Temperature Measurement

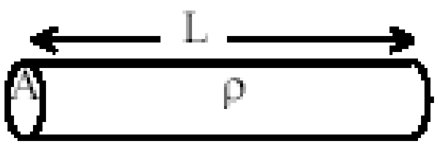
Temperature Measurement

- Resistive Temperature sensors
- Thermoelectric Sensing Elements
- Semiconductor Junction Temperature Transducers
- Radiation Thermometers

Metallic Resistance Thermometer

$$R = \frac{\rho L}{A}$$

R = Resistance



ρ = Resistivity (Ω.m)

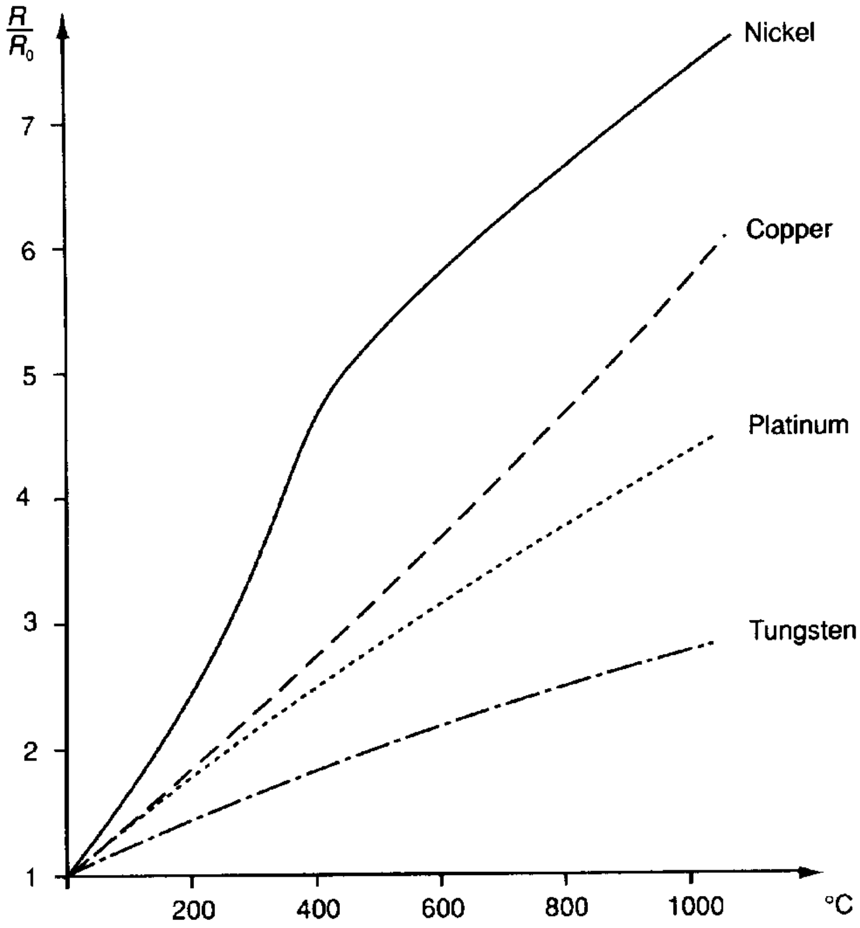
A = Cross-Sectional Area

L = Length

The resistivity of a metal is proportional to the temperature. This provides the physical basis for a temperature sensor. This can me called either:

- Metallic Resistance Thermometer
- Resistive Temperature Detector (RTD)

Resistivity of Metals



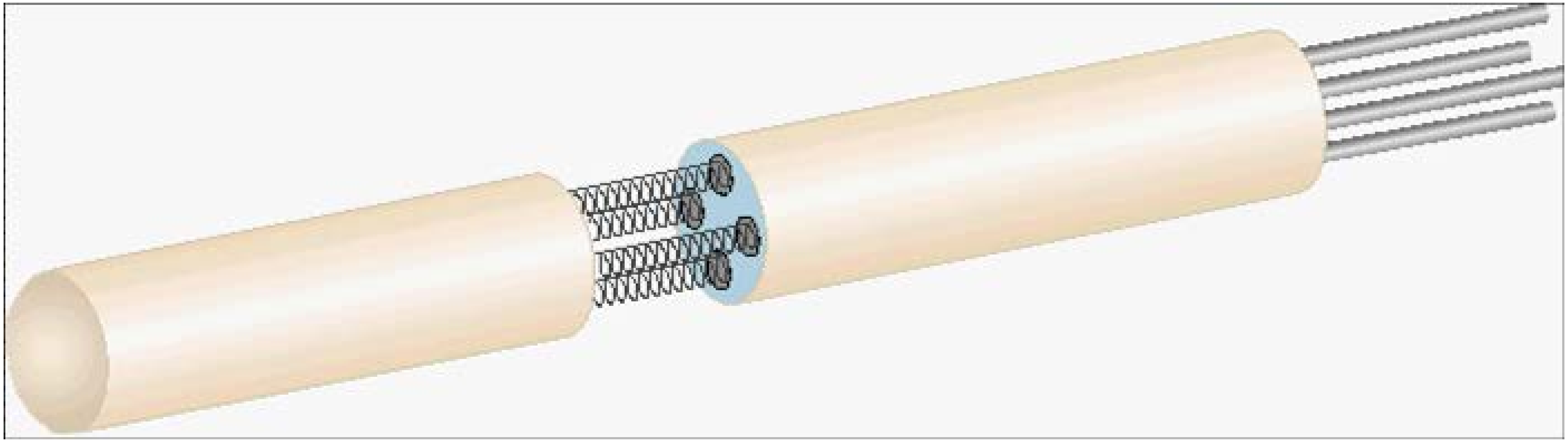
Over a reasonable range of temperature, the response of an RTD is linear with temperature.

$$R(T) = R_0\left(1+\alpha\Delta T\right)$$

The most common type uses Platinum, with
α= 0.0039 °C-1 and
Ro = 100 Ω @ 0°C

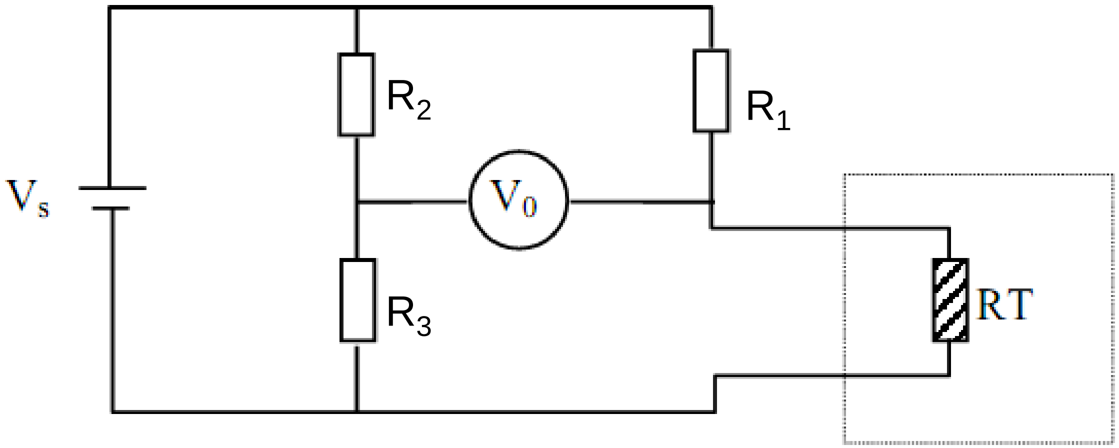
This is called a PT100

RTD construction



Strain free design – wire is free to move/expand within hard-fired ceramic oxide tube. Bores filled with fine powder to provide thermal conductivity.

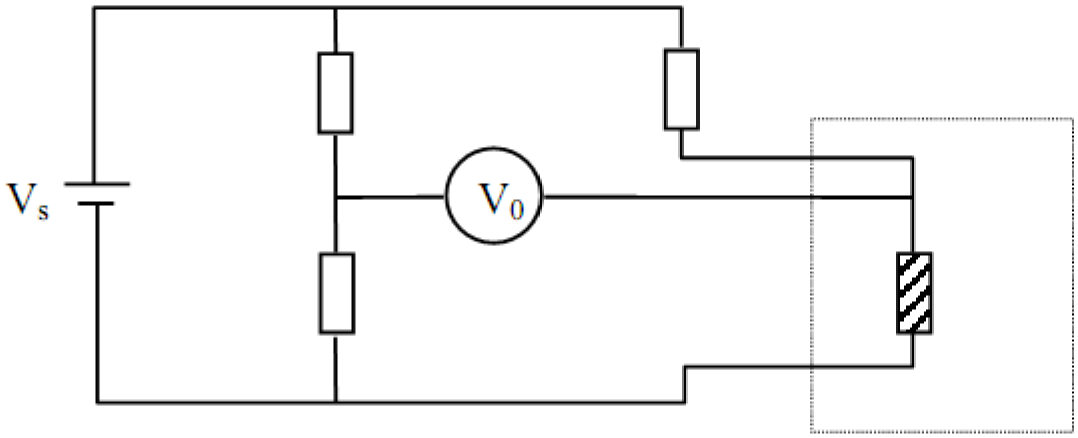
RTD operation using Bridge Circuit



$$V_0 = V_s\left[\frac{R_T}{R_T + R_1} - \frac{R_3}{R_3 + R_2}\right]$$

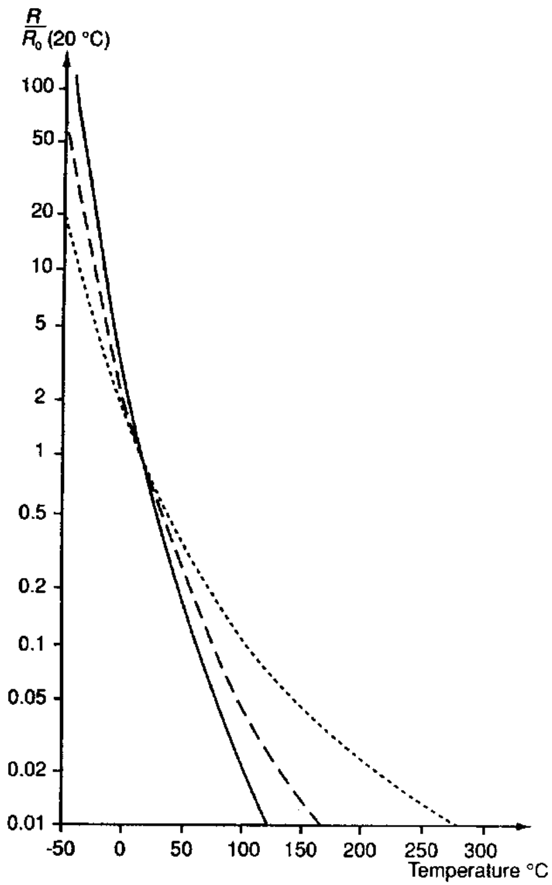
Metallic Resistance Thermometer

“3 wire connection”



This arrangement compensates for the effect of the resistance of the connecting leads. RTD are frequently manufactured as a 3-wire package.

Resistance of NTC Thermistor



A Negative Temperature Coefficient (NTC) thermistor is made from a semiconductor material. The resistivity of a semiconductor falls exponentially with rising temperature. The relationship is:

$$R(T) = A \exp\left(\frac{B}{T}\right)$$

The temperature *T* must be quoted in kelvin degrees (K).

A is constant (Ω)
B is characteristic temperature (2000-4000 K)

NTC thermistor

$$R(T) = A\exp\left(\frac{B}{T}\right)$$

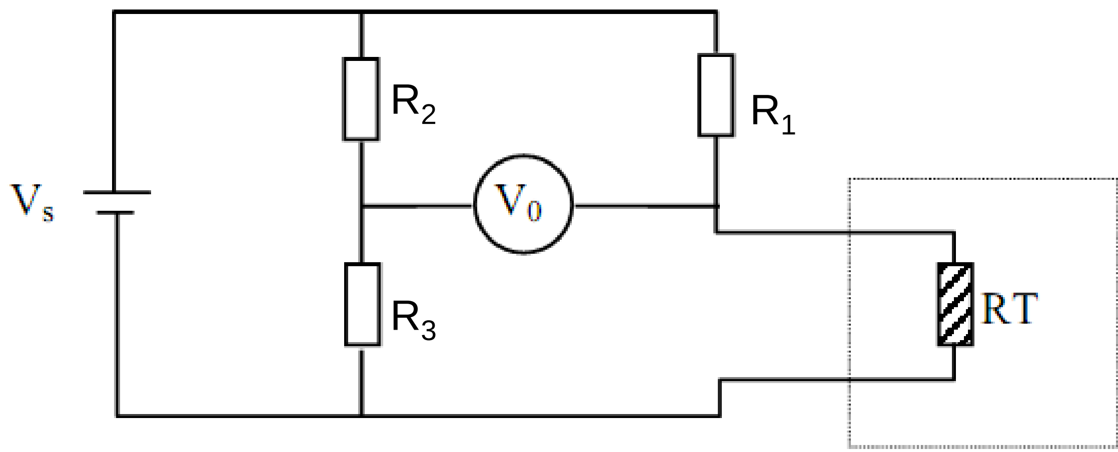
Define reference resistance at reference temperature. R_o @ T_o = 298 K

$$R_o = A\exp\left(\frac{B}{T_o}\right)$$

Substitute this into the general equation to get an alternative expression:

$$R(T) = R_o\exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

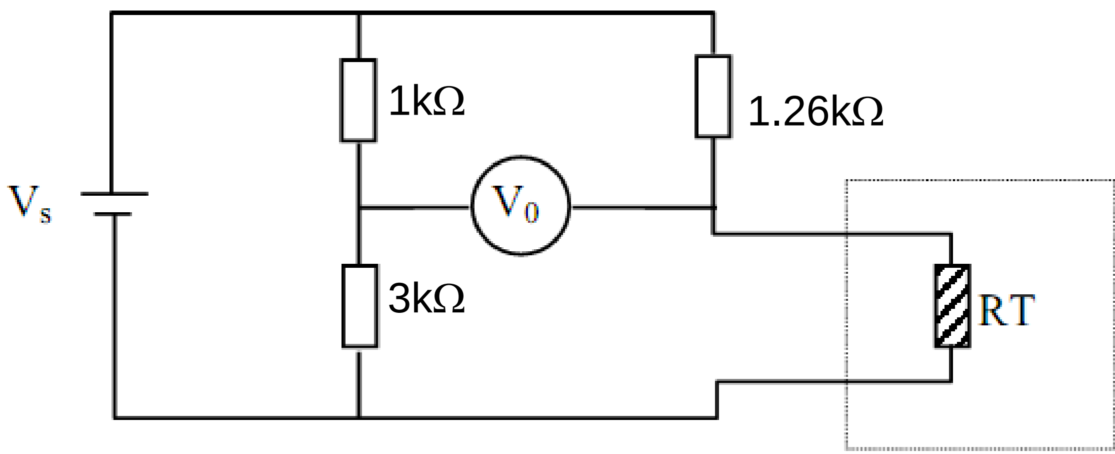
Bridge Circuit to for Thermistor



$$V_0 = V_s\left[\frac{R_T}{R_T + R_1} - \frac{R_3}{R_3 + R_2}\right]$$

- The o/p of this circuit may be highly non-linear,
- maybe you don't care, as long as it is reproducible,
- or maybe you need a linear output.

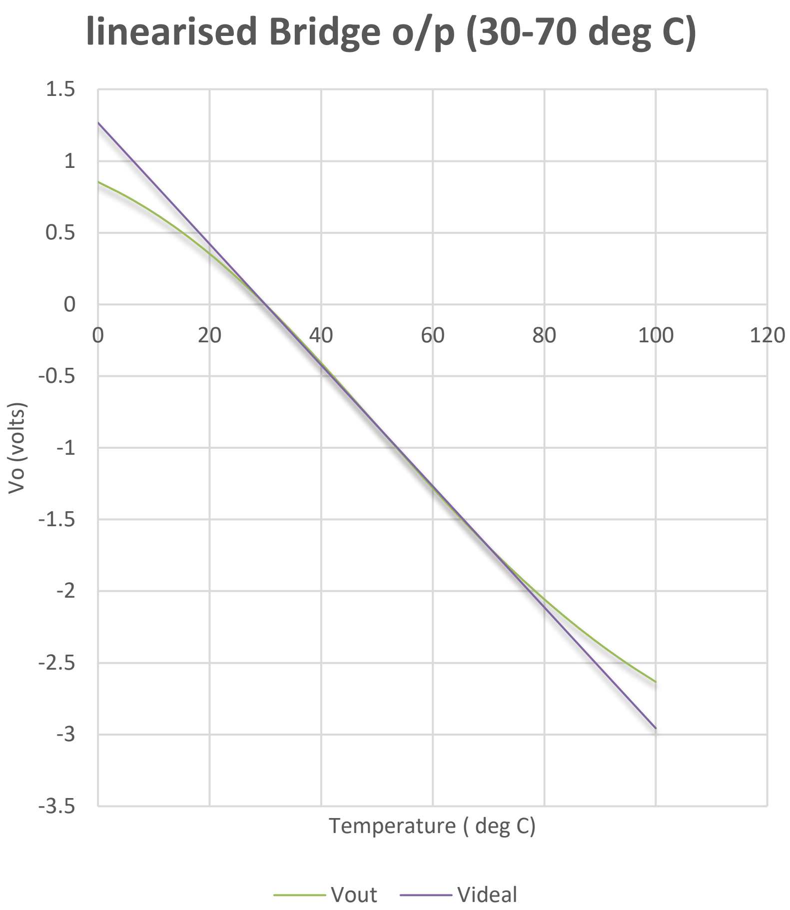
We can design a thermistor – bridge combination to produce a linear output over a finite temperature range. 30 -70 degrees in this example.

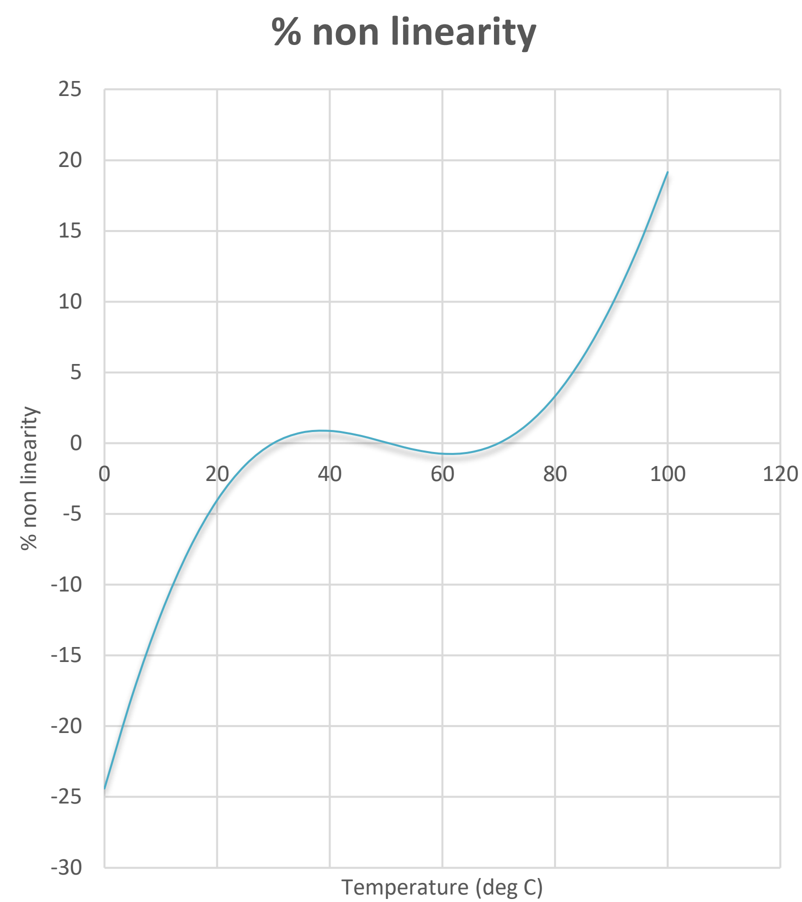


For this particular thermistor:

$$R(T) = (4730)\exp\left[3780\left(\frac{1}{T} - \frac{1}{298}\right)\right]\ \Omega$$

We can design a thermistor – bridge combination to produce a linear output over a finite temperature range. 30 -70 degrees in this example.





Assorted Thermistors

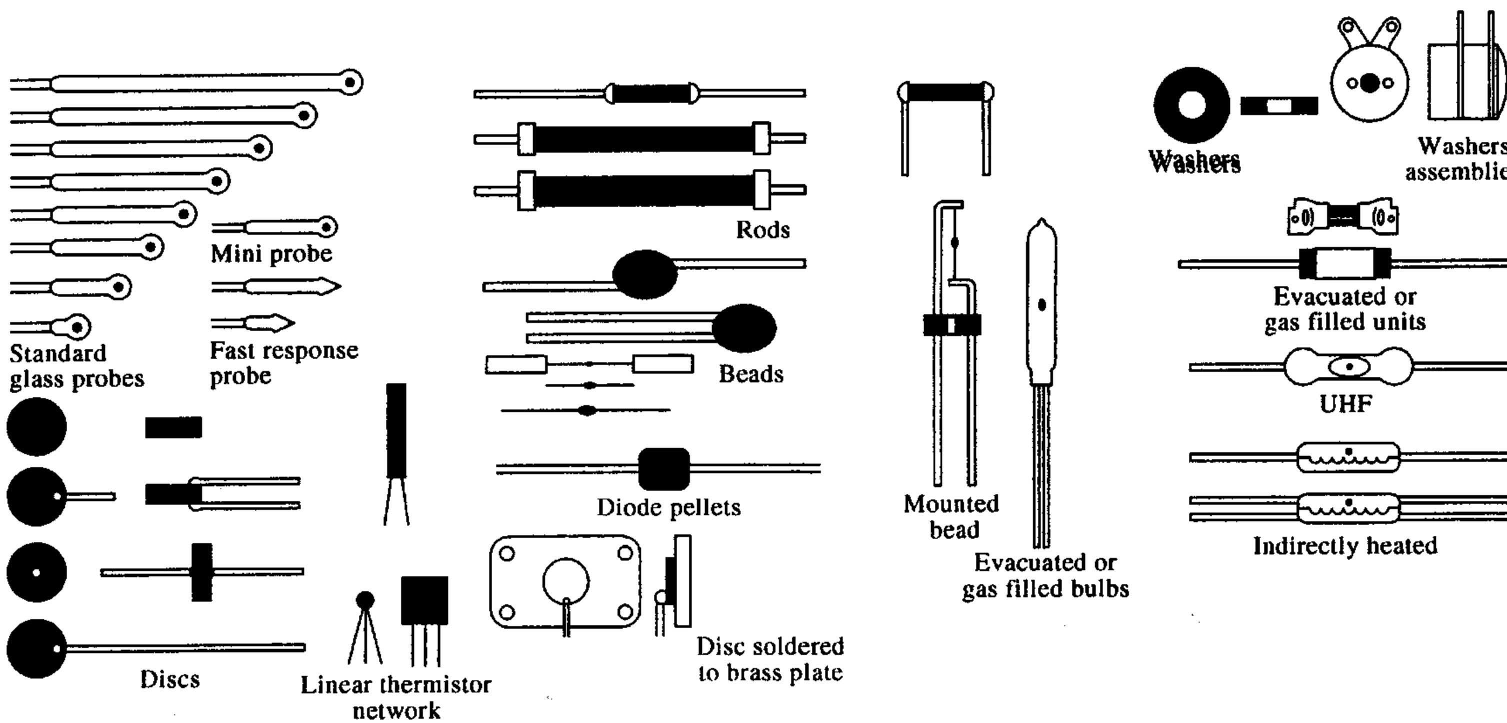


FIGURE 13 – Typical thermistor configurations (Courtesy of Fenwell Electronics, USA).

One issue to watch with Thermistors: Self Heating

- Any resistive temperature sensor needs to be supplied with a current, so that its resistance can be measured.
- But the applied current produces Ohmic heating $P = I^2R$!
- Which could heat up the temperature sensor, causing a *self-heating* error.
- This is unlikely to be a problem with a RTD, since they always have a low resistance and a significant mass. $\Delta T = \Delta Q/(c\ M)$
- But could well be a problem in thermistor installations where the resistance can vary considerably and the mass might be very small.

Thermistor Applications

	Field of application	*Brief description*
A.	Industrial	Measurement and control of temperature in electronic equipment, process heating, air conditioning, refrigeration, liquid level control, flow measurement and control of gases & liquids.
B.	Aerospace & Defense	In-flight telemetry of liquid, gas & surface temperature data in aircrafts, missiles, satellites, etc.
C.	Geological	Oil well drilling and exploration, liquid level indication, flow detection, etc.
D.	Oceanography	Ocean temperature profiles, heat flow measurement, etc.
E.	Bio-medical	Measurement and control of body temperature and of premature baby incubator temperature, measurement of gas or air flow during critical surgery, respiration monitoring, flow and temperature monitoring in physiological activities.

(Thermoelectric) Seebeck Effect

- If two different conductors A and B are joined together, there is a difference in electrical potential across the junction called contact potential.

- The contact potential depends on temperature and so forms the basis of a temperature measurement system.

(Thermoelectric) Seebeck Effect

- The contact potential depends on the metals A and B and the temperature T^0C of the junction, and can be described by a power series of the form:

$$E_T^{AB} = a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + \ldots$$

- The constants a_i depend on the metal.

(Thermoelectric) Seebeck Effect

- The constants a_i depend on the metal. e.g. for an iron vs. constantan (copper nickel alloy) junction:

$$E_T = \left(5.037x10^{1}\right)T + \left(3.043x10^{-2}\right)T^{2} - \left(8.567x10^{-5}\right)T^{3} + \left(1.335x10^{-7}\right)T^{4}\ \mu V$$

- Note that the higher order terms are a lot smaller than the leading term so this relationship between E and T is very close to linear.

Thermocouples

- A Thermocouple is a closed circuit of two junctions, at different temperatures T_1 and T_2 ^{0}C. If a high impedance voltmeter is introduced into the circuit, so that the current flow is negligible, then the measured emf is:

$$E^{AB}_{T_1,T_2} = E^{AB}_{T_1} - E^{AB}_{T_2} = a_1\left(T_1 - T_2\right) + a_2\left(T_1^2 - T_2^2\right) + a_3\left(T_1^3 - T_2^3\right) + \ldots$$

- To measure T_2, we must accurately know T_1 (reference temperature). Thermocouple tables are based on a reference temperature of 0^0C.

Thermocouples

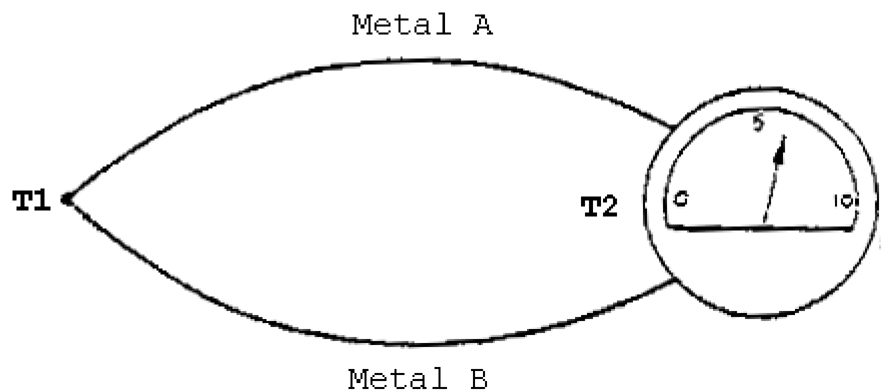
$$E^{AB}_{T_1T_2}$$

- This notation represents the EMF of a thermocouple comprising A and B wires with junction temperatures T_1 and T_2.

- Note that the thermocouple has an electric polarity, like a battery.

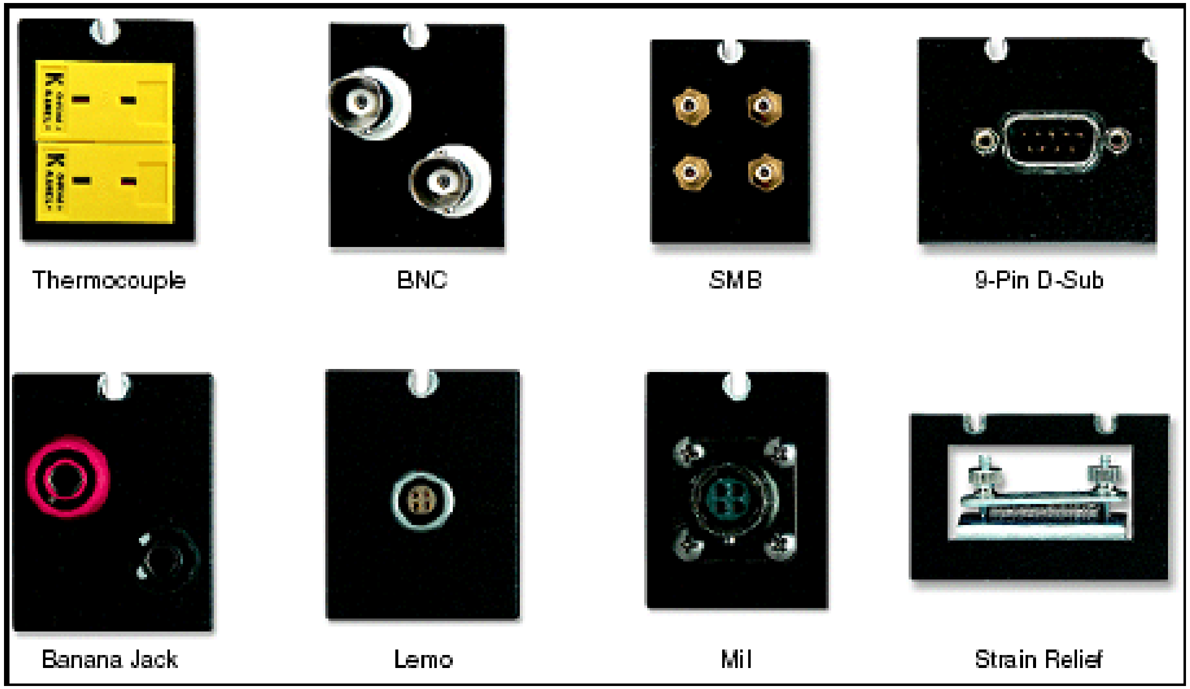
- $$E^{AB} = - E^{BA}$$

$$E_{T_1 T_2}^{AB}$$



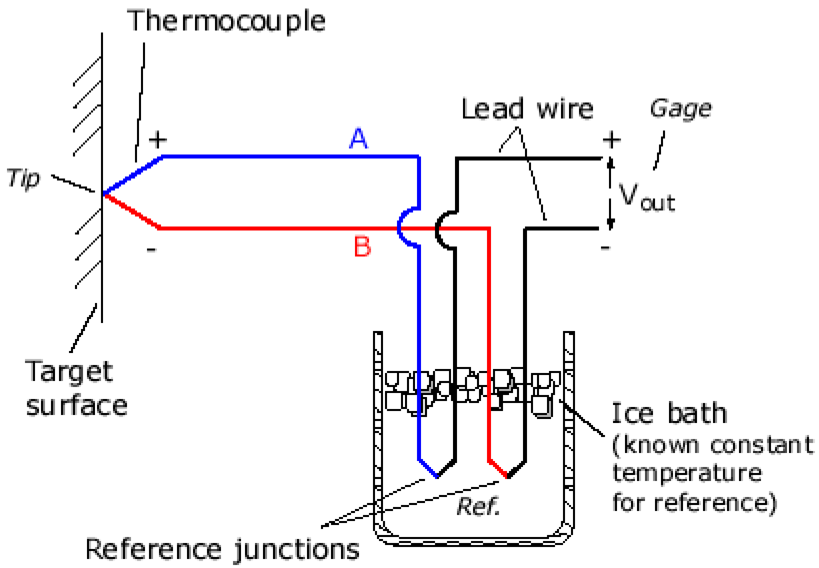
BASIC THERMOCOUPLE
CIRCUIT WITH INSTRUMENT

Figure A



- Standard thermocouple plug is asymmetric to prevent the thermocouple being inserted with the wrong polarity.

Thermocouples



- This is a ‘classical’ thermocouple installation with a realisation of a 0°C reference temperature.

- This is seldom practical outside of a laboratory!

Thermocouples

- Thermocouples are manufactured from various combinations of the base metals as in the following examples;

- Copper and iron,

- the base-metal alloys of

- alumel (Ni/NMn/Al/Si),
- chromel (Ni/Cr),
- constantan (Cu/Ni),
- nicrosil (Ni/Cr/Si)
- and nisil (Ni/Si/Mn),

- the noble metals platinum and tungsten,
-
- and the noble-metal alloys of platinum/rhodium and tungsten/rhenium.

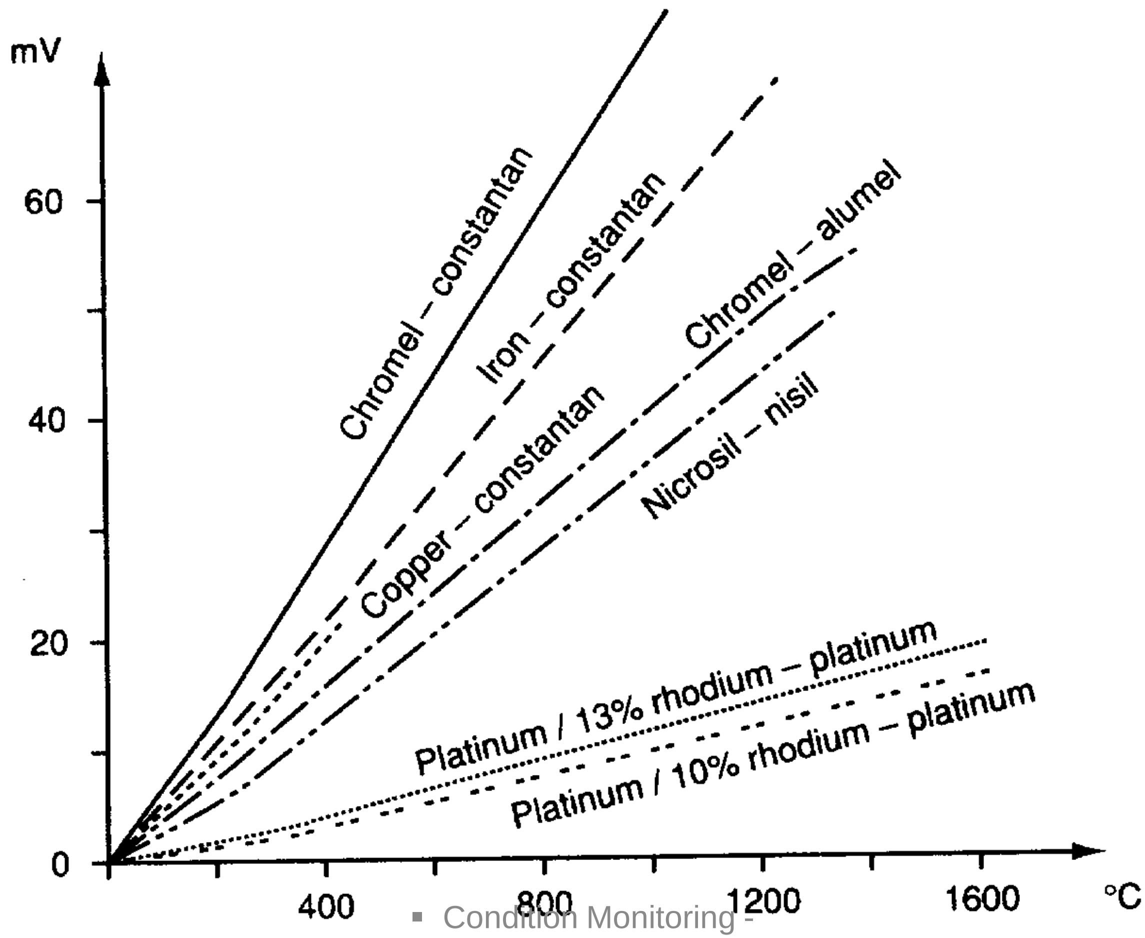
Thermocouples

- Various standard thermocouple types are defined.
- The cheaper, base metal types are less suitable for hostile, oxidizing environments.
- The more expensive, noble metal types tend to have lower sensitivity.
- Some types are limited by the melting points of the brazing materials used at the joints. (?)

Thermocouple Types

Type	Temperature range	EMF values (μV)	Tolerances
Iron and constantan Type J	1.3 mm 0 – 500°C 2.6 mm 0 –600°C	$E_{100,0}$ = 5268 $E_{200,0}$ = 10777 $E_{300,0}$ = 16325 $E_{500,0}$ = 27388	0 - 300°C $\pm$ 3% above 300°C $\pm$ 1%
Copper and constantan Type T	0.7 mm -100 - + 400°C	$E_{-100,0}$ = -3378 $E_{100,0}$ = 4277 $E_{200,0}$ = 9286 $E_{400,0}$ = 20869	0 - 100°C $\pm$ 1% above 100°C $\pm$ 1%
Nickel – chromium v Nickel – chromel v Alumel Type K	1.3 mm 0 – 950°C 2.6 mm 0 – 1150°C	$E_{100,0}$ = 4095 $E_{250,0}$ = 10151 $E_{500,0}$ = 20640 $E_{1000,0}$ = 41269	0 – 400°C $\pm$ 3% above 400°C $\pm$ 0.75%
Platinum v Platinum – 13% rhodium Type R	0 - 1400°C	$E_{300,0}$ = 2400 $E_{600,0}$ = 5582 $E_{900,0}$ = 9203 $E_{1200,0}$ = 13224	0 - 1100°C $\pm$ 1% 1100-1400°C $\pm$ 2%

Thermocouple Characteristics



Five Rules of Thermocouple Behaviour (1)

- The emf of a thermocouple depends only on the temperature of the junctions and is independent of the temperature of the wires connecting the junctions.

- comment – well it wouldn’t be any use otherwise!

Five Rules of Thermocouple Behaviour (2)

- If a third metal is introduced into one arm of the thermocouple, then, provided the two new junctions are at the same temperature, the emf is unchanged.

- comment – this means that you can put a voltmeter into the thermocouple circuit without affecting its performance.

Five Rules of Thermocouple Behaviour (3)

- If a third metal is introduced at one junction, then, provided the two new junctions are at the same temperature, the emf is unchanged.

- Comment - can braze the two metals together at the measuring junction without changing emf.

Five Rules of Thermocouple Behaviour (4)

$$E^{AB}_{T_1T_2} = E^{AC}_{T_1T_2} + E^{CB}_{T_1T_2}$$

- ‘Law of Intermediate metals’

- Consequence - can deduce EMF for an unknown thermocouple from data on known thermocouple pairs.

Five Rules of Thermocouple Behaviour (5)

$$E^{AB}_{T_1T_2} = E^{AB}_{T_1T_3} + E^{AB}_{T_3T_2}$$

- Law of Intermediate Temperatures
- Consequence - can interpret EMFs as temperatures using standard tables given in terms of a reference temperature.

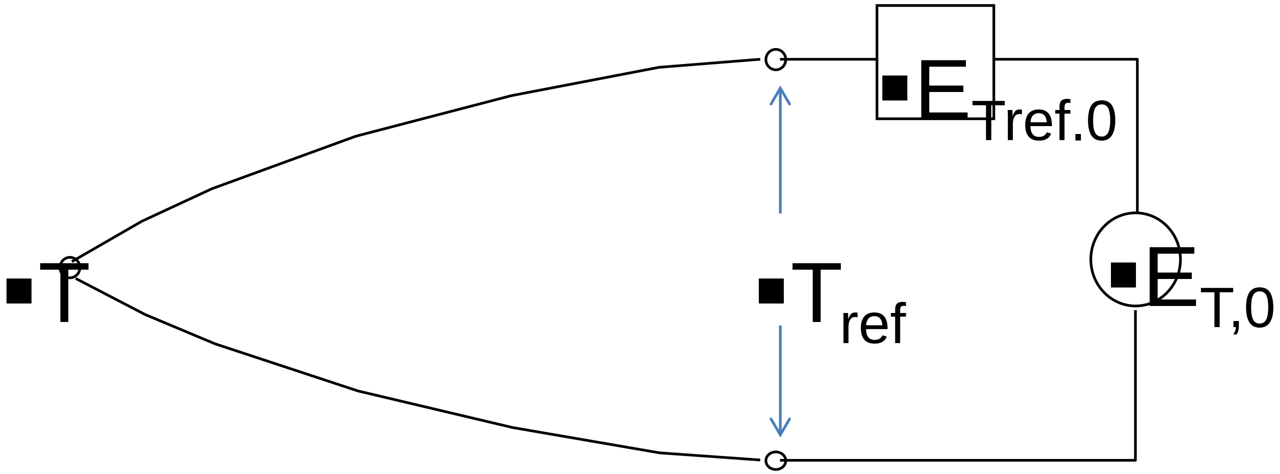
Cold Junction Compensation

- Whilst thermocouple tables are calibrated assuming a zero reference junction temperature, it is not always possible in real applications to maintain such a low reference temperature.

- In many practical applications of thermocouples, it is necessary to locate the reference junction in a variable 'room temperature' environment.

- Correction for this different (variable) reference junction temperature then has to be made using the law of intermediate temperatures.

Cold Junction Compensation



- Need to provide an EMF equal to $E_{T,Tref}$. Then:

$$E^{AB}_{T,0} = E^{AB}_{T,T_{ref}} + E^{AB}_{T_{ref},0}$$

Need this | Measure this | Add this correction

Cold Junction Compensation

- Can use various electric temperature sensors to provide the cold junction compensation (CJC).
- One convenient system is the thermocouple amplifier. This provides a high gain for the small thermocouple signal + CJC.
- Eg. AD595. This provides CJC for type K thermocouple and gives a convenient output of 10 mV/°C

AD595 Thermocouple Amplifier

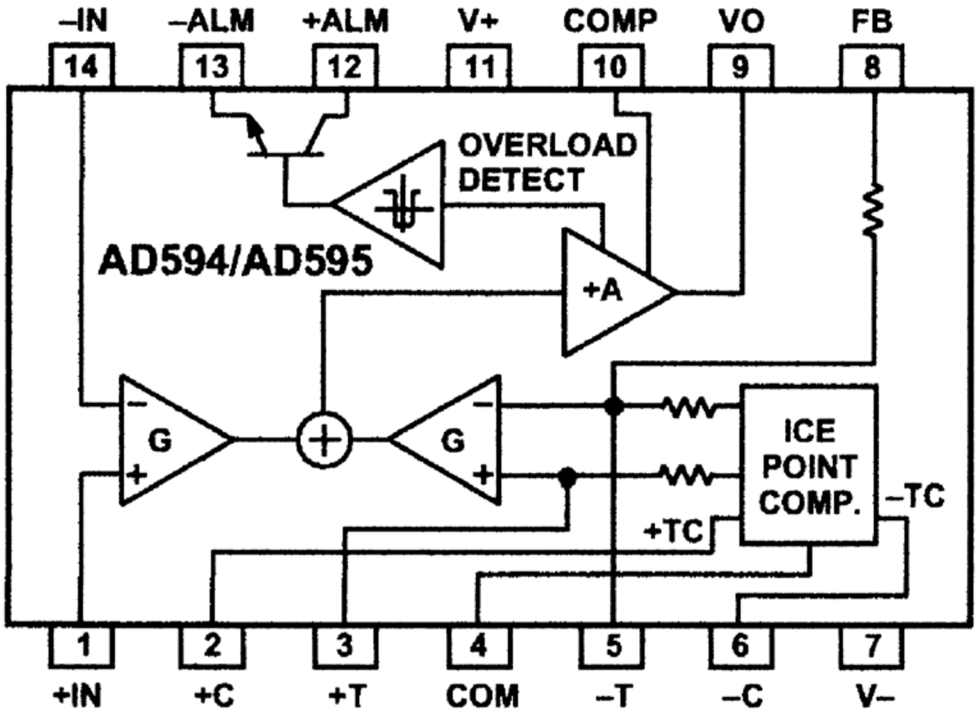


Figure 4. AD594/AD595 Block Diagram

Thermocouple Construction

- Simplest form: two bare wires with their ends soldered or welded to form a junction. Can also put wires and junction into a metal sheath.
-

•use mineral insulation (e.g. magnesium oxide) between wires and sheath. Therefore called “mineral insulated thermocouple probe”.

•sheath protects thermocouple from corrosion, abrasion, etc.

•Sheathed thermocouple will have significantly slower response time than bare thermocouple.

Extension Wires

•In order to make a thermocouple conform to some precisely defined e.m.f-temperature characteristic described by standard tables, it is necessary that all metals used are refined to a high degree of pureness and all alloys are manufactured to an exact specification.

•This makes the materials used expensive, and consequently thermocouples are typically only a few centimetres long.

•This raises the problem of where to put the reference junction.

Extension Wires

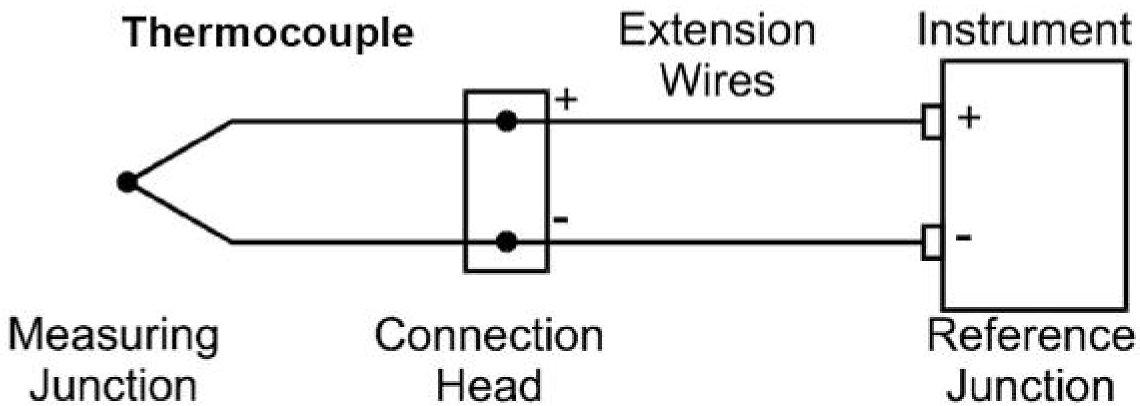
•The reference junction will be at the point where the thermocouple joins the wires leading to the meter.

•To make the reference junction close to the meter, we need to use extension leads made from the same material as the thermocouple - or at least materials with same temperature characteristics as thermocouple wires over specified temperature range.

•For base metal thermocouples – use extension leads made from the same metal as the higher grade thermocouple material.

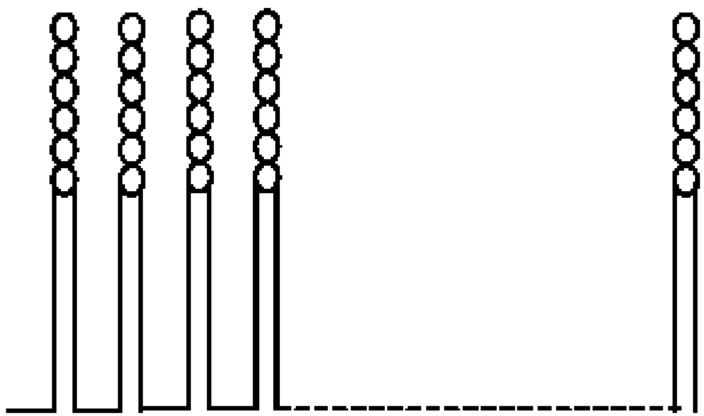
•For platinum thermocouples, use copper alloy with the same thermoelectric behaviour, at least over a narrow, defined, temperature range.

Use of Extension Wires



The thermopile

The thermopile is the name given to a temperature measuring device which consists of several thermocouples connected together in series, such that all the reference junctions are at the same cold temperature and all the hot junctions are exposed to the temperature being measured, as shown below.



The effect of connecting *n* thermocouples together in series is to increase the measurement sensitivity by a factor of *n*. A typical thermopile manufactured by connecting together 25 chromel-constantan thermocouples gives a measurement resolution of 0.001 ^{0}C.

Junction Semiconductor Temperature Sensors

It is common to come across integrated semiconductor temperature sensors. These are very often presented as 'connect to the power supply and measure the output temperature' devices. They operate on the principle that semiconductors such as diodes and transistors are temperature dependent and if two identical silicon transistors are operated at a constant ratio of collector current densities r, the differences in their emitter base voltages can be expressed in terms of the absolute temperature.

The operation of these devices is based on the temperature dependence of the Ebers-Moll equation for a junction transistor.

$$I_C = I_S\left[\exp\left(\frac{V_{BE}}{kT}q\right) - 1\right] \qquad (1)$$

where

q = electronic charge
I_C = collector current
I_S = reverse saturation current
V_{BE} = Base-Emitter voltage
k = Boltzmann's constant
T = Absolute temperature

Junction Semiconductor Temperature Sensors

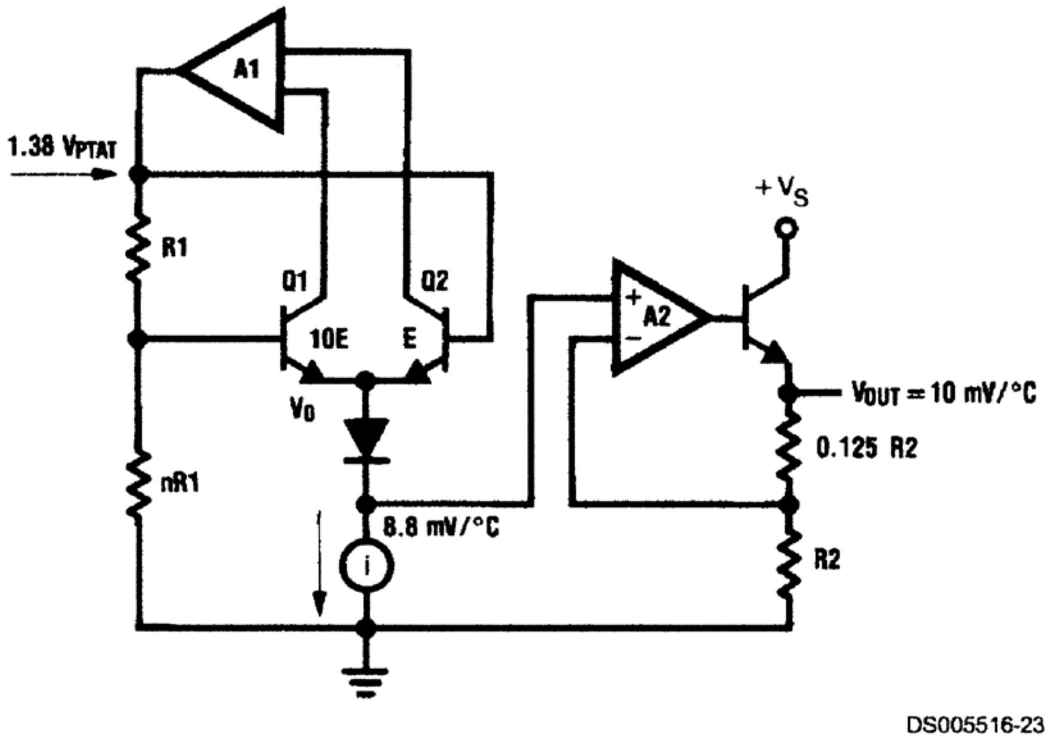
From (1) we have $\ln\left(\frac{I_C}{I_S}+1\right)=V_{BE}\frac{q}{kT}$ and when I_C is large compared to I_S, which is the normal case, this can be written as $V_{BE}=\frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$

Therefore, for two identical transducers 1 and 2, operating at different currents I_C,

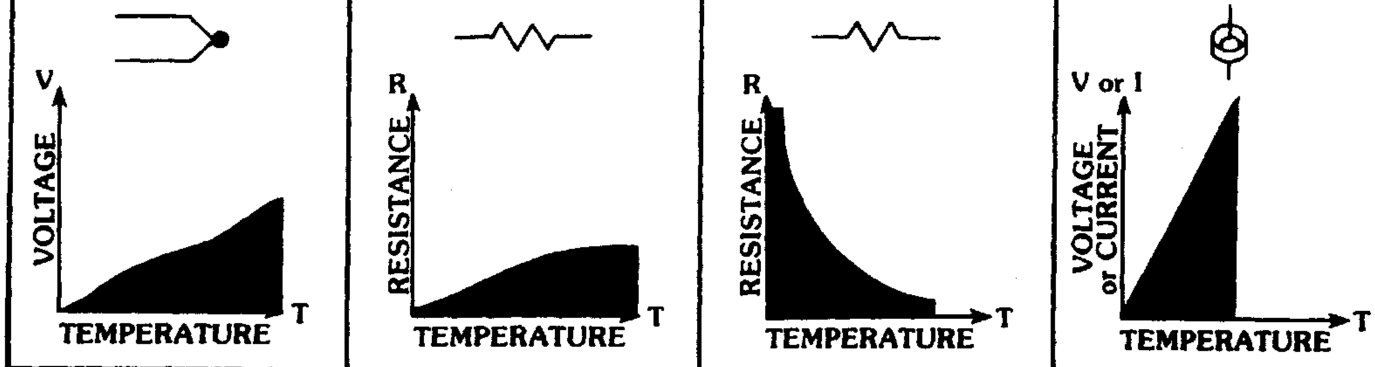
$$V_{BE_1}-V_{BE_2}=\frac{kT}{q}\ln\left(\frac{I_{C_1}}{I_{C_2}}\right) \qquad (2)$$

At 20 °C, for example, ΔV_{BE}=25.3 mV $\ln(I_{C1}/I_{C2})$. Given fixed currents we can use (2) as the basis of an integrated circuit temperature sensor.

LM35 temperature sensor IC



LM35 is a 3 pin IC package. Powered by 5-30 Vdc, produces output 10 mV/°C.



	Thermocouple	RTD	Thermistor	I.C. Sensor
Advantages	☐ Self-powered ☐ Simple ☐ Rugged ☐ Inexpensive ☐ Wide variety ☐ 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 ☐ Current source required ☐ Small ΔR ☐ Low absolute resistance ☐ Self-heating	☐ Non-linear ☐ Limited temperature range ☐ Fragile ☐ Current source required ☐ Self-heating	☐ $T < 200°C$ ☐ Power supply required ☐ Slow ☐ Self-heating ☐ Limited configurations

FIGURE 2 – Four most commonly employed temperature transducers (Courtesy of Omega Engineering Inc, USA).

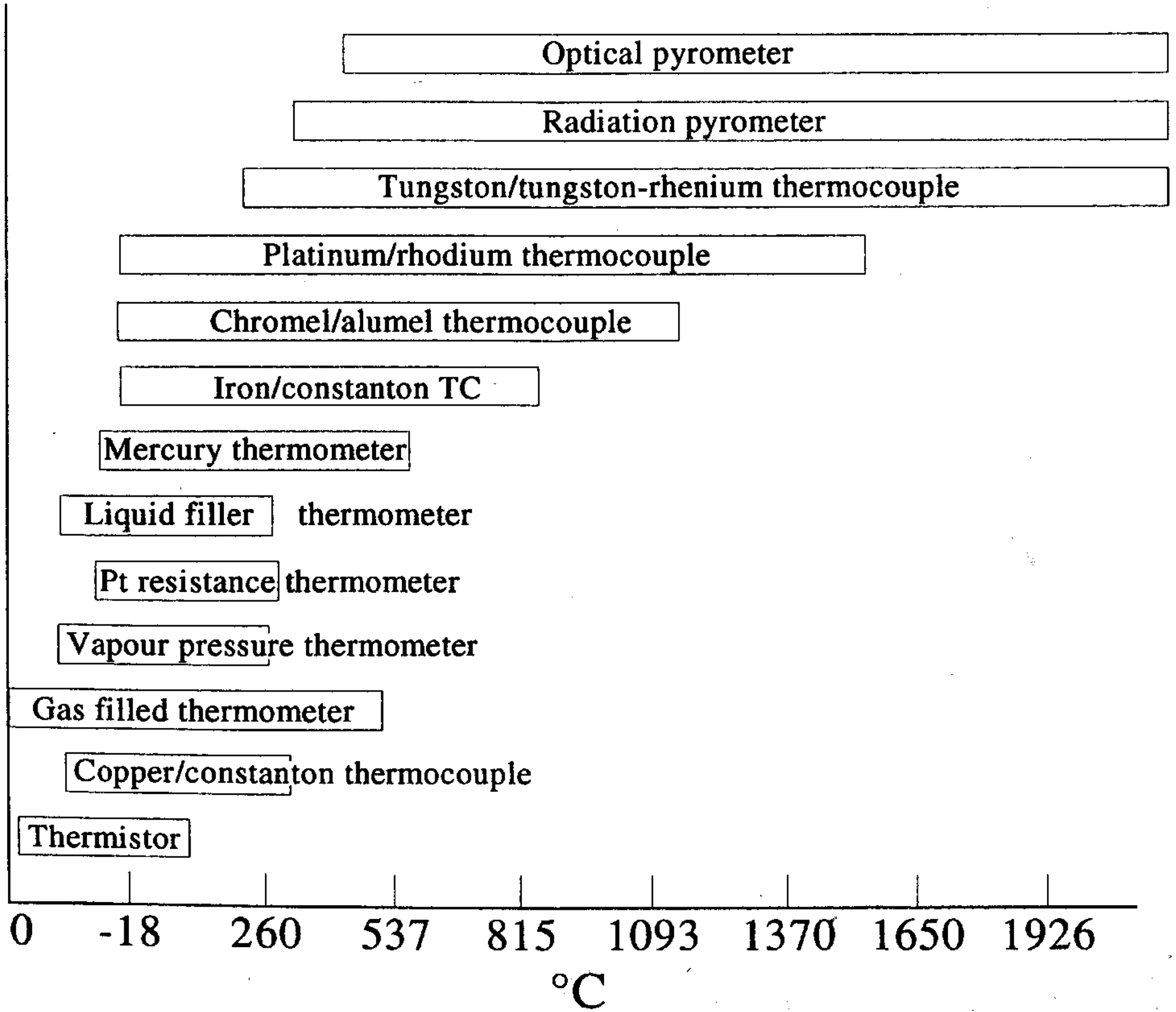


FIGURE 1 – Ranges of temperature measuring instruments.

Dynamic Response of Thermal Sensors

•The thermal sensors we have discussed operate by being placed in contact with the system whose temperature is to be measured.

•The sensor must reach thermal equilibrium with the system.

•Heat must flow in or out.

•This takes time. The time depends on the heat capacity of the sensor, the effective area through which heat can flow and the heat transfer coefficient across the surface.

Dynamic Response of Thermal Sensors

- The heat transfer is driven by the temperature difference across the surface.

- $W = U A (T_{\text{ext}} - T)$

- Where

- W is the rate of heat transfer (Watts)
- U is the heat transfer coefficient (Watts m^{-2} $°C^{-1}$)
- A is the effective area for heat transfer (m^2)
- T_{ext} is the external temperature

Dynamic Response of Thermal Sensors

- W is the rate of increase of thermal energy of the sensor:

$$W = \frac{dQ}{dt} = cm\frac{dT}{dt}$$

  - Where:

  - Q = thermal energy (Joules)
  - c = specific heat capacity of sensor material (J kg^{-1} C^{-1})
  - m = mass of sensor (kg)

Dynamic Response of Thermal Sensors

- Equating the two expressions:

$$cm\frac{dT(t)}{dt} = UA\left(T_{ext} - T(t)\right)$$

or

$$\tau\frac{dT(t)}{dt} = \left(T_{ext} - T(t)\right)$$

where

$$\tau = \left(\frac{cm}{UA}\right)$$

τ is the *time constant* of the sensor.

- This is a first order differential equation. Temperature sensors such as this are first order systems because their dynamics are governed by a first order equation.

Step Function Response

- Imagine taking a cold thermocouple and plunging it suddenly into hot water. This is a good approximation to a step function input. The solution of the previous equation, corresponding to a temperature step function input, from initial temperature T_i to final temperature T_f is:

$$T(t) = (T_f - T_i)\left[1 - e^{-\frac{t}{\tau}}\right] + T_i$$

or

$$T = \Delta T\left[1 - e^{-\frac{t}{\tau}}\right] + \text{Offset Temp}$$

First Order Step Response