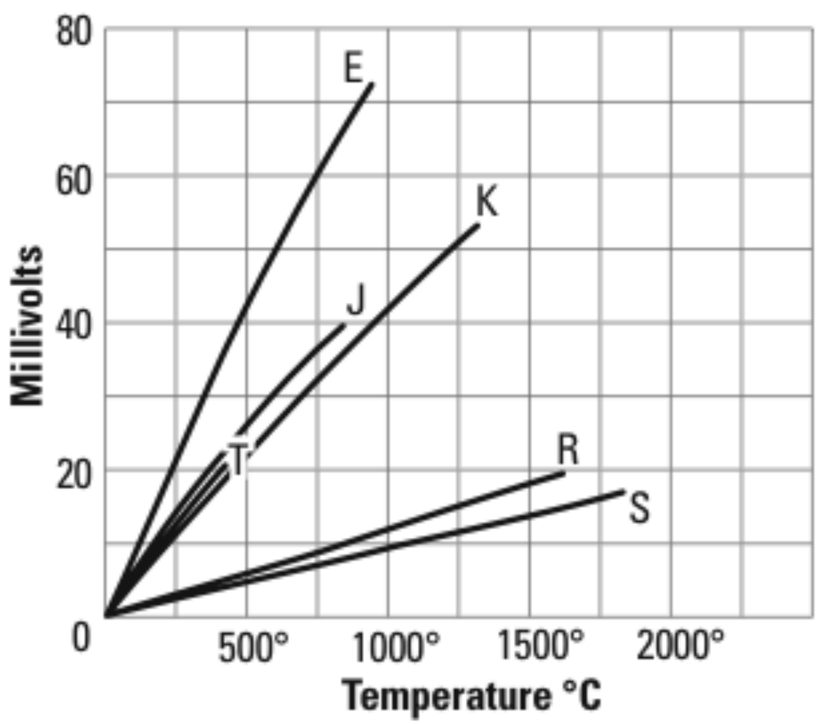
Given Sensed Voltage +equivalent reference Voltage Compute Temperature

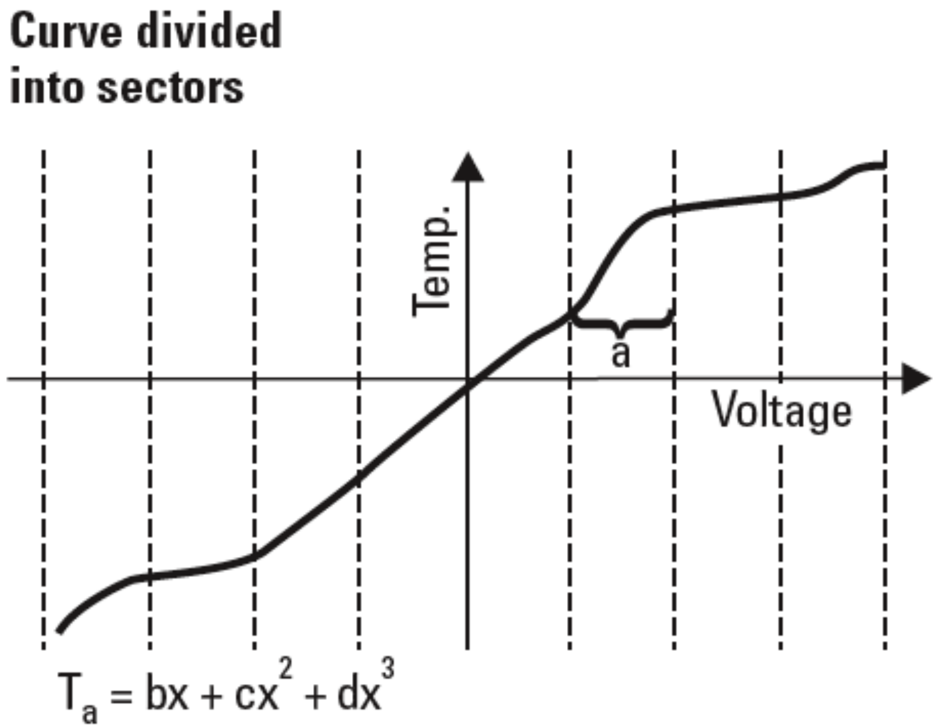
- National Institute of Standards and Technology, (U.S. Commerce Department)

- NIST reference functions and tables of thermocouple ***emf*** versus temperature adopted as standards by the American Society for Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC).

Thermocouple Calibration Data (2)

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





NIST Type-J Thermocouple Calibration Data (1)

****

- 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*

$$V_{eq}(T_{Ref}) = \sum_{0}^{n} a_n \left(T_{Ref}\right)^n$$

"Reference 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 (2)

****

- 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

"Sensed Voltage to Temperature"

$$T(J_1) = \sum_{0}^{n} b_n \left(V_{meter} + V_{eq}\right)^n$$

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

UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Example (1)

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 $V_{eq}(T_{Ref}) = \sum_{0}^{n} a_n \left(T_{Ref}\right)^n$ for reference junction

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

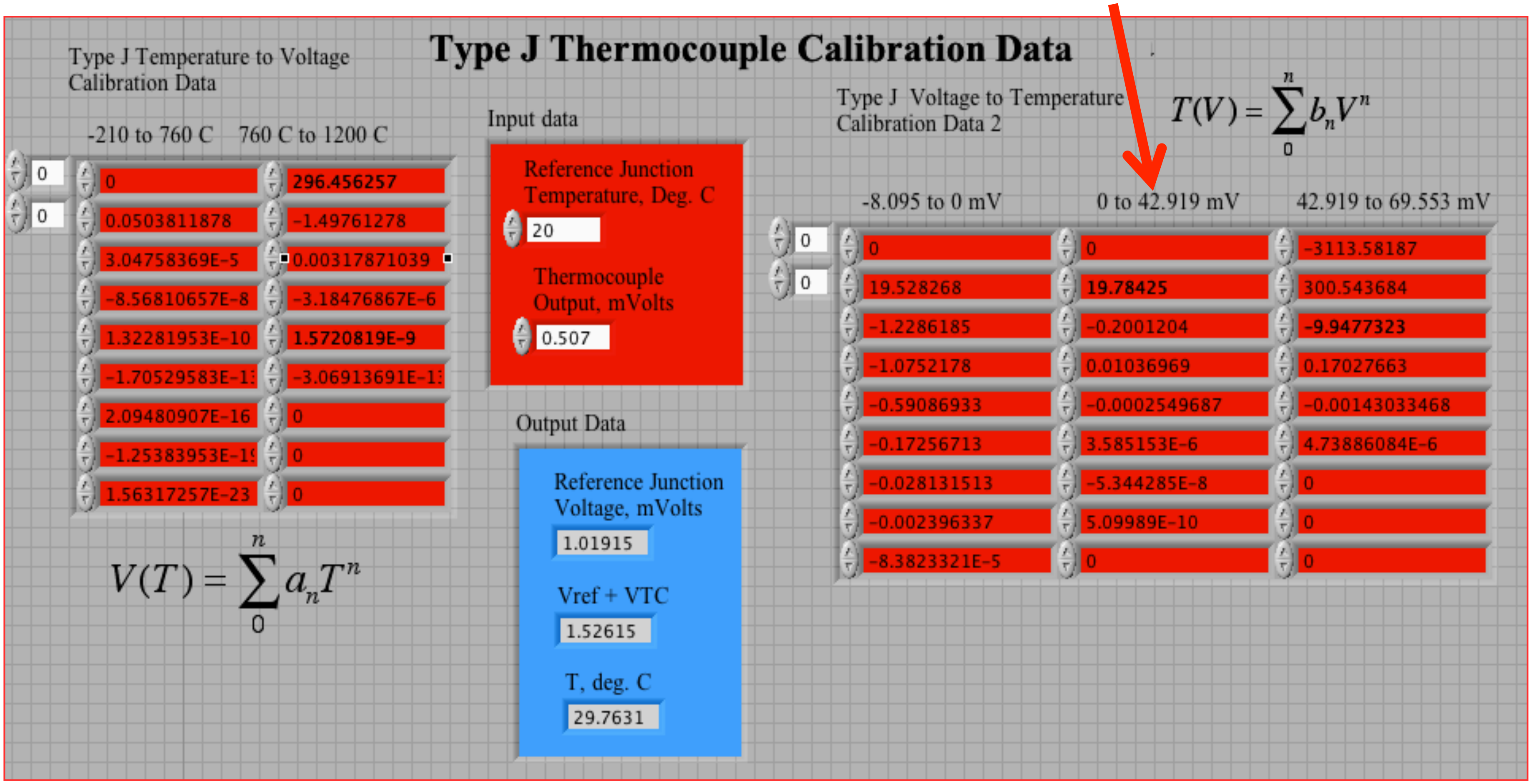
0.000000000000E+00
0.503811878150E-01
0.304758369300E-04
-0.856810657200E-07
0.132281952950E-09
-0.170529583370E-12
0.209480906970E-15
-0.125383953360E-18
0.156317256970E-22

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

Example (2)

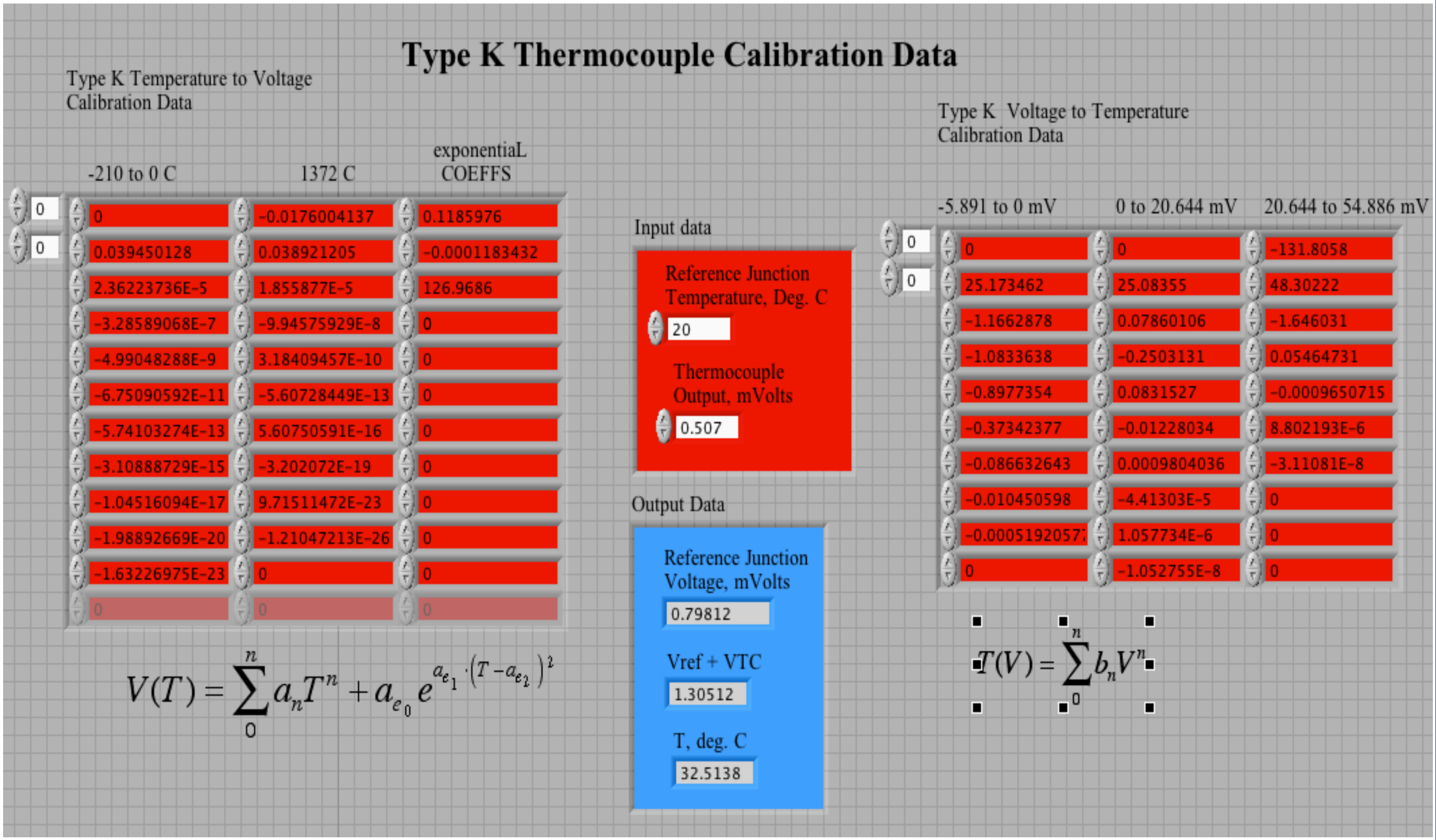
So our voltage relative to 0°C is the measured voltage plus the 20° value: 1.01915 + 0.507 = 1.52615.

Going back to the table, this corresponds to 29.7631°C.



Example (3)

Same Sensed Inputs … but now use Type K calibration



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):

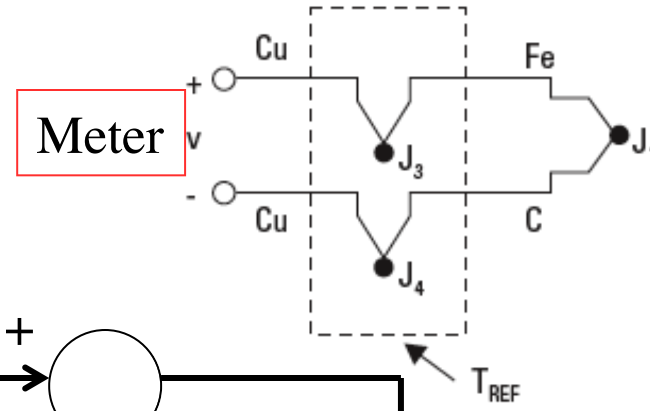
All Thermocouple Types in ASCII or text format (NIST WEB file) (131K)
Type B Thermocouple(19K)
Type E Thermocouple(14K)
Type J Thermocouple(16K)
Type K Thermocouple(18K)
Type N Thermocouple(17K)
Type R Thermocouple(20K)
Type S Thermocouple(20K)
Type T Thermocouple(9K)

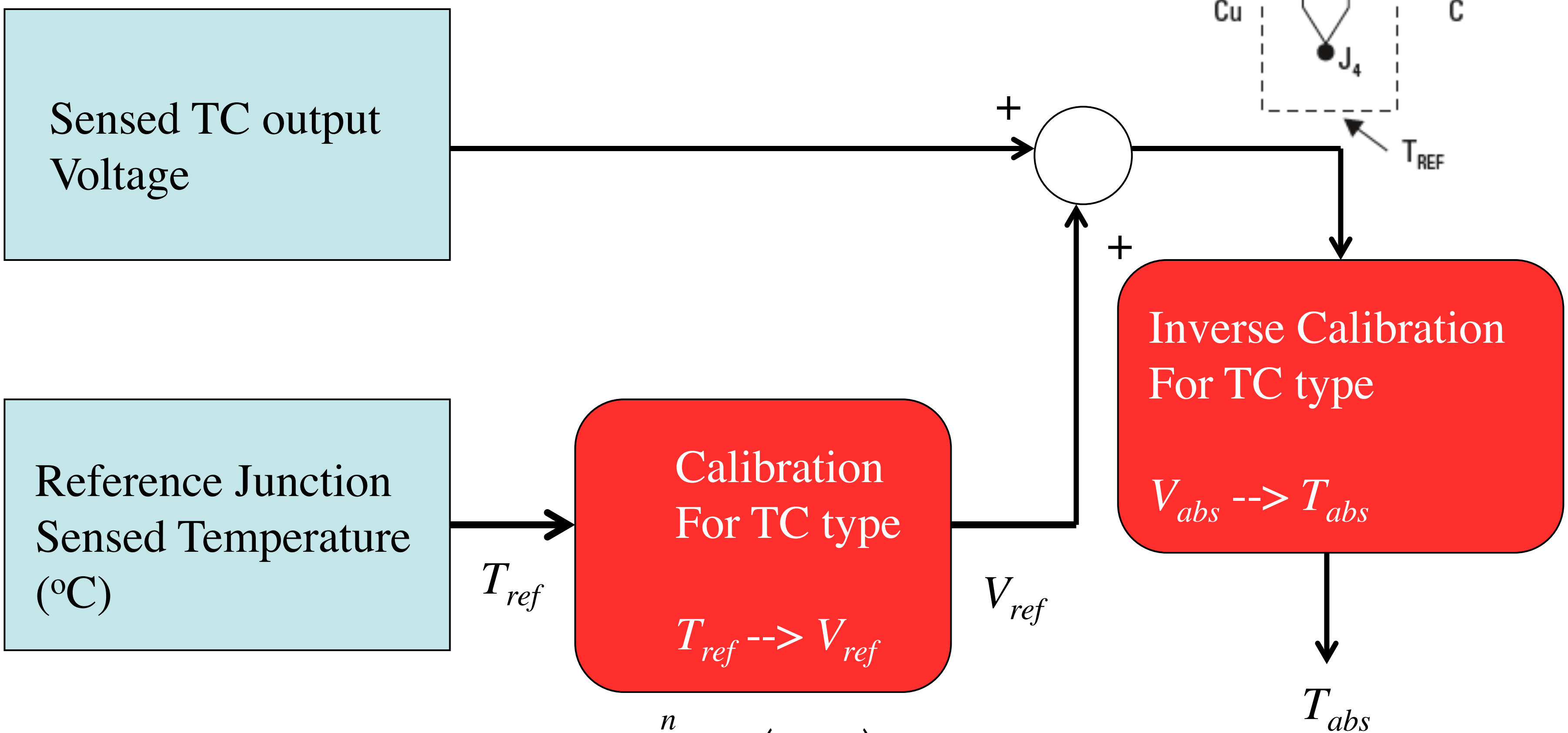
- Calibration VI's for Type J, Type K, Type T … TC's built and linked on MAE3340 *Section 10* web page

Generalized Procedure (1)

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 $V_{J1} = V_{meter} + V_{ref}$.
5) Find the temperature that corresponds to V_{J1} from tables or a polynomial.
6) … Be sure to use the table data that corresponds to your TC type

Generalized Procedure (2)





$$V_{eq}(T_{Ref}) = \sum_{0}^{n} a_n \left(T_{Ref}\right)^n$$

$$T(J_1) = \sum_{0}^{n} b_n \left(V_{meter} + V_{eq}\right)^n$$

Required *TC* Measurement Sensitivities

Required DVM sensitivity

Thermocouple Type	SeebeckCoefficient at 25° C (μV/°C)	DVM Sensitivity for 0.1° C (μV)
E	61	6.1
J	52	5.2
K	40	4.0
R	6	0.6
S	6	0.6
T	41	4.1

- Thermocouple output voltages are small.
- Even for common type K thermocouple, voltmeter must resolve 4 μV to detect a 0.1° C change.
- Demands both excellent resolution *(more bits, more better)* and measurement accuracy from acquisition system.

Why Bother Even Using TC's? (1)

• Since the thermistor can directly sense absolute, even bother with thermocouple and reference junction compensation?

• Single most important answer is that the thermistor, RTD, or integrated circuit transducer are only useful over only limited temperature range.

•Thermocouples can be used over a *very wide* range of temperatures

• More rugged than thermistors, (TC's are often welded to a metal part or clamped under a screw.

• Easily manufactured on the spot, either by soldering or welding.

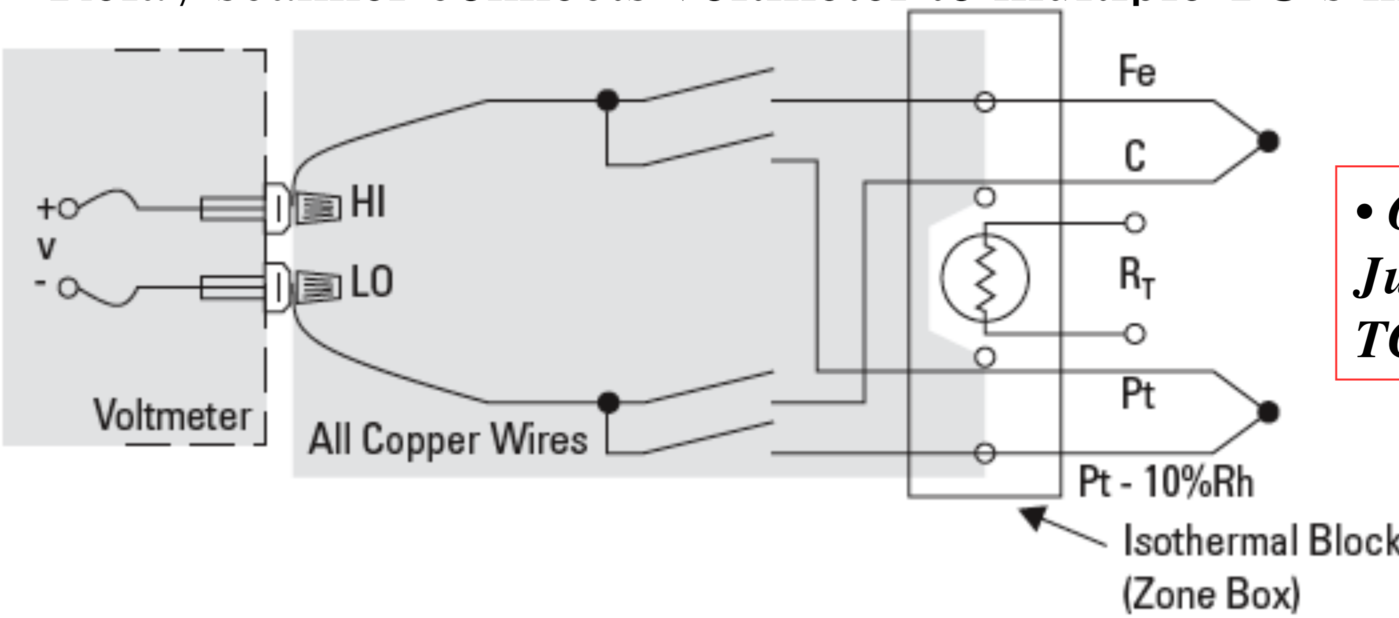
• TC's are the most versatile temperature transducers available

Why Bother Even Using TC's? (2)

• Thermocouple measurement are especially convenient when required to monitor a large number of locations points.

• Accomplished using reference junction for more than one TC.

• Relay scanner connects voltmeter to multiple TC's in sequence.

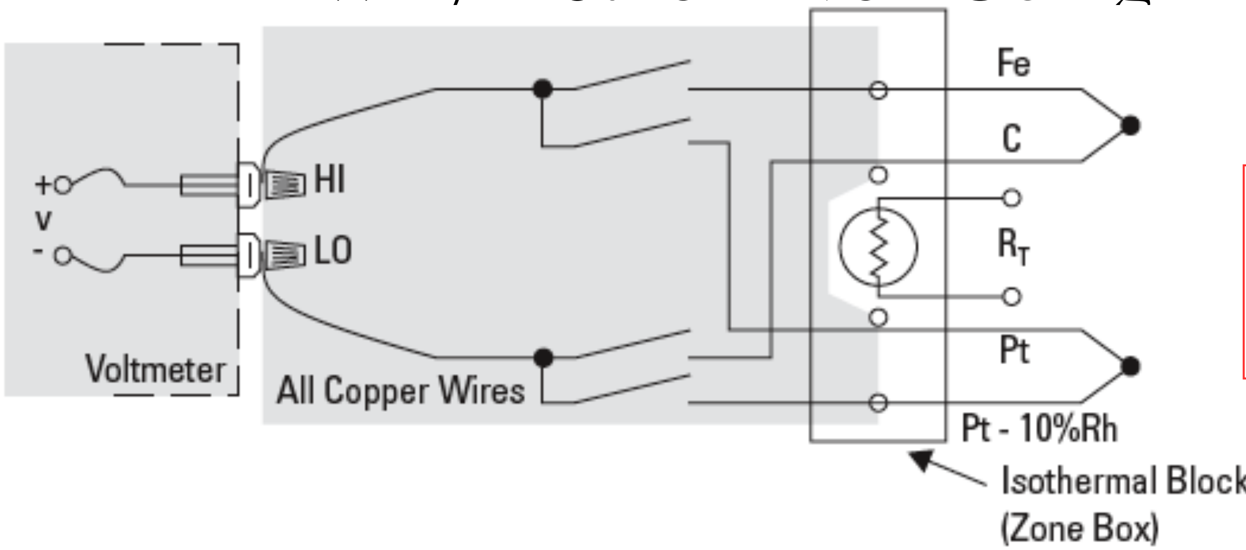


• One reference Junction for many TC's

UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Why Bother Even Using TC's? (3)



• ***One reference Junction for many TC's***

• Many TC's are connected on same block, copper leads are used throughout, and technique is independent of types of TC' chosen.

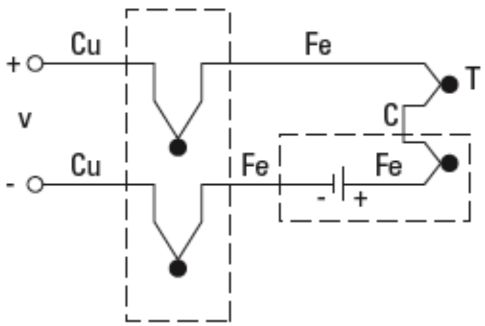
• When using a data acquisition system with a built-in zone box, simply connect TC as if a pair of test leads.

• All conversions are performed by instrument's software.

Hardware TC Compensation (1)

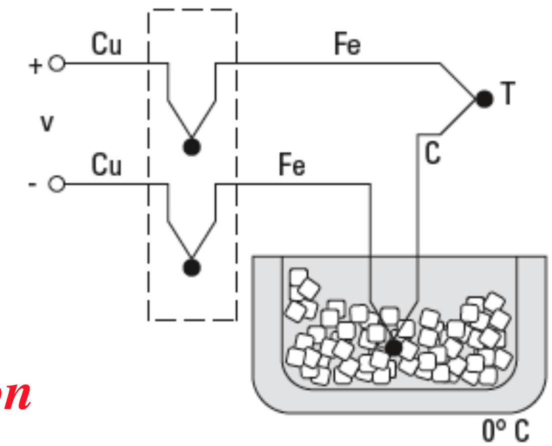
- Rather than measure temperature of reference junction and computing equivalent voltage, insert battery or other source to cancel offset voltage of reference junction.

- Combination of hardware compensation voltage and reference junction voltage equivalent to a 0°C junction



Hardware Compensation

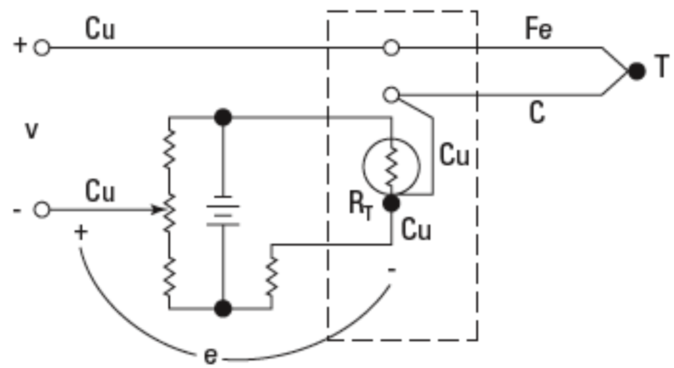
=



Ice bath

=

Software Compensation

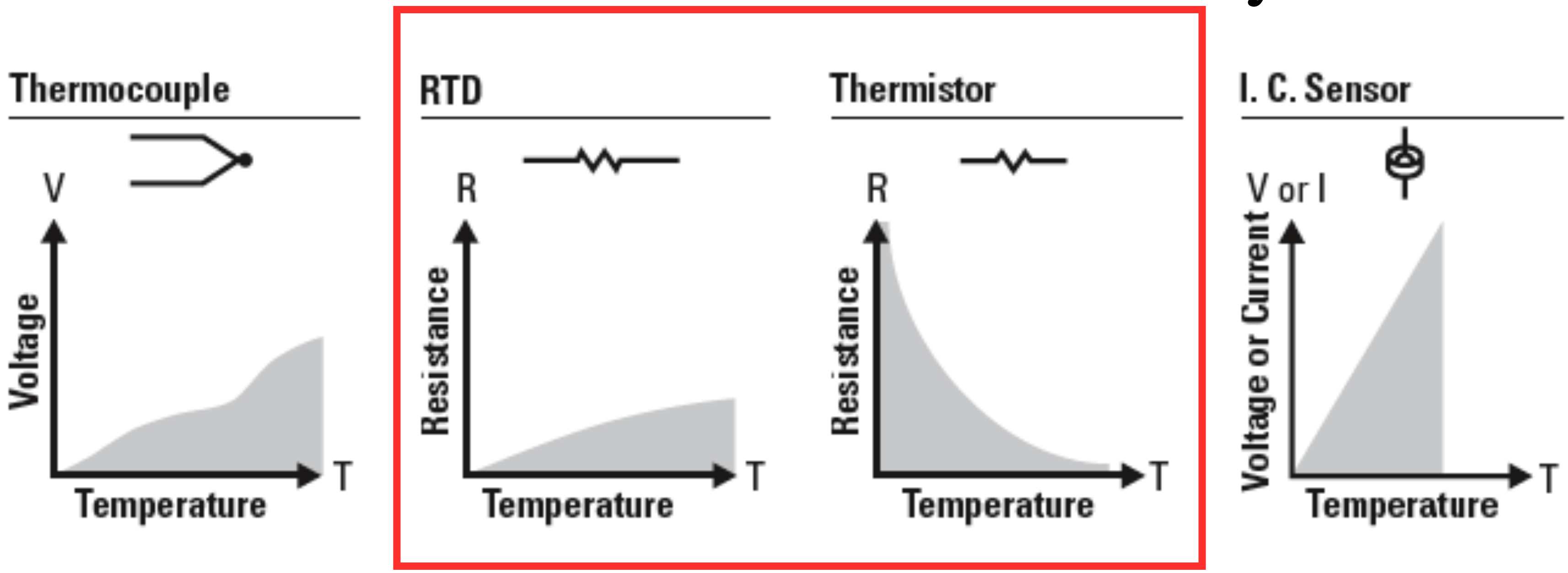


Hardware TC Compensation (2)

Hardware Compensation	Software Compensation
• Fast	• Requires more software manipulation time
• Restricted to one themocouple type per reference junction	• Versatile – accepts any thermocouple
• Hard to reconfigure – requires hardware change for new thermocouple type	• Easy to reconfigure

- No reference junction required

Electrical Resistance Thermometry



$$R = \frac{\rho_e l}{A_c}$$

The resistivity of most materials is temperature dependent, and we can use this fact to sense temperature

Resistance Temperature Detectors (1)

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

Davy

Siemens

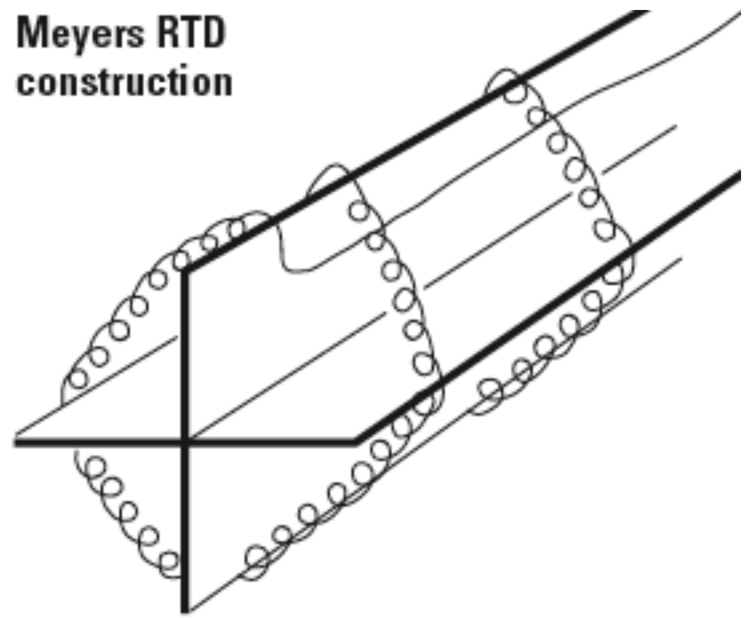
• Fifty years later, William Siemens proffered use of platinum as element in a resistance thermometer.

• 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 (2)

- 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. Meyers in 1932.12
- Helical coil of platinum wound on a crossed mica web and mounted inside a glass tube.
- Minimized strain on the wire while maximizing resistance

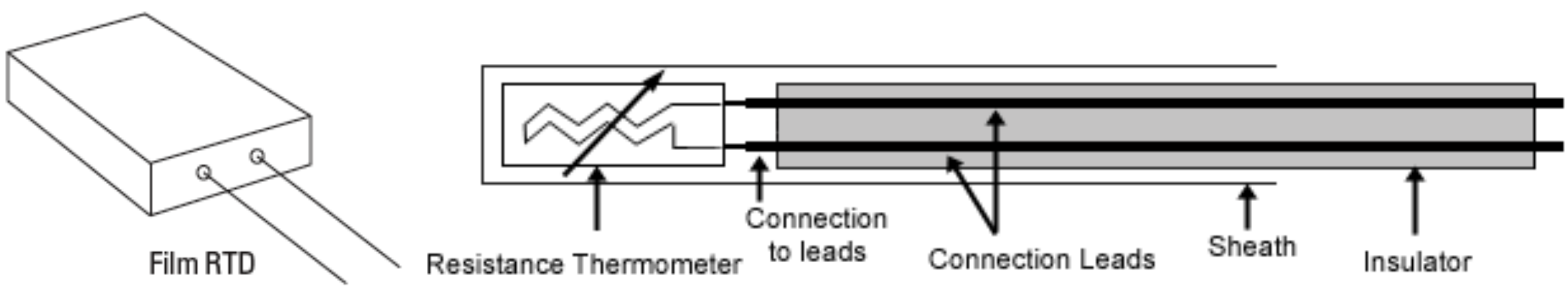


RTD (3)

• Modern RTD's use a platinum or metal-glass slurry film deposited onto a small flat ceramic substrate.

• Substrate is etched with a laser trimming system, and sealed.

• 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.

RTD (4)

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:

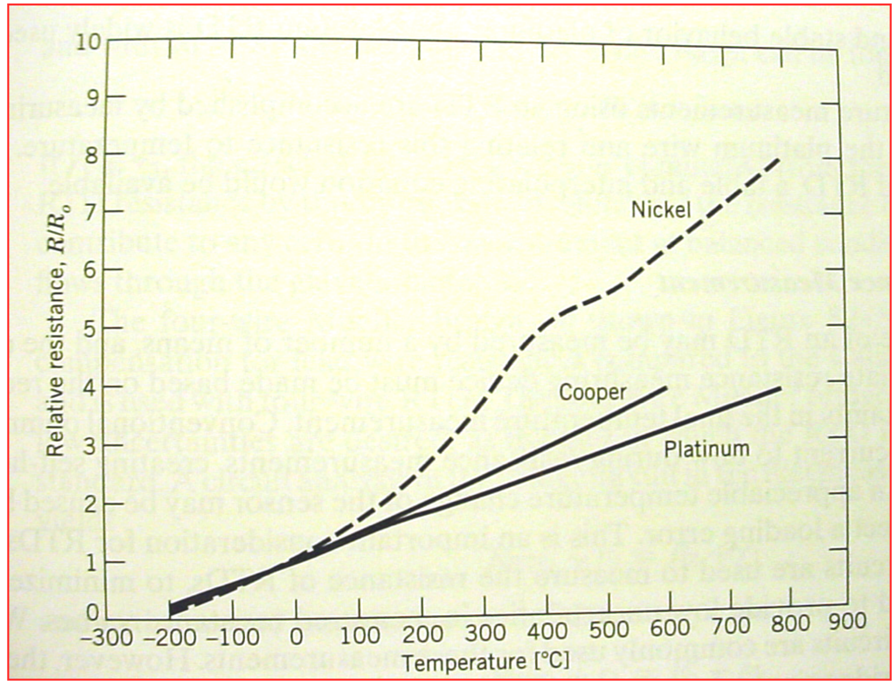
R_T = resistance at temperature T

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



Type of Element	Case Material	Temperature Range °C (°F)	Resistance, Ω	Temperature coefficient, A, Ω/(Ω°C) (approx.)	Limits of* Error, °C	Response,† s
Platinum (Laboratory)	Pyrex Glass	−190 to 540 (−310 to 1000)	25 at 0°C	0.0039	±0.01	
Platinum (Industrial)	Stainless Steel	−200 to 125 (−325 to 260)‡ −18 to 540 (0 to 1000)§	25 at 0°C 25 at 0°C	0.0039	±1 ±2	10 to 30 10 to 30
Platinum (Film)	Ceramic Coating	−50 to 600 (−60 to 1100)	1000 at 0°C	0.0039	±0.25	~1
Rhodium-Iron	Alumina and Glass	−272 to 200 (−458 to 390)	27 at 0°C	0.0037	±0.04	
Copper	Brass	−75 to 120 (−100 to 250)	10 at 25°C	0.0038	±0.5	20 to 60
Nickel	Brass	0 to 120 (32 to 250)	100 at 20°C	0.0067	±0.3	20 to 60

RTD Materials

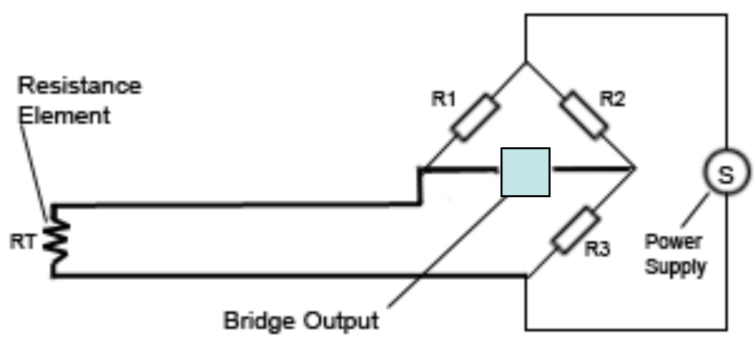
- Most common RTD's are made of platinum, nickel, or nickel alloys.
- Nickel derivative wires are cheap and used over limited temperature range. Non-linear and drift with time.
- Best Measurements, platinum is clearly best.

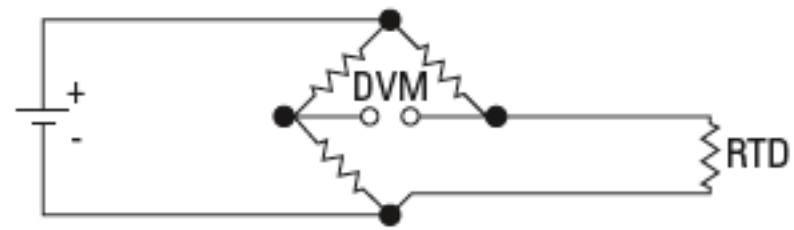
Metal		Resistivity Ω/CMF (cmf = circular mil foot)
Gold	Au	13.00
Silver	Ag	8.8
Copper	Cu	9.26
Platinum	Pt	59.00
Tungsten	W	30.00
Nickel	Ni	36.00

2-WIRE RTD Bridge Circuit

- The simplest RTD configuration uses two wires.

- Use only when very accurate absolute temperature
is not required



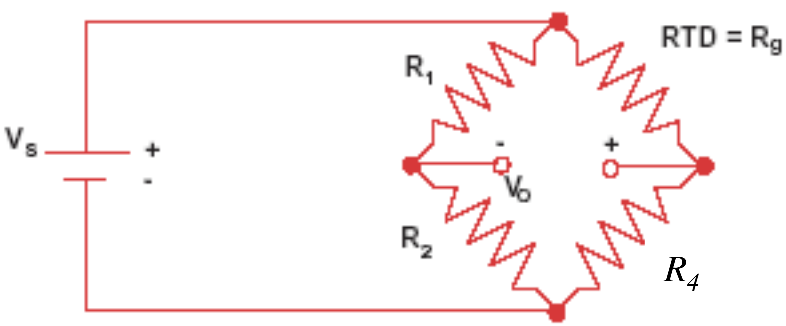


- Wheatstone bridge is used to sense Resistance and then temperature Calibration is applied

$$R = R_0 \begin{bmatrix} 1 + A\left(T - T_0\right) + \\ B\left(T - T_0\right)^2 + ... \end{bmatrix}$$

2-WIRE RTD Bridge Circuit (2)

- Assume no lead wire resistance and $R_1 = R_2$



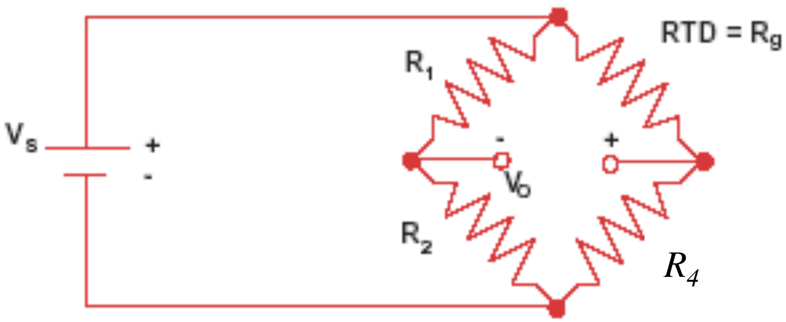
$$V_0 = V_{ex}\frac{R_1 \cdot R_4 - R_1 \cdot R_{RTD}}{(R_1 + R_1)\cdot(R_{RTD} + R_4)} = \frac{V_{ex}}{2}\cdot\left(\frac{R_4 - R_{RTD}}{R_4 + R_{RTD}}\right) =$$

$$\frac{V_{ex}}{2}\cdot\left(\frac{R_4}{R_4 + R_{RTD}}\right) - \frac{V_{ex}}{2}\cdot\left(\frac{R_{RTD}}{R_4 + R_{RTD}}\right) = V_{ex}\cdot\left(\frac{R_4}{R_4 + R_{RTD}}\right) - \frac{V_{ex}}{2}\cdot\left(\frac{R_4 + R_{RTD}}{R_4 + R_{RTD}}\right) =$$

$$V_{ex}\cdot\left(\frac{R_4}{R_4 + R_{RTD}}\right) - \frac{V_{ex}}{2}$$

2-WIRE RTD Bridge Circuit (3)

- Solve for R_{RTD}



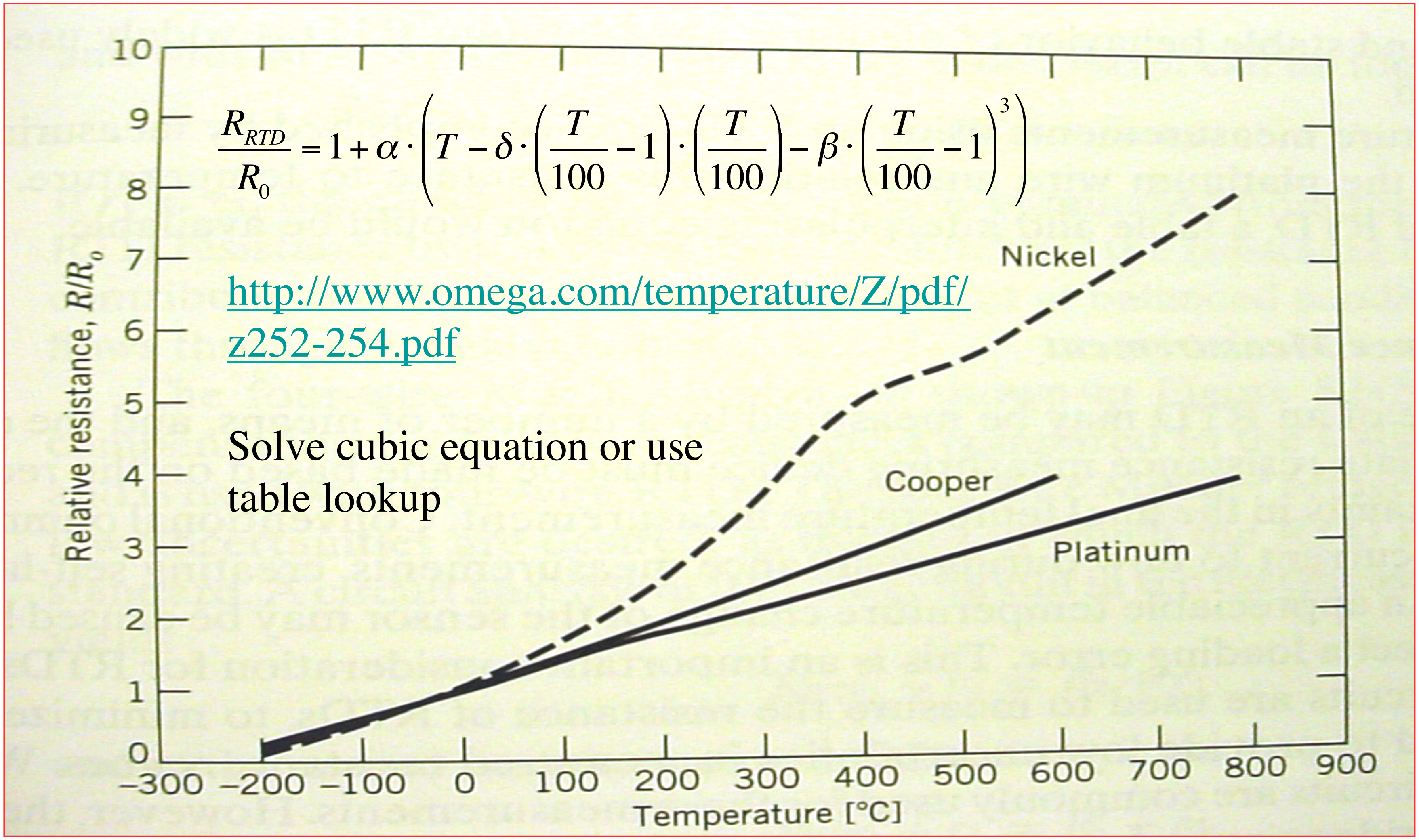
$$V_0 = V_{ex} \cdot \left(\frac{R_4}{R_4 + R_{RTD}} \right) - \frac{V_{ex}}{2} \rightarrow R_{RTD} = R_4 \cdot \left(\frac{V_{ex} - 2 \cdot V_0}{V_{ex} - 2 \cdot V_0} \right)$$

Use RTD Calibration to Solve for Temperature

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

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

Use RTD Calibration to Solve for Temperature



$$\frac{R_{RTD}}{R_0} = 1 + \alpha\cdot\left(T - \delta\cdot\left(\frac{T}{100} - 1\right)\cdot\left(\frac{T}{100}\right) - \beta\cdot\left(\frac{T}{100} - 1\right)^3\right)$$

http://www.omega.com/temperature/Z/pdf/z252-254.pdf

Solve cubic equation or use table lookup

RTD Lead Wire Compensation

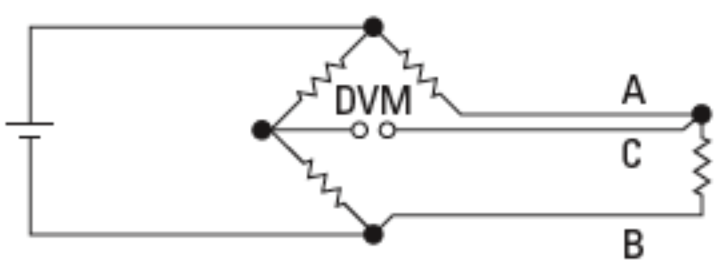
- For High Accuracy, need to have a very accurate resistance measurement system …

- *What if lead wire resistance is not zero?*

- Even copper lead wires have significant resistance.

- *Must* remove effect of the lead measurements.

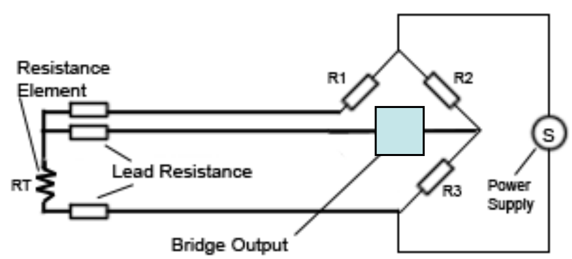
3-Wire Bridge



- To minimize effects of resistances a three wire configuration can be used.

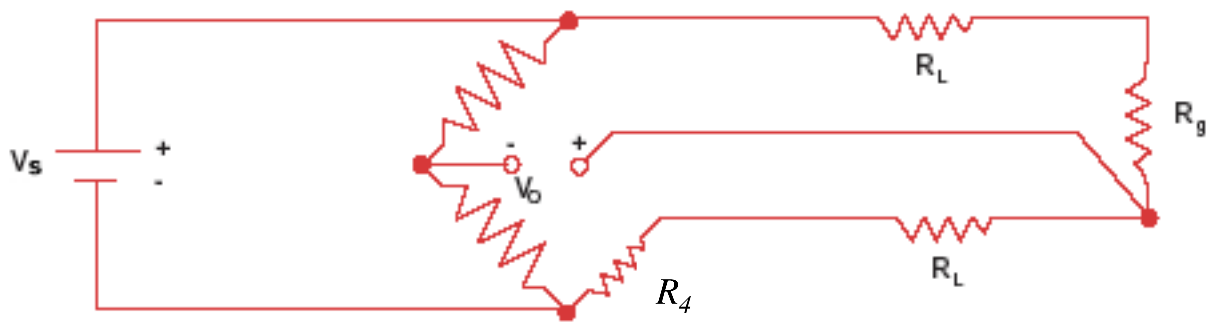
With method two leads to sensor are on adjoining arms, there is a lead resistance in each arm of bridge and lead resistance is cancelled out.

If wires A and B are closely matched in length, their impedance effects cancel because each is in an opposite leg of bridge. Third wire, C, acts as a sense lead and carries no current for high impedance meter.



RTD Lead Wire Compensation (2)

- Lead Wire Resistance → R_L

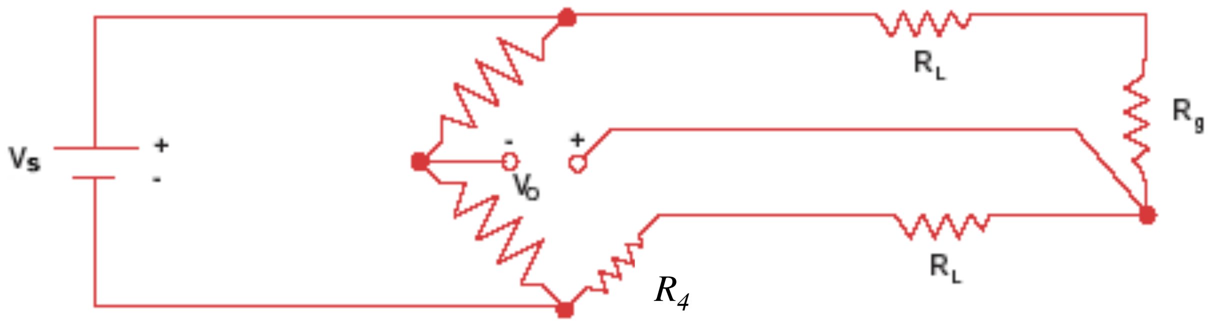


- *Equivalent Resistances …*

$$\left.\begin{aligned} R_4' &= R_4 + R_L \\ R_{RTD}' &= R_{RTD} + R_L \end{aligned}\right| \rightarrow V_0 = V_{ex}\,\frac{R_1\cdot\left(R_4+R_L\right)-R_1\cdot\left(R_{RTD}+R_L\right)}{\left(R_1+R_1\right)\cdot\left(R_{RTD}+R_4+2\cdot R_L\right)} =$$

$$\frac{V_{ex}}{2}\cdot\left(\frac{R_4-R_{RTD}}{\left(R_{RTD}+R_4\right)+2\cdot R_L}\right)$$ …. *slight reduction in bridge output*

RTD Lead Wire Compensation (2)



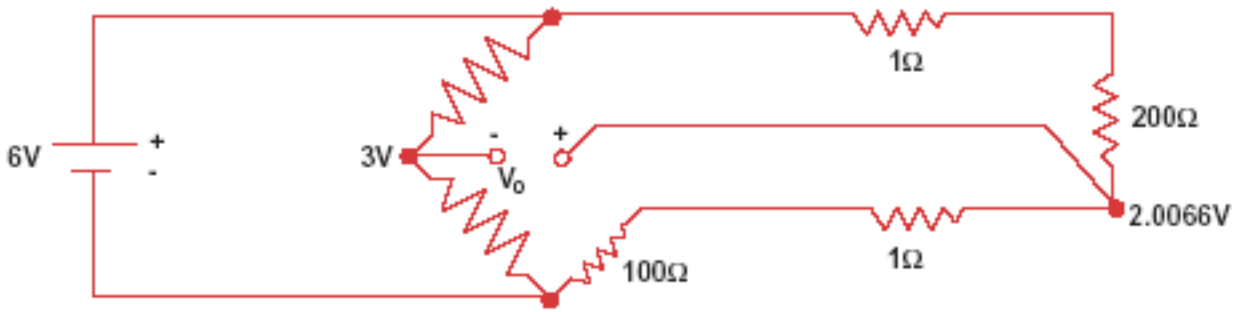
$$V_0 = \frac{V_{ex}}{2} \cdot \left(\frac{R_4 - R_{RTD}}{\left(R_{RTD} + R_4\right) + 2 \cdot R_L} \right)$$

- Solve for R_{RTD} …. *Wire resistance causes small bias in reading …*

$$R_{RTD} = R_4 \cdot \left(\frac{V_{ex} - 2 \cdot V_0}{V_{ex} + 2 \cdot V_0} \right) - R_L \cdot \left(\frac{4 \cdot V_0}{V_{ex} + 2 \cdot V_0} \right)$$

RTD Lead Wire Compensation (2)

Example calculation



Output Voltage … $V_0 = \frac{V_{ex}}{2} \cdot \left(\frac{R_4 - R_{RTD}}{(R_{RTD} + R_4) + 2 \cdot R_L} \right) = \frac{6}{2} \frac{(100 - 200)}{100 + 200 + 2 \cdot 1}$ = -0.993377 *Volts*

• *Assume Unknown wire resistance to calculate R_{RTD} …*

$$R_{RTD} = R_4 \cdot \left(\frac{V_{ex} - 2 \cdot V_0}{V_{ex} + 2 \cdot V_0} \right) = 100 \frac{(6 - 2(-0.993377))}{(6 + 2(-0.993377))}$$

= 199.01 *Ohms*

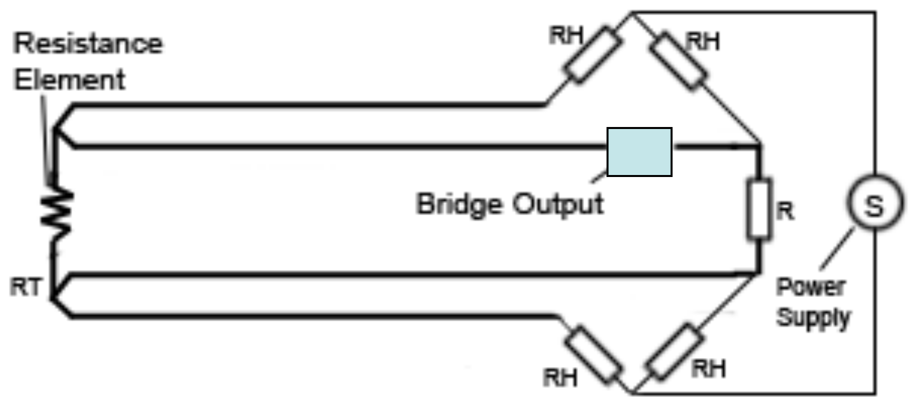
~ 0.5% error

For a Platinum RTD … this resistance error corresponds to a 2.5 deg. C temperature error

RTD Lead Wire Compensation (4)

• Four wire RTD configuration further increases accuracy

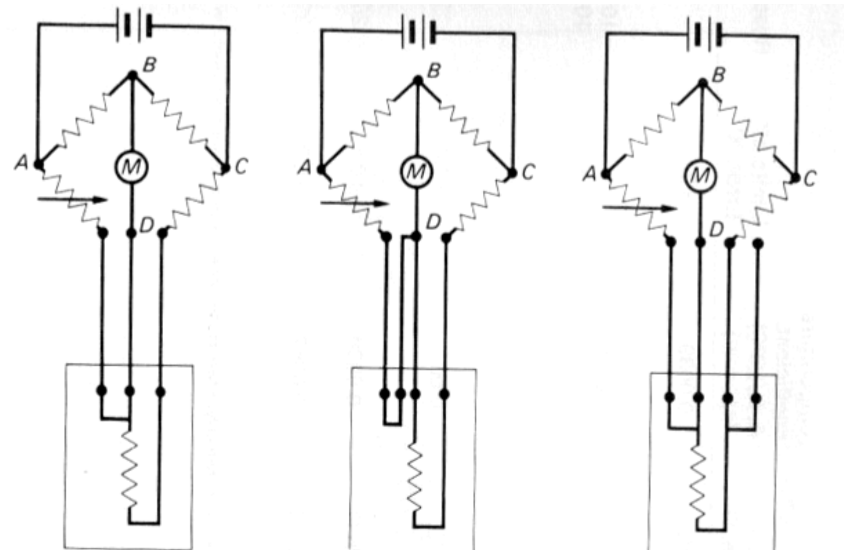
• Provides full cancellation of spurious effects and cable resistance of up to 15 Ω can be handled.

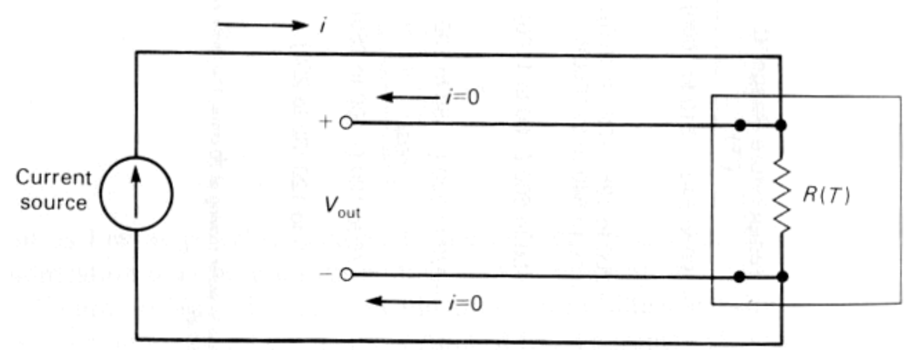


Not going to analyze this circuit .. But I think you can see the point!

RTD Lead Wire Examples

If we want the high accuracy of which RTD's are capable, we need to have a very accurate resistance measurement system *and* a means to remove the effect of the lead wires from our measurements. Even copper lead wires have significant resistance.





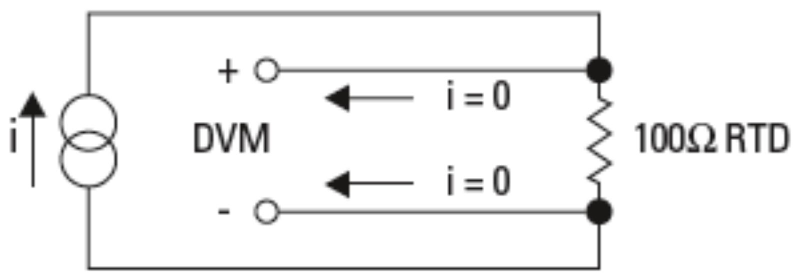
(d) Four-wire constant-current circuit

RTD Current Loop Circuit

• Technique of using a current source along with a remotely sensed digital voltmeter alleviates many problems associated with the bridge.

• Since no current flows through the voltage sense leads, there is no *V= I•R* drop in these leads and thus no lead resistance error in the measurement.

4-wire Current-loop RTD



• Disadvantage of using 4-wire RTD is that we need one more Extension wire than the 3-wire bridge And acurrent source

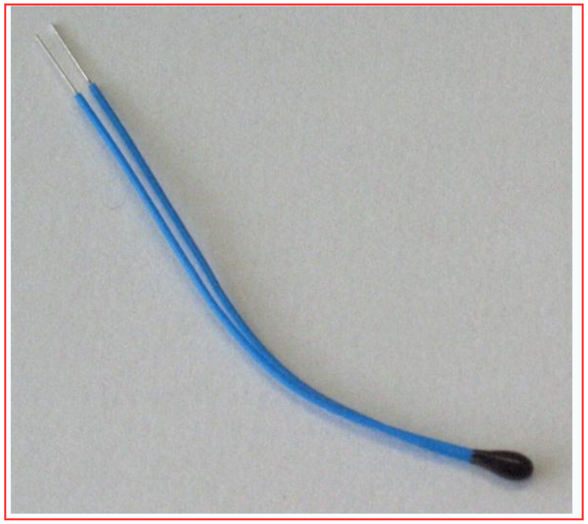
• Output voltage read by the DVM is directly proportional to RTD resistance, so only one conversion equation is necessary.

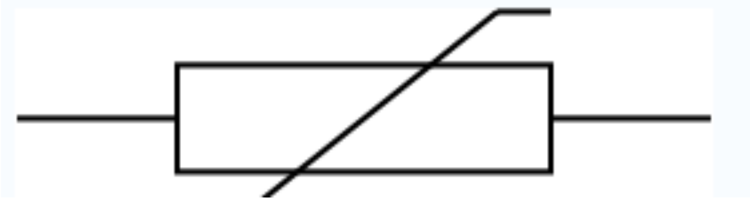
• Three bridge-completion resistors are replaced by one reference resistor. DVM measures only voltage dropped across RTD and is insensitive to length of lead wires

Thermistors (1)

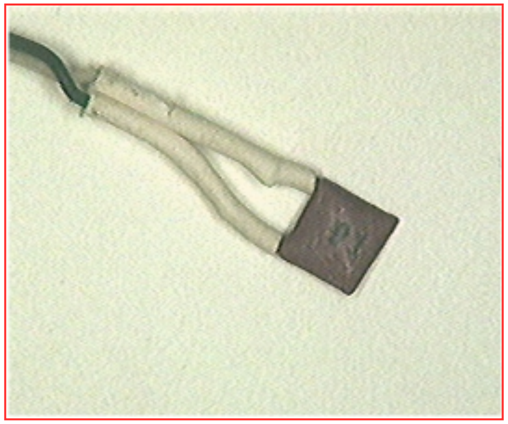
- A **thermistor** is a type of resistor used to measure temperature changes, relying on the change in its resistance with changing temperature.

- Thermistor is a combination of the words thermal and resistor.





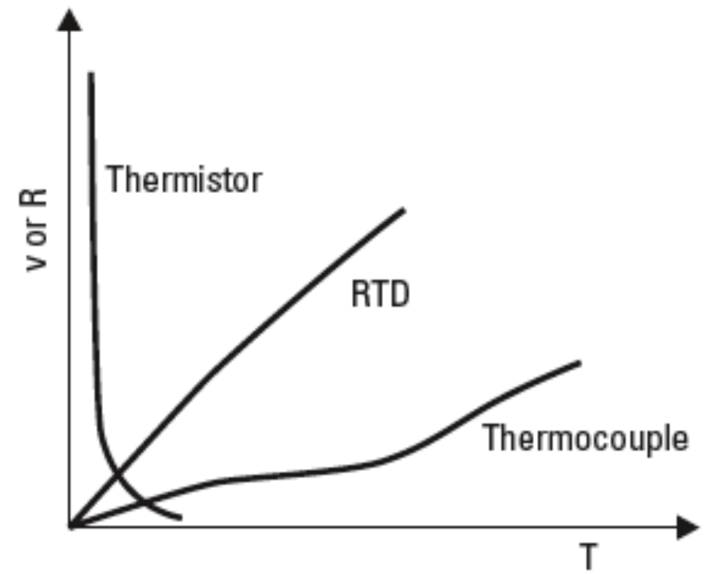
Thermistor Symbol



Thermistors (2)

Usually made of a semiconductor and have the following properties:

- Much larger *dR/dT* than RTD's
- Rugged
- Fast Response
- Inconsistent, must be calibrated individually
- Can change over time



- Like RTD, thermistor is also a temperature-sensitive resistor.

--- thermocouple is the most versatile temperature transducer
--- PRTD is most stable,
--- Thermistor is most sensitive.

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

Thermistors (3)

- The Steinhart-Hart equation is a widely used third-order approximation:

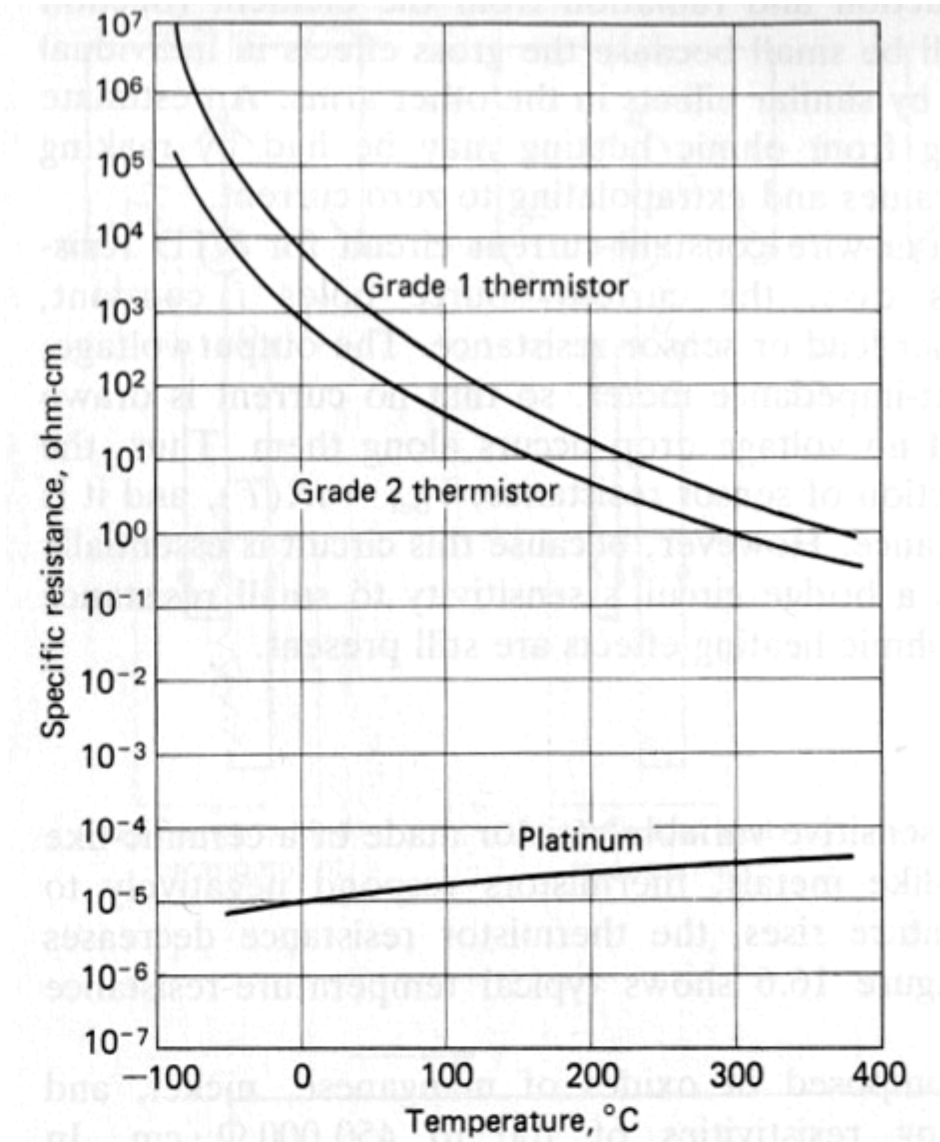
$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \ln\left(\frac{R}{R_0}\right)$$

In terms of Temperature

$$R = R_0 e^{\beta\left(1/T - 1/T_0\right)}$$

$\{R_0, T_0\}$-->known calibration pair
$\beta \rightarrow$ calibration "slope"

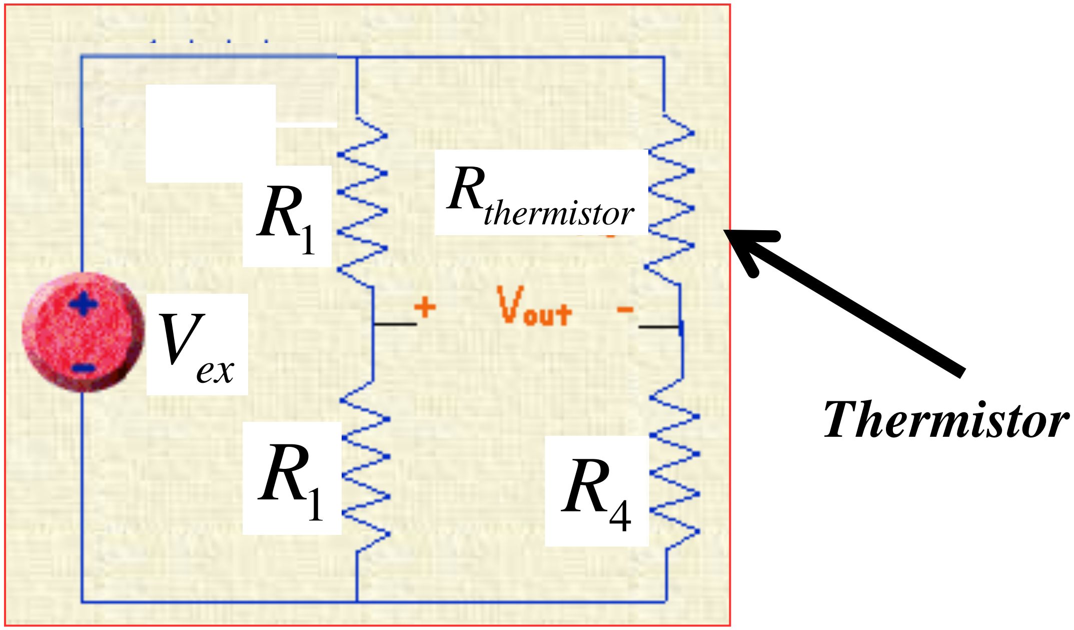
T's in absolute Units ~ Deg. R, K



Thermistors (4)

- Like RTD's, Thermistors are most commonly used in bridge circuits

T (°C)	R(Ω)
0	16,330
25	5000
50	1801

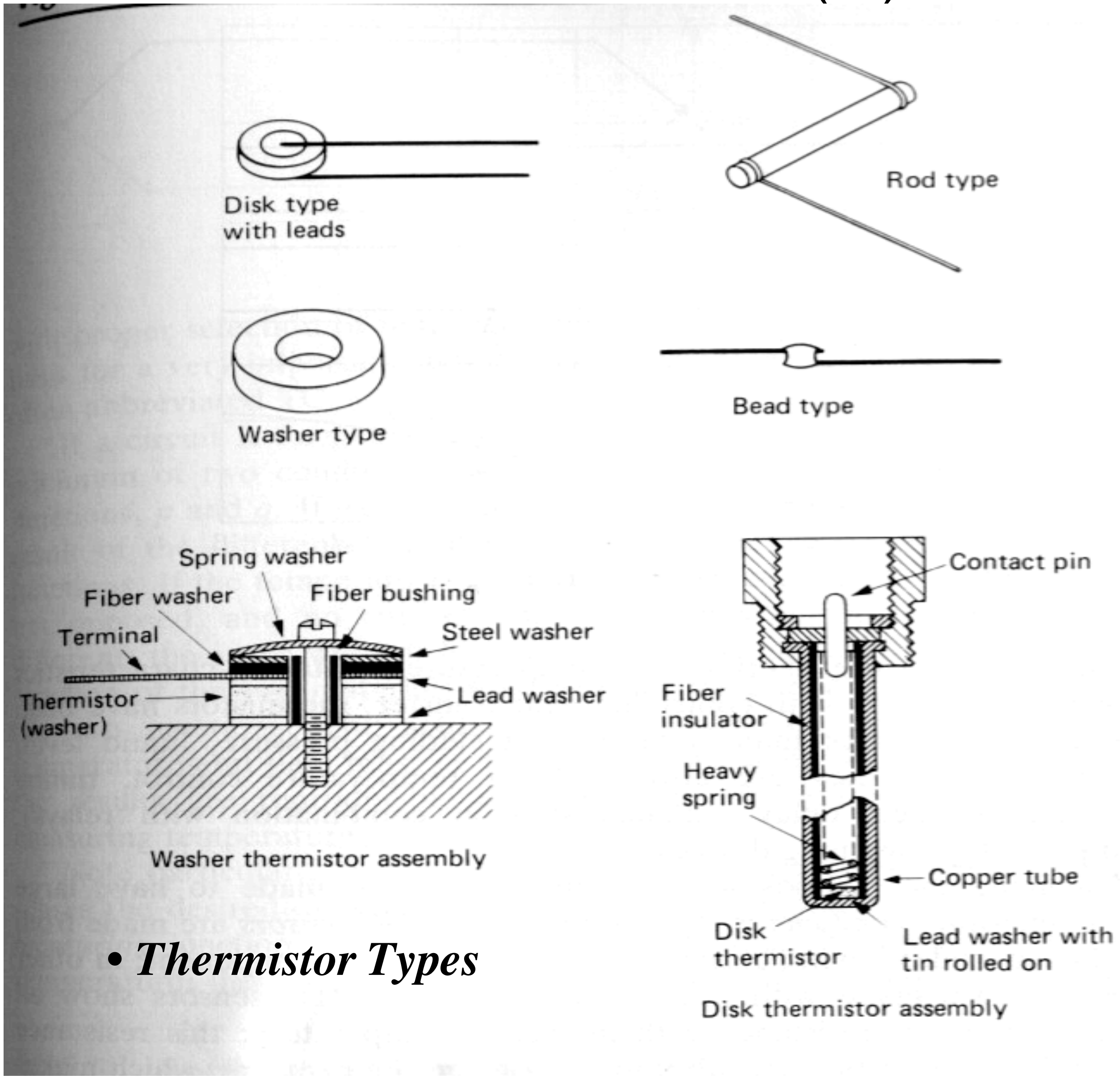


- Large changes in Resistance produce large Output voltages

Similar Problems to RTDs as regards lead Wire Effects on reading

$$R_{Thermistor} = R_4 \cdot \left(\frac{V_{ex} - 2 \cdot V_0}{V_{ex} + 2 \cdot V_0} \right) - R_L \cdot \left(\frac{4 \cdot V_0}{V_{ex} + 2 \cdot V_0} \right)$$

Thermistors (5)



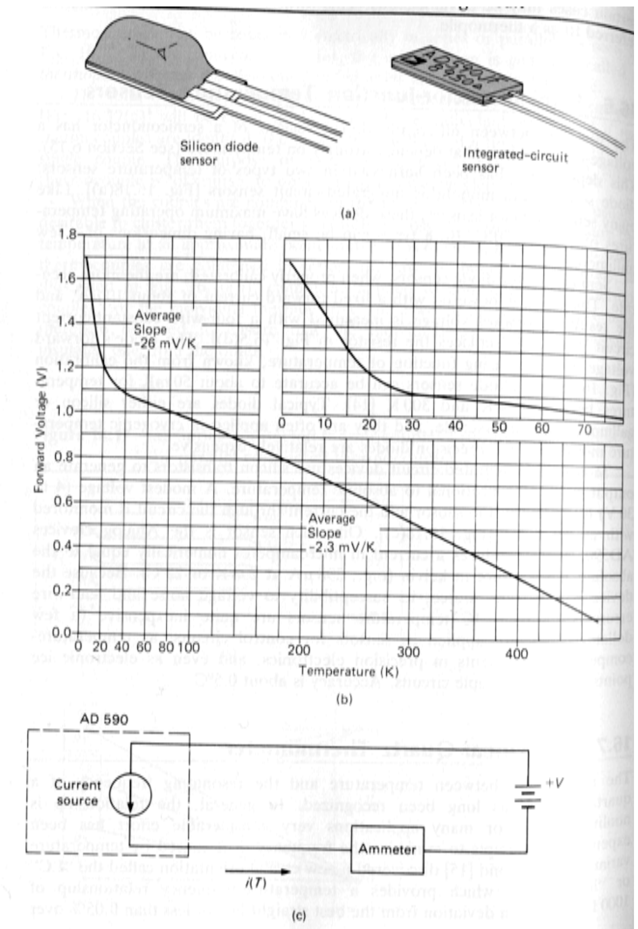
- ***Thermistor Types***

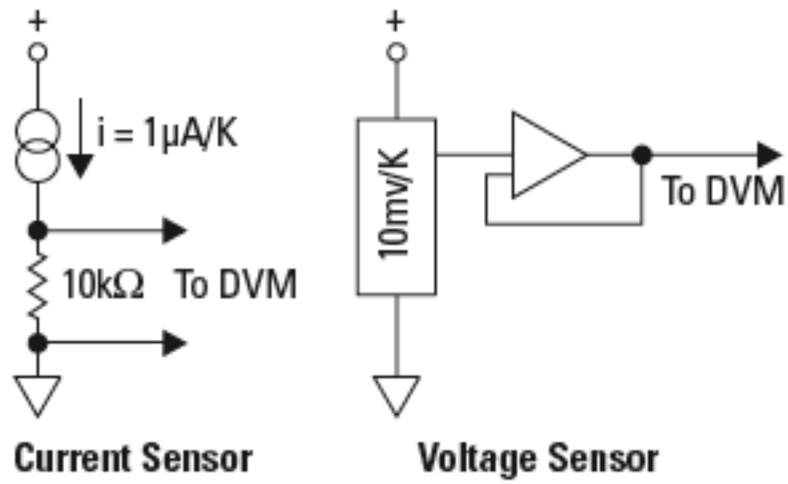
Thermistors (6)

Type (see Fig. 16.7)	Resistance At 0°C	Resistance At 25°C	Resistance At 50°C	Approximate Maximum Continuous Temperature, °C
Bead	165 kΩ	60 kΩ	25 kΩ	—
Glass-coated bead	8.8 kΩ	3.1 kΩ	1.3 kΩ	300
Washer	28.3 Ω	10 Ω	4.1 Ω	150
Washer	3270 Ω	1000 Ω	360 Ω	150
Rod	103 kΩ	31.5 kΩ	11.3 kΩ	150
Rod	327 kΩ	100 kΩ	36 kΩ	150
Disk	283 Ω	100 Ω	40.7 Ω	125

- ***Thermistor Calibrations***

Semiconductor-Junction Temperature Sensors





Temperature Sensor Comparisons (Revisited)

	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

Due Last Week of Cass at Your Lab Session, April 21-25, 2014.

UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Homework 8: Part 1a

Look at the following results for a Thermistor calibration

Temperature, °F	Resistance, kΩ
82	3.16
80	3.23
72.5	3.89
65	4.47
61	4.76
58	5.31
54	5.77
50.5	6.37
47.5	6.80

CALIBRATED TEMPERATURE-RESISTANCE PAIR For Thermistor

$T_0 = 20\ ^oC$

$R_0 = 4.24\ k\Omega$

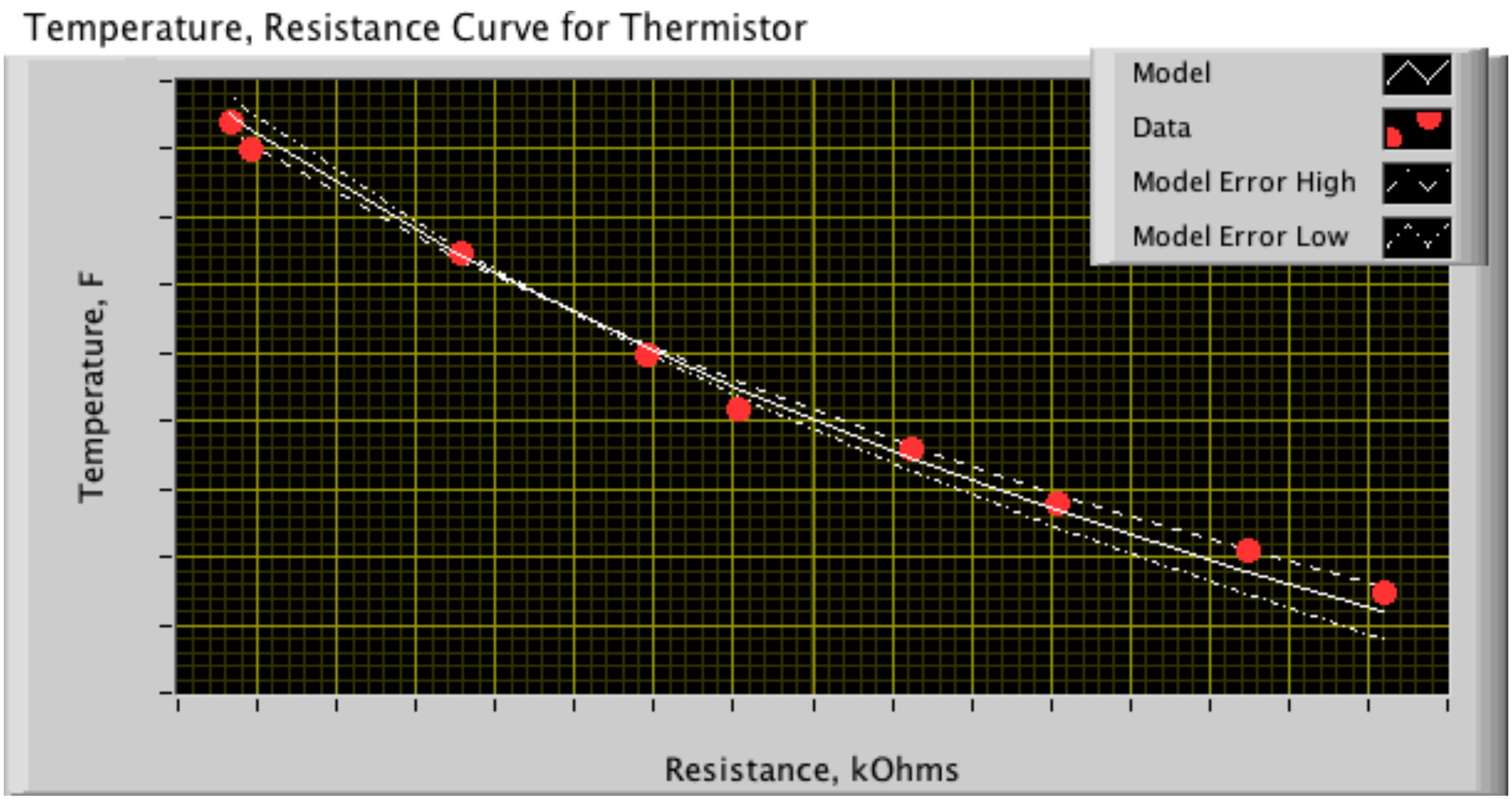
• Using the Steinhart-Hart equation, calculate the mean value for "β" and assess the confidence interval for this mean estimate at the 95% confidence level. (assume student-t distribution). ***Be careful about your units for temperature! Use Absolute Units***

• Compare your model based on your average β against calibration data by Plotting T *vs*. R curve on same plot with calibration data. Plot R on ordinate-axis, T on abscissa.

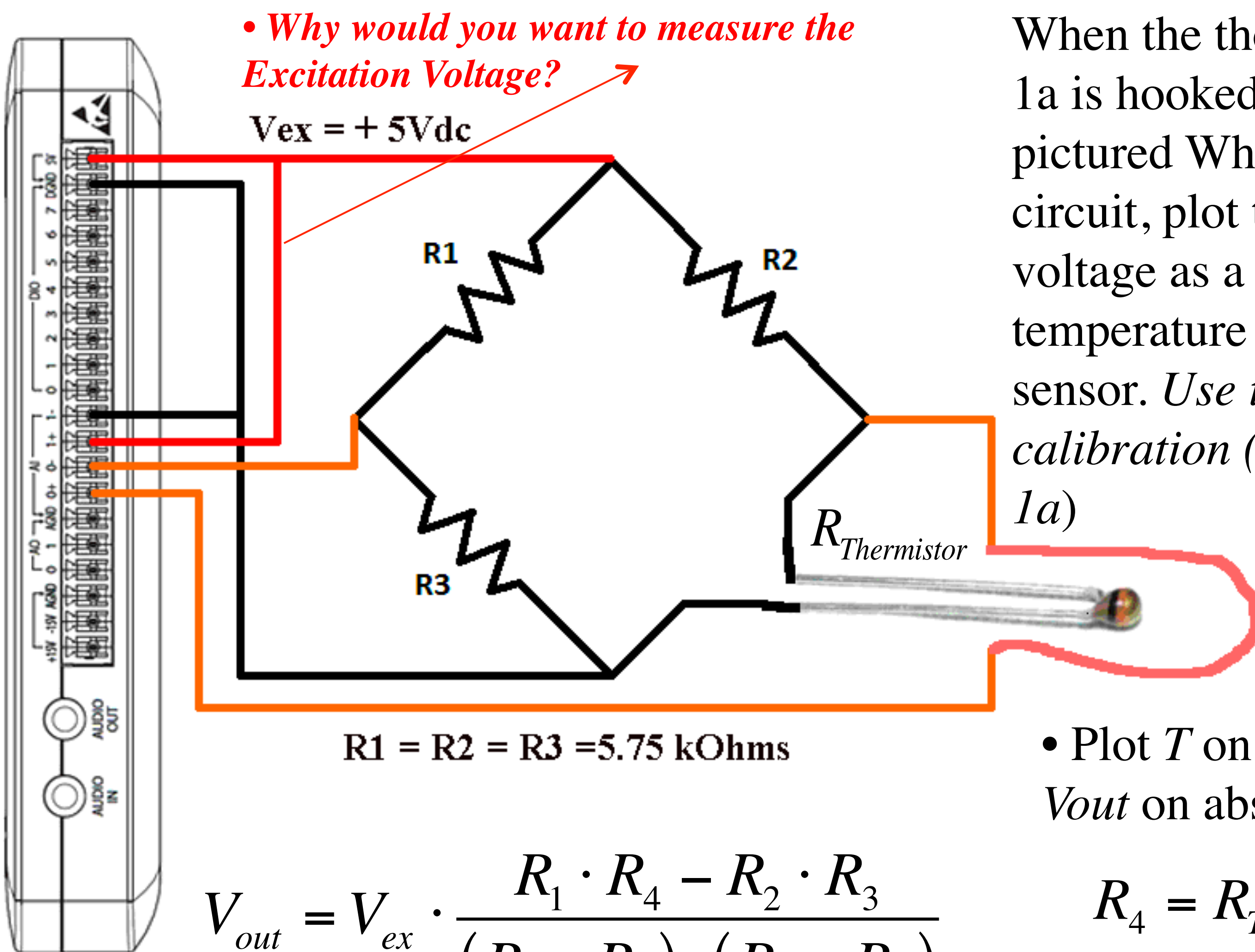
• Use your ***"high"*** and ***"low"*** confidence interval estimates for β to plot error bounds for the temperature model on this plot … how do these boundaries agree with your data?

Homework 8: Part 1a (2)

- Hint .. Your comparison plot should look something like …



Homework 8: Part 1b



When the thermistor from part 1a is hooked up as a part of the pictured Wheatstone bridge circuit, plot the expected output voltage as a function of temperature on the thermistor sensor. *Use thermistor calibration (β) model from part 1a*)

$$V_{out} = V_{ex} \cdot \frac{R_1 \cdot R_4 - R_2 \cdot R_3}{(R_1 + R_2) \cdot (R_3 + R_4)}$$

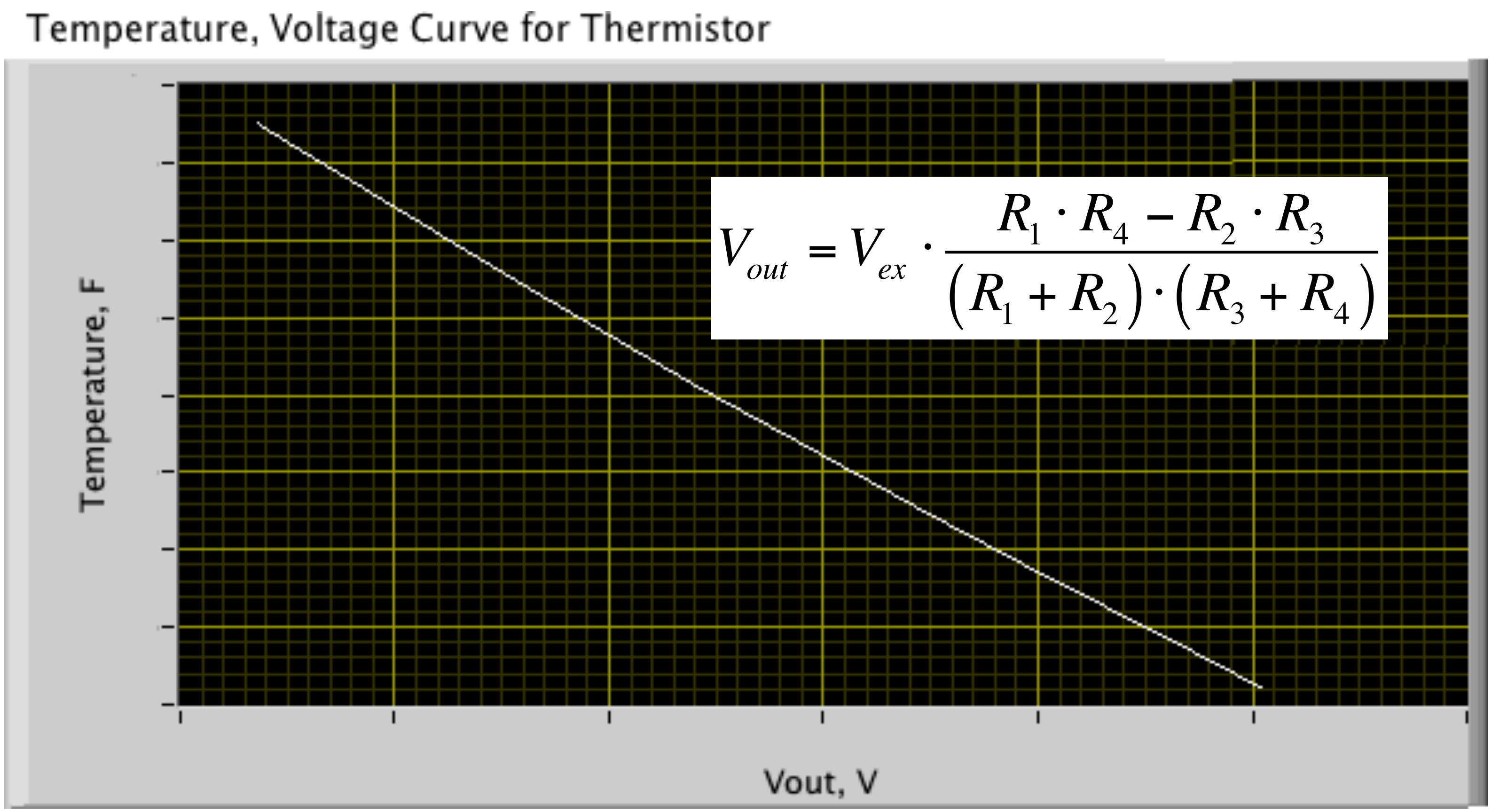
- Plot *T* on ordinate-axis, *Vout* on abscissa.

$$R_4 = R_{Thermistor}$$

- ***Ignore lead wire resistance***

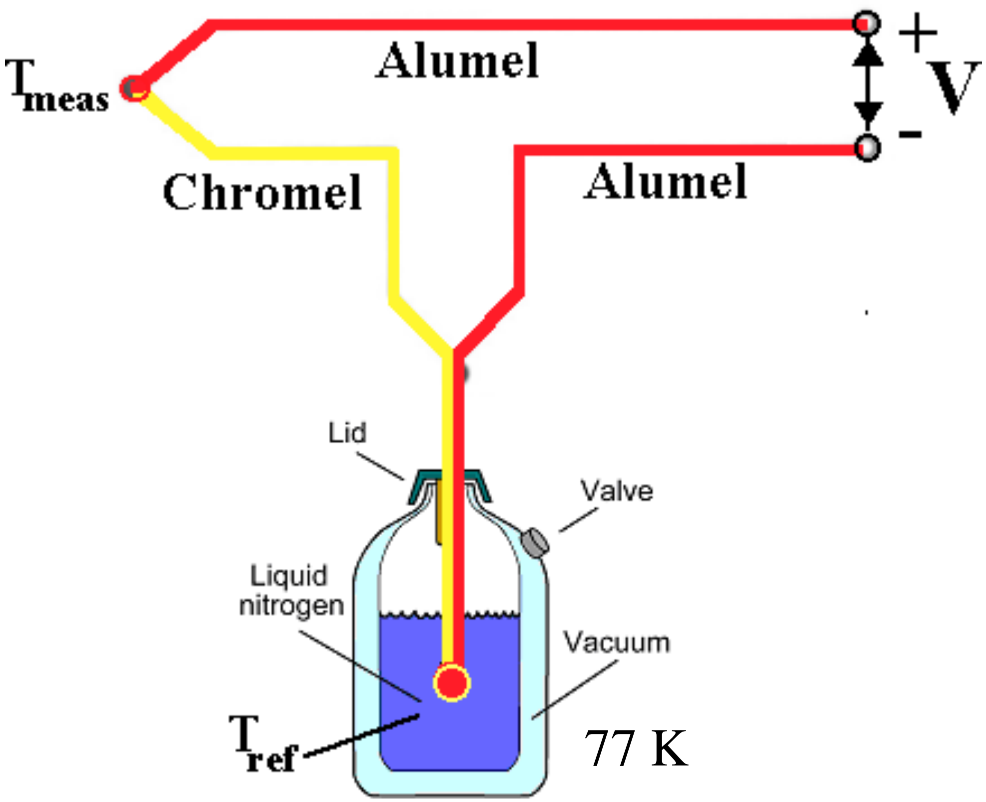
Homework 8: Part 1a (2)

- Hint .. Your Voltage/Temperature plot should look something like …



$$V_{out} = V_{ex} \cdot \frac{R_1 \cdot R_4 - R_2 \cdot R_3}{(R_1 + R_2) \cdot (R_3 + R_4)}$$

Homework 8: Part 2a

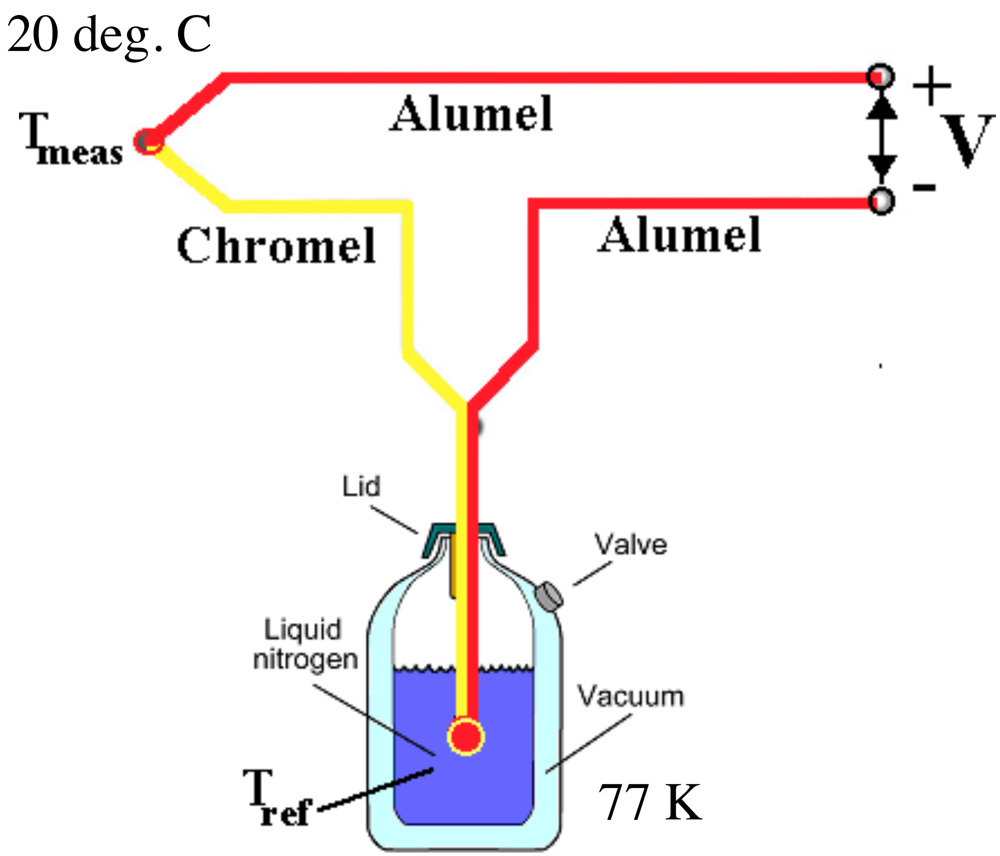


a) A type-K thermocouple has its reference junction submersed in liquid nitrogen at 77 K.

-- The measured output voltage is 1.340 mV

-- What is the temperature of the measurement junction?

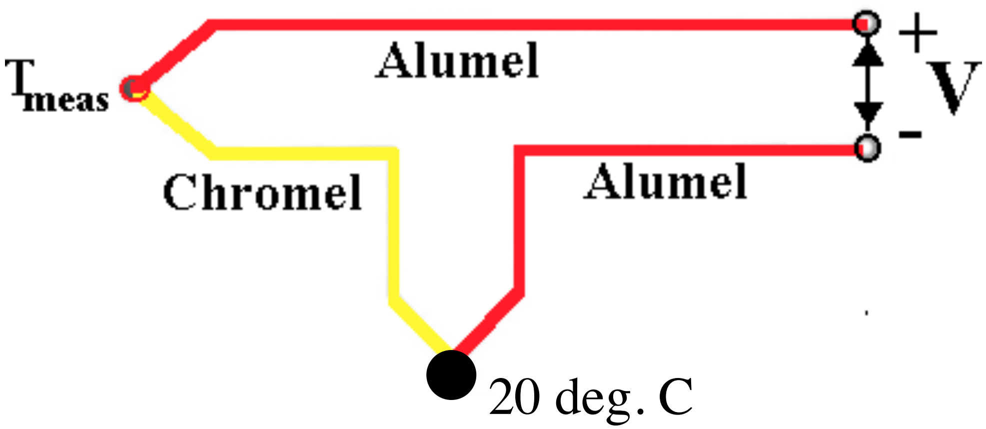
Homework 8: Part 2b



b) What is the output voltage when the temperature of the measurment junction is 20 deg. C

-- Assume that the reference junction is still immersed in the liquid N_2.

Homework 8: Part 2c



c) What is the output voltage when the reference junction is removed from the liquid nitrogen bath and warmed to 20 deg. C

-- Assume that the temperature at the measurement junction is the same as for part 2a.

Appendix I: Thermocouple Types

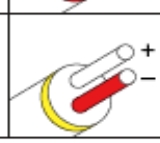
Connectors | Connectors

ANSI Code	ANSI MC 96.1 Color Coding Thermocouple Grade	ANSI MC 96.1 Color Coding Extension Grade	Alloy Combination + Lead	Alloy Combination – Lead	Comments Environment Bare Wire	Maximum T/C Grade Temp. Range	EMF (mV) Over Max. Temp. Range	IEC 584-3 Color Coding Thermocouple Grade	IEC 584-3 Color Coding Intrinsically Safe	IEC Code
J			IRON Fe (magnetic)	CONSTANTAN COPPER-NICKEL Cu-Ni	Reducing, Vacuum, Inert. Limited Use in Oxidizing at High Temperatures. Not Recommended for Low Temperatures.	−210 to 1200°C −346 to 2193°F	−8.095 to 69.553			J
K			CHROMEGA® NICKEL-CHROMIUM Ni-Cr	ALOMEGA® NICKEL-ALUMINUM Ni-Al (magnetic)	Clean Oxidizing and Inert. Limited Use in Vacuum or Reducing. Wide Temperature Range, Most Popular Calibration	−270 to 1372°C −454 to 2501°F	−6.458 to 54.886			K
T			COPPER Cu	CONSTANTAN COPPER-NICKEL Cu–Ni	Mild Oxidizing, Reducing Vacuum or Inert. Good Where Moisture Is Present. Low Temperature & Cryogenic Applications	−270 to 400°C −454 to 752°F	−6.258 to 20.872			T
E			CHROMEGA® NICKEL-CHROMIUM Ni-Cr	CONSTANTAN COPPER-NICKEL Cu-Ni	Oxidizing or Inert. Limited Use in Vacuum or Reducing. Highest EMF Change Per Degree	−270 to 1000°C −454 to 1832°F	−9.835 to 76.373			E
N			OMEGA-P® NICROSIL Ni-Cr-Si	OMEGA-N® NISIL Ni-Si-Mg	Alternative to Type K. More Stable at High Temps	−270 to 1300°C −450 to 2372°F	−4.345 to 47.513			N
R	NONE ESTABLISHED		PLATINUM-13% RHODIUM Pt-13% Rh	PLATINUM Pt	Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature	−50 to 1768°C −58 to 3214°F	−0.226 to 21.101			R

• *Color Codes Connectors*

Thermocouple Types (2)

Connectors | Connectors

ANSI Code	ANSI MC 96.1 Color Coding: Thermocouple Grade	ANSI MC 96.1 Color Coding: Extension Grade	Alloy Combination: + Lead	Alloy Combination: – Lead	Comments Environment Bare Wire	Maximum T/C Grade Temp. Range	EMF (mV) Over Max. Temp. Range	IEC 584-3 Color Coding: Thermocouple Grade	IEC 584-3 Color Coding: Intrinsically Safe	IEC Code
										N
										R
S	NONE ESTABLISHED		PLATINUM-10% RHODIUM Pt-10% Rh	PLATINUM Pt	Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature	–50 to 1768°C –58 to 3214°F	–0.236 to 18.693			S
U	NONE ESTABLISHED		COPPER Cu	COPPER-LOW NICKEL Cu-Ni	Extension Grade Connecting Wire for R & S Thermocouples, Also Known as RX & SX Extension Wire.					U
B	NONE ESTABLISHED		PLATINUM-30% RHODIUM Pt-30% Rh	PLATINUM-6% RHODIUM Pt-6% Rh	Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temp. Common Use in Glass Industry	0 to 1820°C 32 to 3308°F	0 to 13.820			B
G* (W)	NONE ESTABLISHED		TUNGSTEN W	TUNGSTEN-26% RHENIUM W-26% Re	Vacuum, Inert, Hydrogen. Beware of Embrittlement. Not Practical Below 399°C (750°F). Not for Oxidizing Atmosphere	0 to 2320°C 32 to 4208°F	0 to 38.564	NO STANDARD USE ANSI COLOR CODE		G (W)
C* (W5)	NONE ESTABLISHED		TUNGSTEN-5% RHENIUM W-5% Re	TUNGSTEN-26% RHENIUM W-26% Re	Vacuum, Inert, Hydrogen. Beware of Embrittlement. Not Practical Below 399°C (750°F) Not for Oxidizing Atmosphere	0 to 2320°C 32 to 4208°F	0 to 37.066	NO STANDARD USE ANSI COLOR CODE		C (W5)
D* (W3)	NONE ESTABLISHED		TUNGSTEN-3% RHENIUM W-3% Re	TUNGSTEN-25% RHENIUM W-25% Re	Vacuum, Inert, Hydrogen. Beware of Embrittlement. Not Practical Below 399°C (750°F)–Not for Oxidizing Atmosphere	0 to 2320°C 32 to 4208°F	0 to 39.506	NO STANDARD USE ANSI COLOR CODE		D (W3)

** Not official symbol or standard designation*

† JIS color code also available.

Thermocouple Types

Thermocouple Type	Useful/General Application Range	Notes
B	1370-1700°C (2500-3100°F)	Easily contaminated, require protection.
C*	1650-2315°C (3000-4200°F)	No oxidation resistance. Vacuum, hydrogen or inert atmospheres.
E**	95-900°C (200-1650°F)	Highest output of base metal thermocouples. Not subject to corrosion at cryogenic temperatures.
J	95-760°C (200-1400°F)	Reducing atmosphere recommended. Iron leg subject to oxidation at elevated temperatures--use larger gauge to compensate.
K**	95-1260°C (200-2300°F)	Well suited for oxidizing atmospheres.
N	650-1260°C (1200-2300°F)	For general use, better resistance to oxidation and sulfur than Type K.
R	870-1450°C (1600-2640°F)	Oxidizing atmosphere recommended. Easily contaminated, require protection.
S	980-1450°C (1800-2640°F)	Laboratory standard, highly reproducible. Easily contaminated, require protection.
T**	-200-350°C (-330-660°F)	Most stable at cryogenic temperatures ranges. Excellent in oxidizing and reducing atmospheres within temperature range.

UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Thermocouple Tolerances

(Reference Junction at 0°C)

• No sampling and reference sensor error

American Limits of Error ASTM E230-ANSI MC 96.1

ANSI Code		Standard Limits†		Special Limits†	
J	Temp Range	>0 to 750°C	>32 to 1382°F	0 to 750°C	32 to 1382°F
	Tolerance Value	2.2°C or 0.75%	4.0°F or 0.75%	1.1°C or 0.4%	2.0°F or 0.4%
K	Temp Range	>0 to 1250°C	>32 to 2282°F	0 to 1250°C	32 to 2282°F
	Tolerance Value	2.2°C or 0.75%	4.0°F or 0.75%	1.1°C or 0.4%	2.0°F or 0.4%
	Temp. Range*	-200 to 0°C	-328 to 32°F		
	Tolerance Value	2.2°C or 2.0%	4.0°F or 2.0%		
T	Temp Range	>0 to 350°C	>32 to 662°F	0 to 350°C	32 to 662°F
	Tolerance Value	1.0°C or 0.75%	1.8°F or 0.75%	0.5°C or 0.4%	1°F or 0.4%
	Temp. Range*	-200 to 0°C	-328 to 32°F		
	Tolerance Value	1.0°C or 1.5%	1.8°F or 1.5%		
E	Temp Range	>0 to 900°C	>32 to 1652	0 to 900°C	32 to 1652°F
	Tolerance Value	1.7°C or 0.5%	3°F or 0.5%	1.0°C or 0.4%	1.8°F or 0.4%
	Temp. Range*	-200 to 0°C	-328 to 32°F		
	Tolerance Value	1.7°C or 1.0%	3°F or 1.0%		
N	Temp Range	>0 to 1300°C	>32 to 2372°F	0 to 1300°C	32 to 2372°F
	Tolerance Value	2.2°C or 0.75%	4.0°F or 0.75%	1.1°C or 0.4%	2.0°F or 0.4%
	Temp. Range*	-270 to 0°C	-454 to 32°F		
	Tolerance Value	2.2°C or 2.0%	4.0°F or 2.0%		
R S	Temp Range	0 to 1450°C	32 to 2642°F	0 to 1450°C	32 to 2642°F
	Tolerance Value	1.5°C or 0.25%	2.7°F or 0.25%	0.6°C or 0.1%	1°F or 0.1%
B	Temp Range	800 to 1700°C	1472 to 3092°F	Not Established	
	Tolerance Value	0.5%	0.9°F		
G*C*D*	Temp Range	0 to 2320°C	32 to 4208°F	Not Established	
	Tolerance Value	4.5°C or 1.0%	0.9°F		

** Not official symbol or standard designation* *† Whichever value is greater.*

Note: *Material is normally selected to meet tolerances above 0°C. If thermocouples are needed to meet tolerances below 0°C, the purchaser shall state this as selection of material is usually required.*

Thermocouple Accuracies (2)

- **No sampling and reference sensor error**

IEC Tolerance Class EN 60584-2; JIS C 1602

IEC Code		Class 1	Class 2	Class 3†
J	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 375°C ±1.5°C 375 to 750°C ±0.4% Reading	-40 to 333°C ±2.5°C 333 to 750°C ±0.75% Reading	Not Established
K N	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 375°C ±1.5°C 375 to 1000°C ±0.4%	-40 to 333°C ±2.5°C 333 to 1200°C ±0.75% Reading	-167 to 40°C ±2.5°C -200 to -167°C ±1.5% Reading
T	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 125°C ±0.5°C 125 to 350°C ±0.4% Reading	-40 to 133°C ±1°C 133 to 350°C ±0.75% Reading	-67 to 40°C ±1°C -200 to -67°C ±1.5% Reading
E	Temp Range Tolerance Value Temp. Range Tolerance Value	-40 to 375°C ±1.5°C 375 to 800°C ±0.4% Reading	-40 to 333°C ±2.5°C 333 to 900°C ±0.75% Reading	-167 to 40°C ±2.5°C -200 to -167°C ±1.5% Reading
R S	Temp Range Tolerance Value Temp. Range Tolerance Value	0 to 1100°C ±1°C 1100 to 1600°C ±[1 + 0.3% x (Rdg-1100)]°C	0 to 600°C ±1.5°C 600 to 1600°C ±0.25% Reading	Not Established
B	Temp Range Tolerance Value Temp. Range Tolerance Value	Not Established	600 to 1700°C ±0.25% Reading	600 to 800°C +4°C 800 to 1700°C ±0.5% Reading

† Material is normally selected to meet tolerances above -40°C. If thermocouples are needed to meet limits of Class 3, as well as those of Class 1 or 2, the purchaser shall state this, as selection of material is usually required.

J, K Thermocouples (1)

Type J ***Positive Terminal: Iron …. Negative Terminal: Constantan***

The Type J may be used, exposed or unexposed, where there is a deficiency of free oxygen. For cleanliness and longer life, a protecting tube is recommended. Since JP (iron) wire will oxidize rapidly at temperatures over 540°C (1000°F), it is recommended that larger gauge wires be used to compensate. Maximum recommended operating temperature is 760°C (1400°F).

Type K ***Positive Terminal: Chromel …. Negative Terminal: Alumel***

Due to its reliability and accuracy, Type K is used extensively at temperatures up to 1260°C (2300°F). It's good practice to protect this type of thermocouple with a suitable metal or ceramic protecting tube, especially in reducing atmospheres. In oxidizing atmospheres, such as electric furnaces, tube protection is not always necessary when other conditions are suitable; however, it is recommended for cleanliness and general mechanical protection. Type K will generally outlast Type J because the JP (iron) wire rapidly oxidizes, especially at higher temperatures.

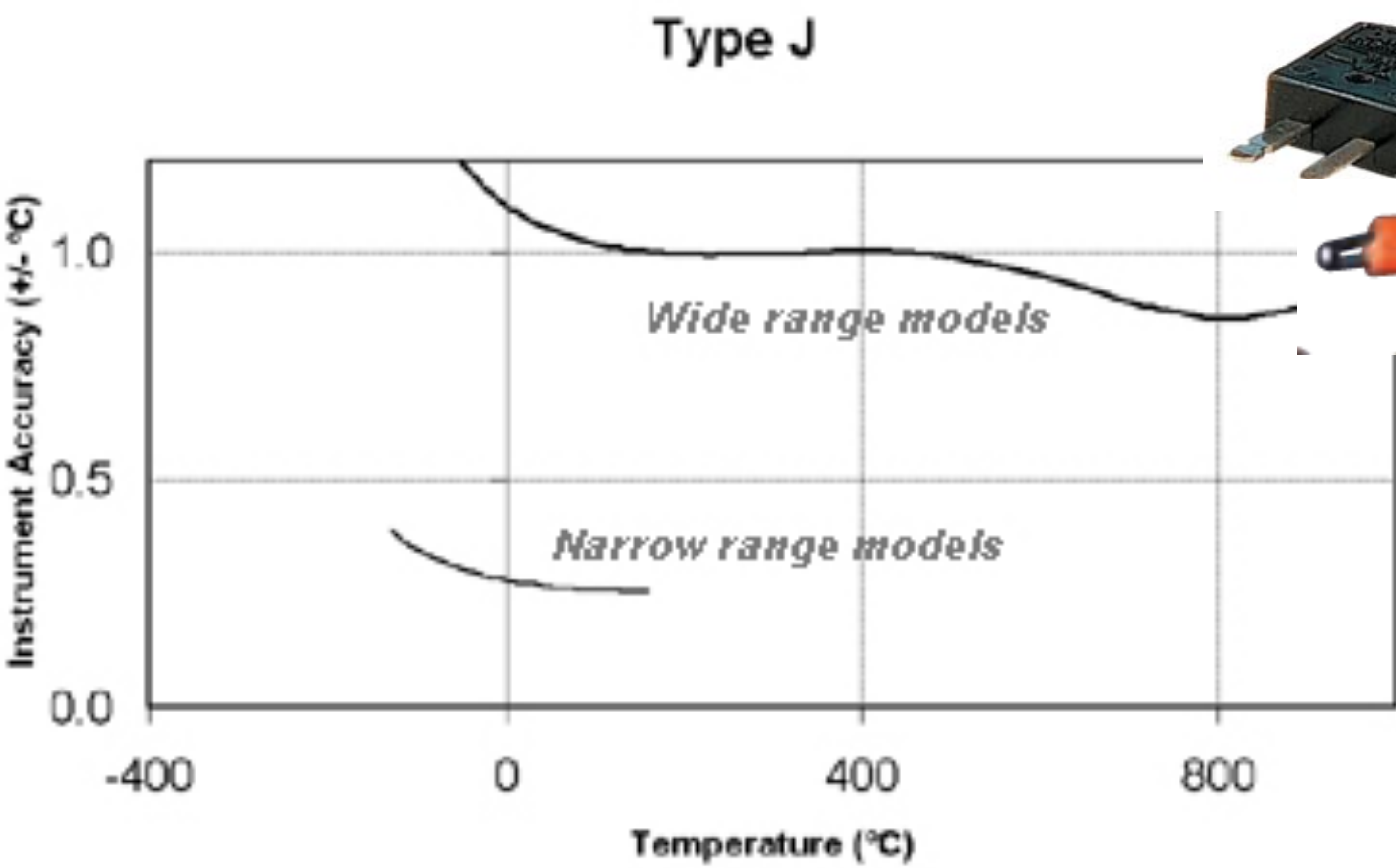
Constantan is a copper-nickel alloy usually consisting of 55% Copper and 45% Nickel.

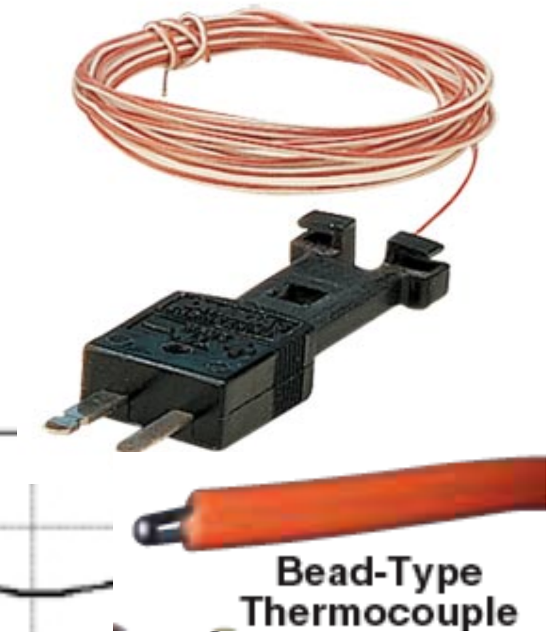
Chromel is an alloy made of approximately 90 percent nickel and 10 percent chromium

Alumel is an alloy consisting of 95% nickel, 2% manganese, 2% aluminium and 1% silicon.

J, K Thermocouples (2)

- **Graphical Display of Accuracy**





J, K Thermocouples (3)

- **Graphical Display of Accuracy**