Lecture 4

Temperature measurement – Chapter 8

What is temperature trying to characterize?

- Temperature is a measure of the internal energy of matter.
  - Gas constant given in J/mole K
  - Boltzmann's constant given in J/atom K
  - Avogadro's constant relates moles to atoms
  - RT, kT represent the thermal energy of moles or atoms
- Temperature is defined by certain energy transitions *(How were those energy transitions defined?)*
  - Ice-water equilibrium at atmospheric pressure is 0°C
  - Water-water vapor equilibrium at atmospheric pressure is 100 °C
  - Triple point of water 273.16 K (0.01°C)
  - Triple point of hydrogen – 13.8 K
  - Melting point of gold at 1 atm – 1337.33 K
  - Melting point of gallium at 1 atm – 302.91 K
- Wikipedia has an interesting article on how absolute zero is defined.
  - http://en.wikipedia.org/wiki/Absolute_zero

Types of temperature sensors

- Thermometers based on liquid expansion
- Resistance temperature devices
- Thermistors
- Thermocouples
- Optical sensors based on absorption of radiated energy
  - Semiconductor
  - Pyrometer
  - Thermopile

Temperature devices based on resistance change with temperature

- Resistance of metals increases with increasing temperature
  - Mean free path of electrons decreases as the amplitude of the oscillation of the atoms increases.
  - Sensors based on this principle in metals are called RTD’s
- Resistance of semiconductors and semiconducting oxides decreases with temperatures
  - Greater fraction of electrons can exceed the valence electron-conduction electron bandgap as the thermal energy of the electrons increases.
  - Sensors based on these materials are generally called thermistors.

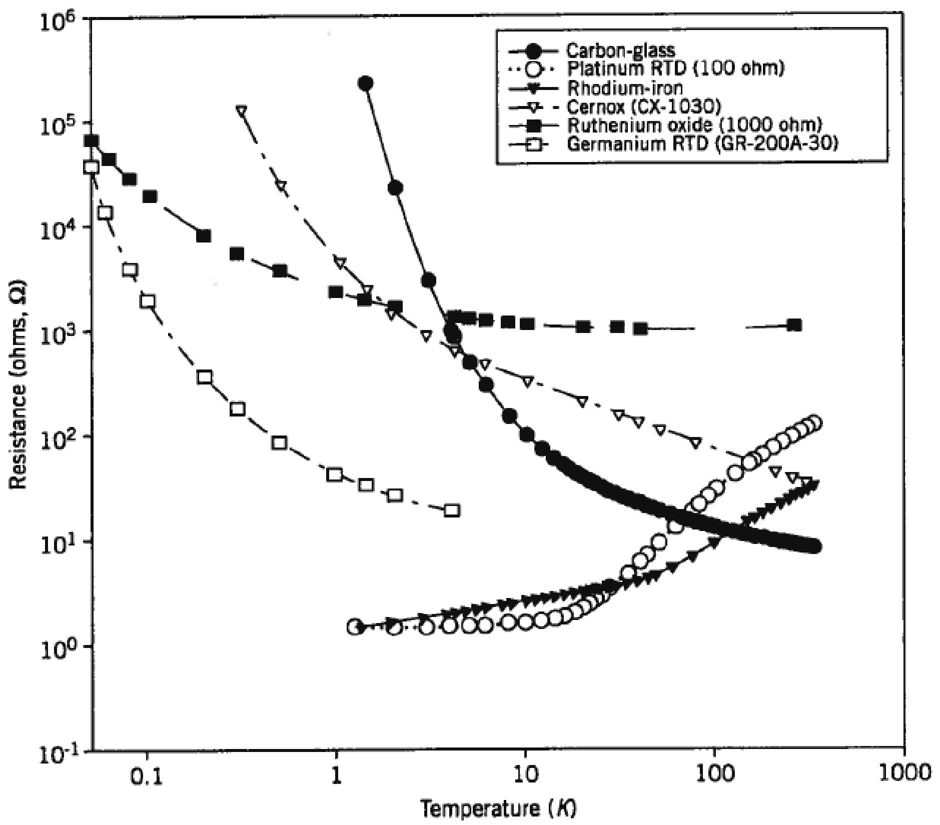
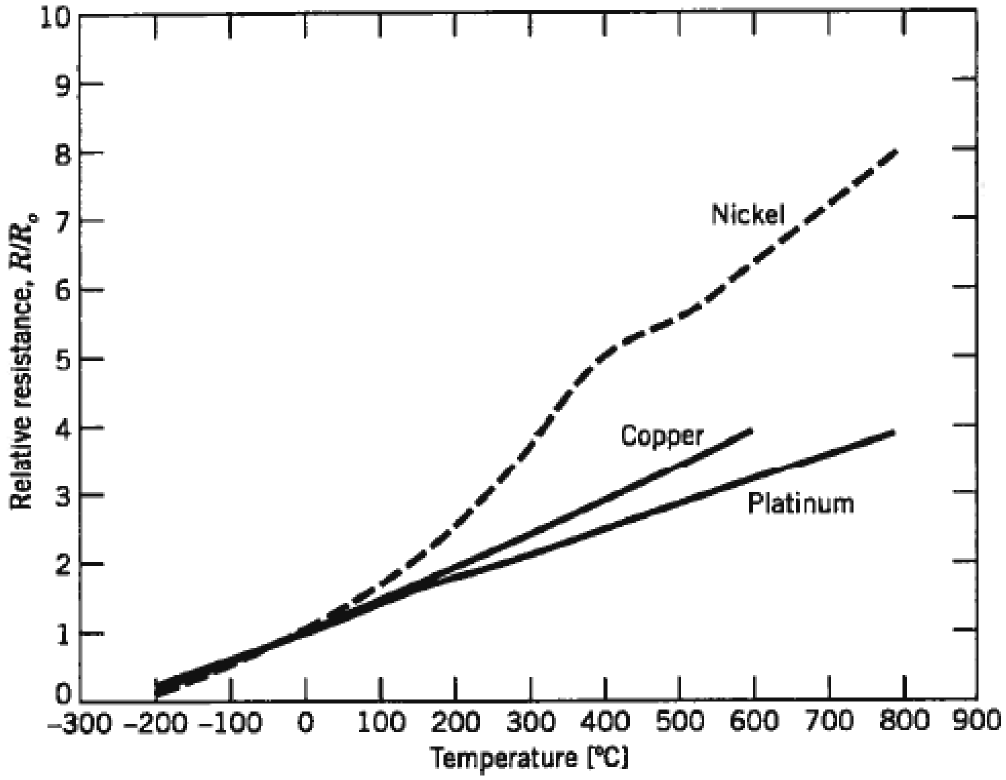
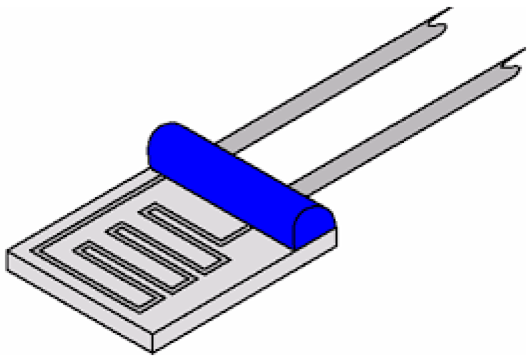


Figure 8.4 Resistance as a function of temperature for selected materials used as temperature sensors. (Adapted from Yeager, C. J. and S. S. Courts, A Review of Cryogenic Thermometry and Common Temperature Sensors, *IEEE Sensors Journal*, 1 (4), 2001.)

RTD's





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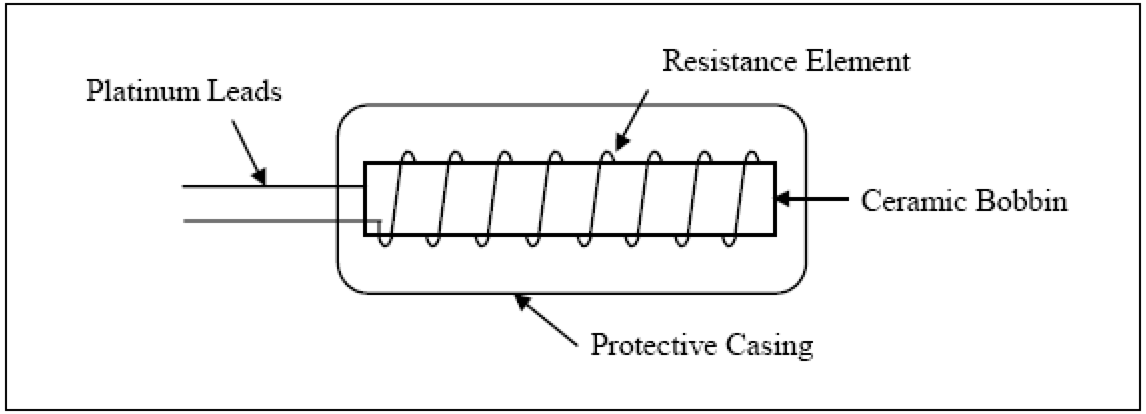


Figure 7-14. Typical RTD – resistance temperature detectors

http://www.globalspec.com/RefArticleImages/14C30B12BB33EFDB238326585A818CDB_07_39.gif

Platinum is material of choice for RTD's due to high linearity and stability (Cu oxidizes)

Linearity ±0.3% from 0-200°C and ±1.2% from 200-800°C.

Strain gages are based on resistance changes of this magnitude so RTD designers avoid or compensate and correct for strain in Pt.

Constants depend on purity.

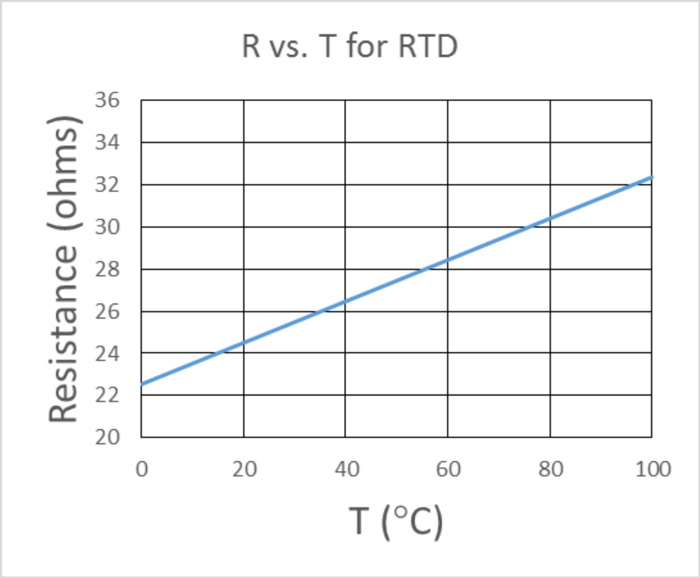
Can have uncertainty as low as ±0.005°C.

Wheatstone bridges typically used to measure R. Must correct for leadwire resistance.

$$R = R_o\left(1+\alpha\left(T-T_o\right)+\beta\left(T-T_o\right)^2+....\right)$$

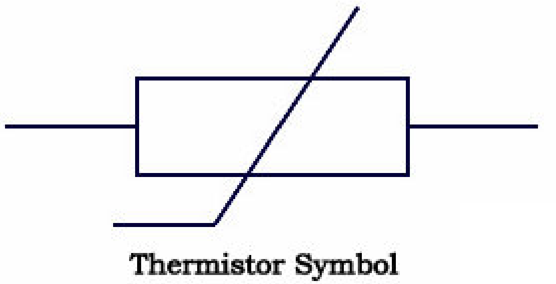
$$\cong R_o\left(1+\alpha\left(T-T_o\right)\right)$$

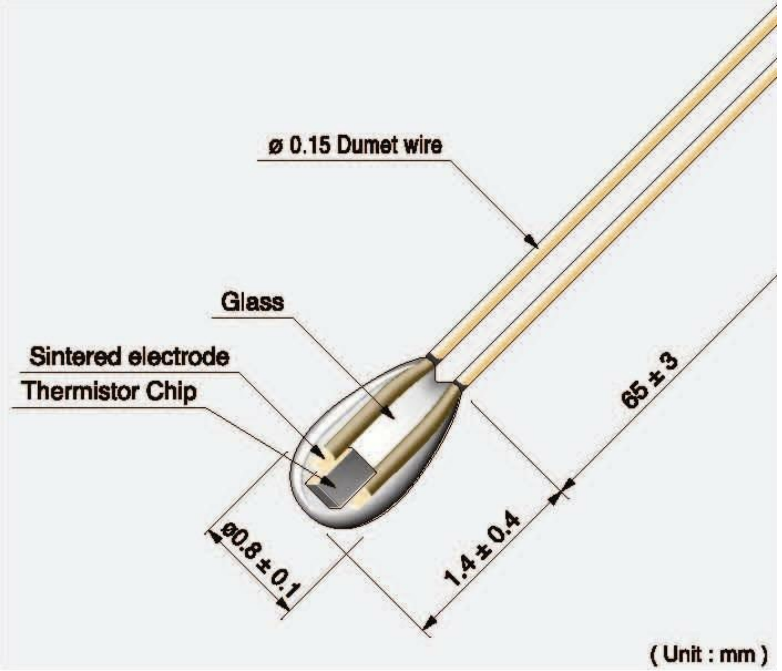
$$\alpha_{Pt} = 0.003927\,/^o\,C$$

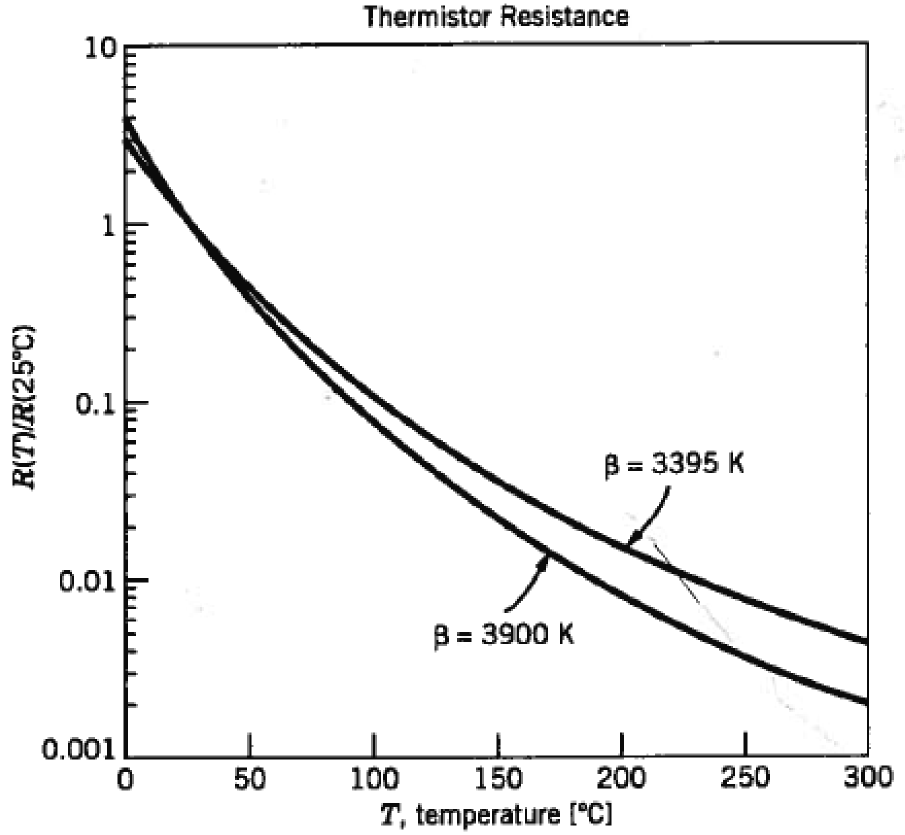


Thermistors typically decrease in resistance with increasing temperature

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







http://i01.i.aliimg.com/wsphoto/v0/579017211_1/NTC-thermistor-PT5-51F-R100-3-3KOhms-R25-49-12KOhms-operating-temp-50C-to-250C-fast.jpg

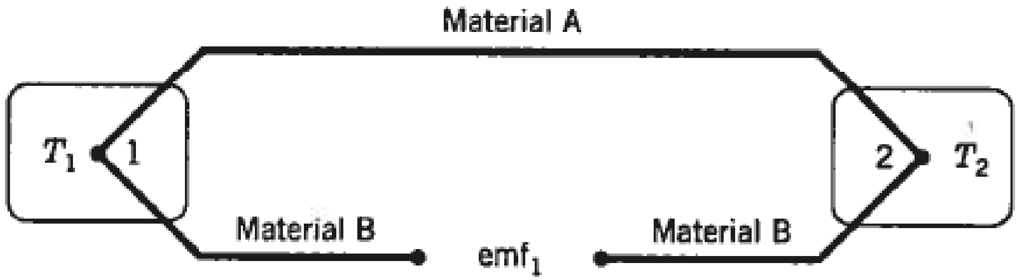
Thermoelectric temperature measurement

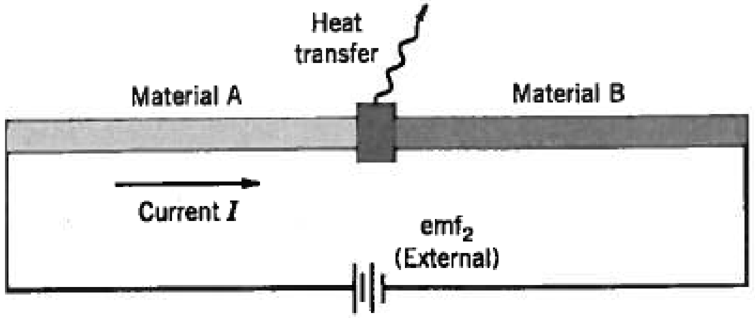
$$\alpha_{AB} = \left[\frac{\partial(emf)}{\partial T}\right]_{open\ circuit} \qquad Seebeck\ \ Effect$$

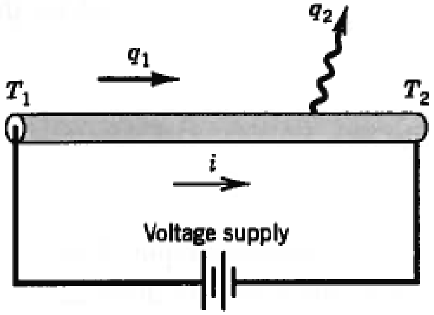
$$Q = \pi_{AB} I \qquad Peltier\ \ Effect$$

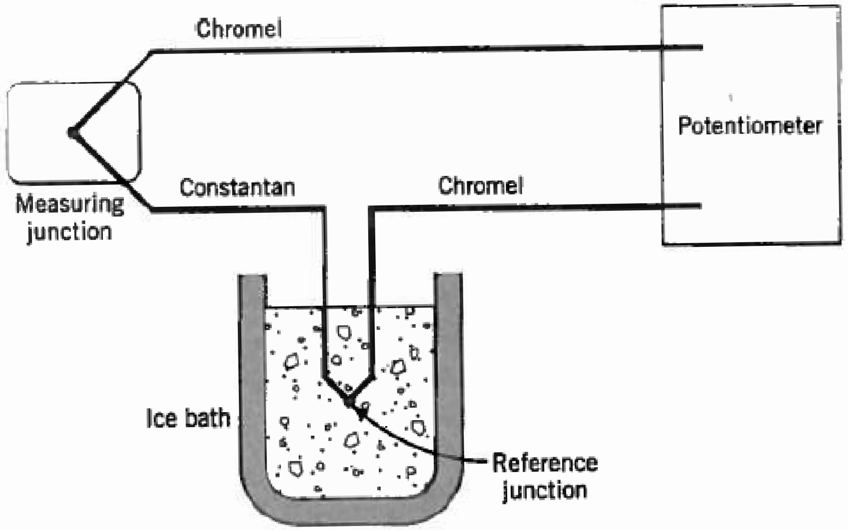
$$\pi_{AB} = \alpha_{AB} T$$

$$Q_\sigma = \sigma I (T_1 - T_2) \qquad Thomson\ \ Effect$$

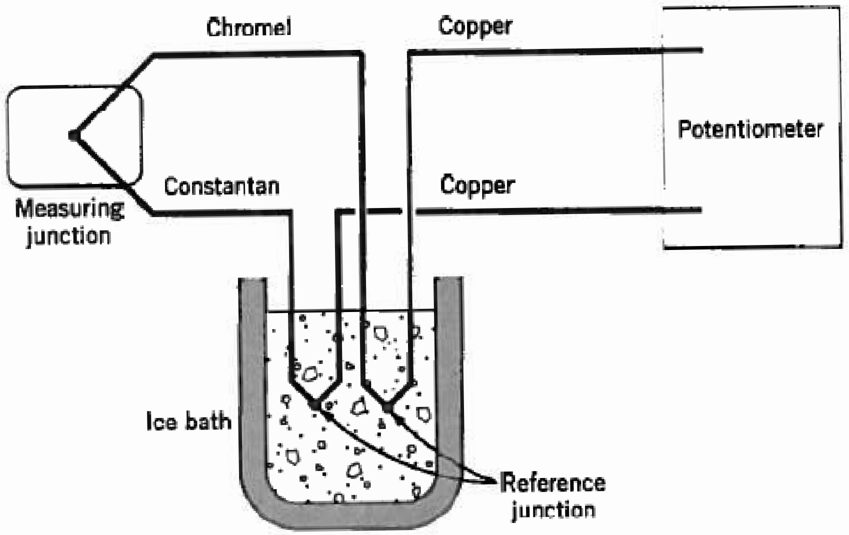




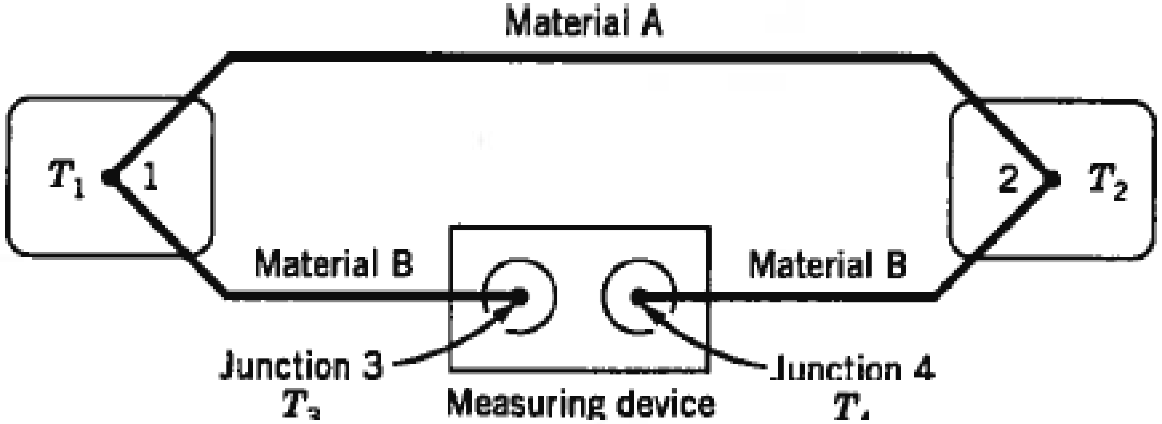


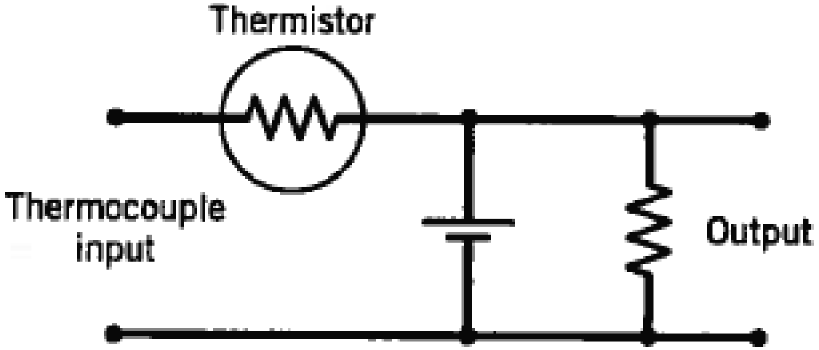

Chromel
Potentiometer
Measuring junction
Constantan
Chromel
Ice bath
Reference junction

(a)


Chromel
Copper
Potentiometer
Measuring junction
Constantan
Copper
Ice bath
Reference junction

(b)


Material A
T_1
1
2
T_2
Material B
Material B
Junction 3
Measuring device
Junction 4


Thermistor
Thermocouple input
Output

Thermocouple combinations

Table 8.4 Thermocouple Designations

Type	Material Combination: Positive	Negative	Applications
E	Chromel(+)	Constantan(−)	Highest sensitivity (<1000°C)
J	Iron(+)	Constantan(−)	Nonoxidizing environment (<760°C)
K	Chromel(+)	Alumel(−)	High temperature (<1372°C)
S	Platinum/ 10% rhodium	Platinum(−)	Long-term stability high temperature (<1768°C)
T	Copper(+)	Constantan(−)	Reducing or vacuum environments (<400°C)

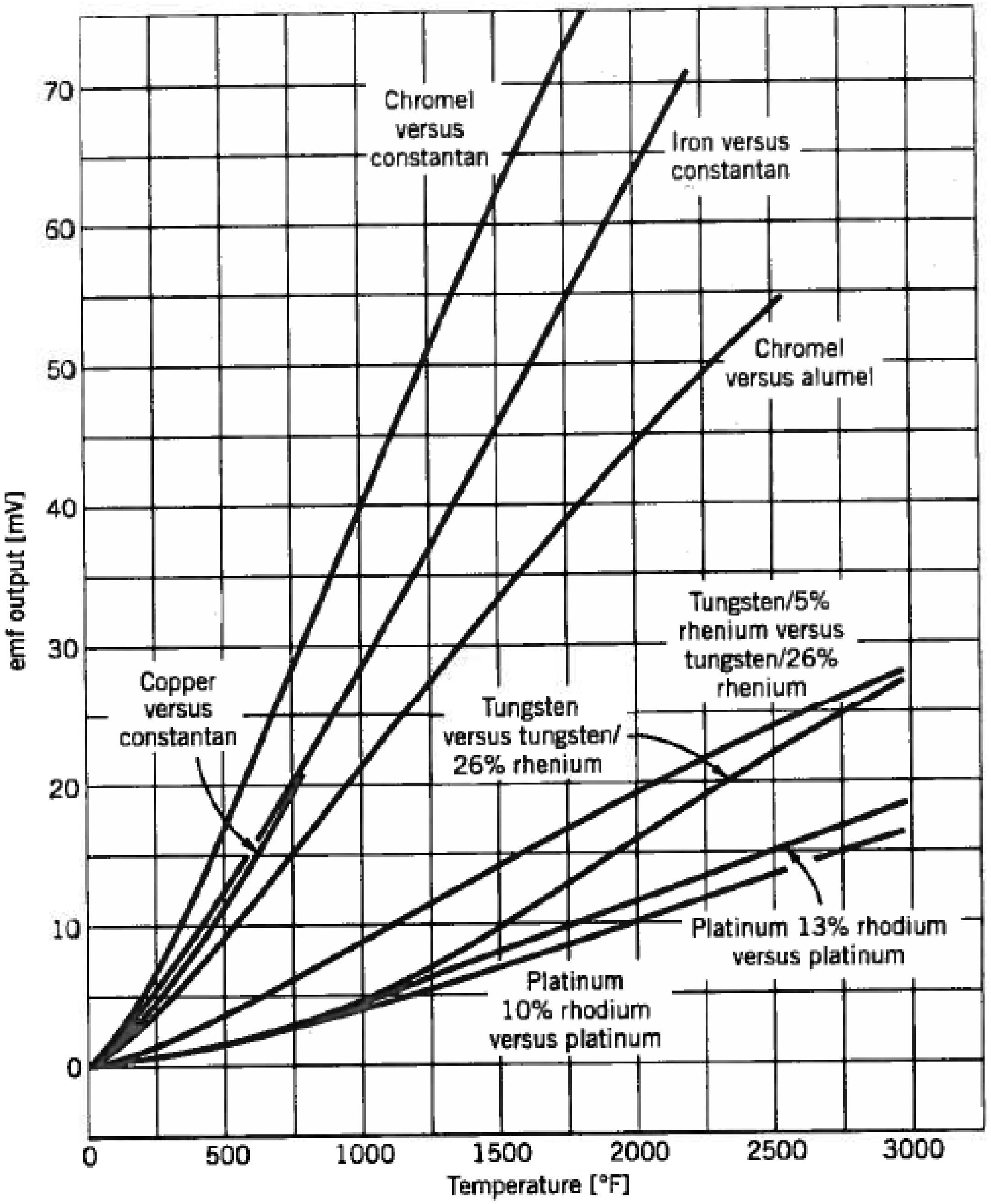


Table 8.5 Standard Thermocouple Compositions[a]

	Wire		
Type	Positive	Negative	Expected Systematic Uncertainty[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%

Alloy Designations

Constantan: 55% copper with 45% nickel

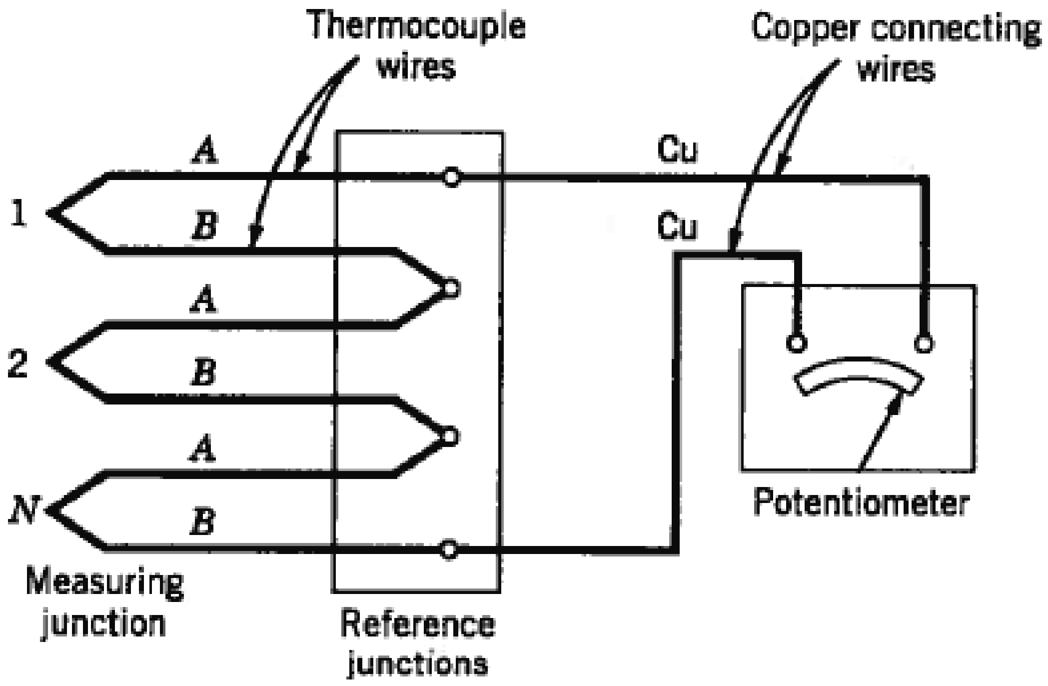
Chromel: 90% nickel with 10% chromium

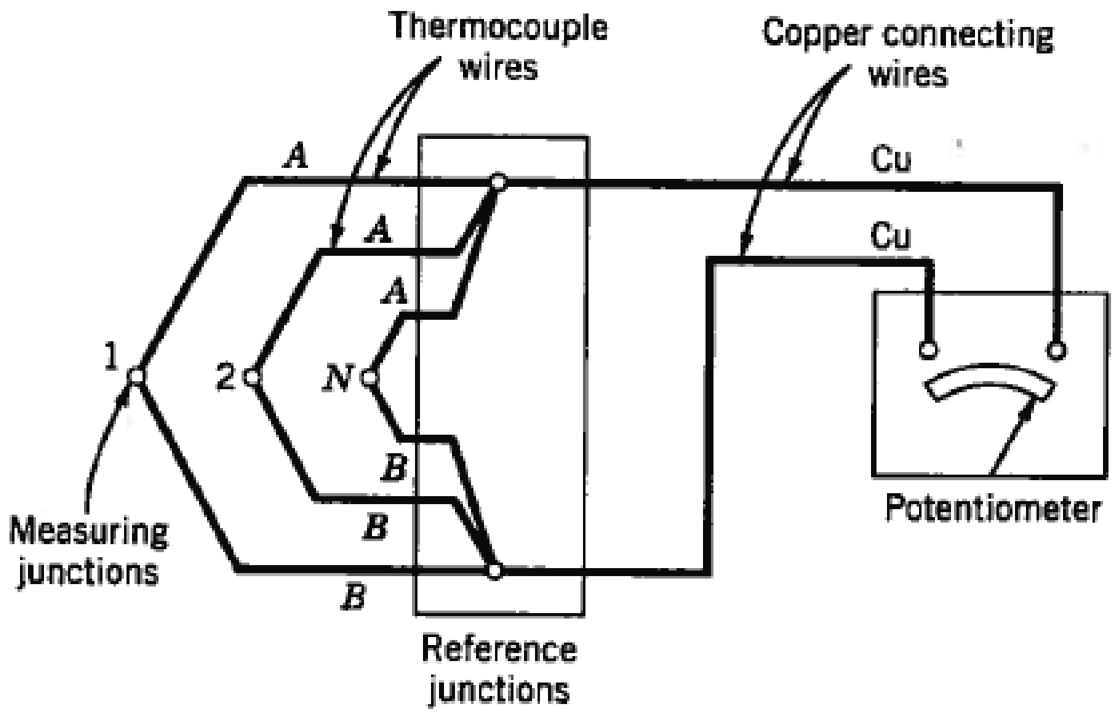
Alumel: 94% nickel with 3% manganese, 2% aluminum, and 1% silicon

[a]From Temperature Measurements ANSI PTC 19.3-1974.

[b]Use greater value; these limits of error do not include installation errors.

Thermopile vs. thermocouples in parallel.





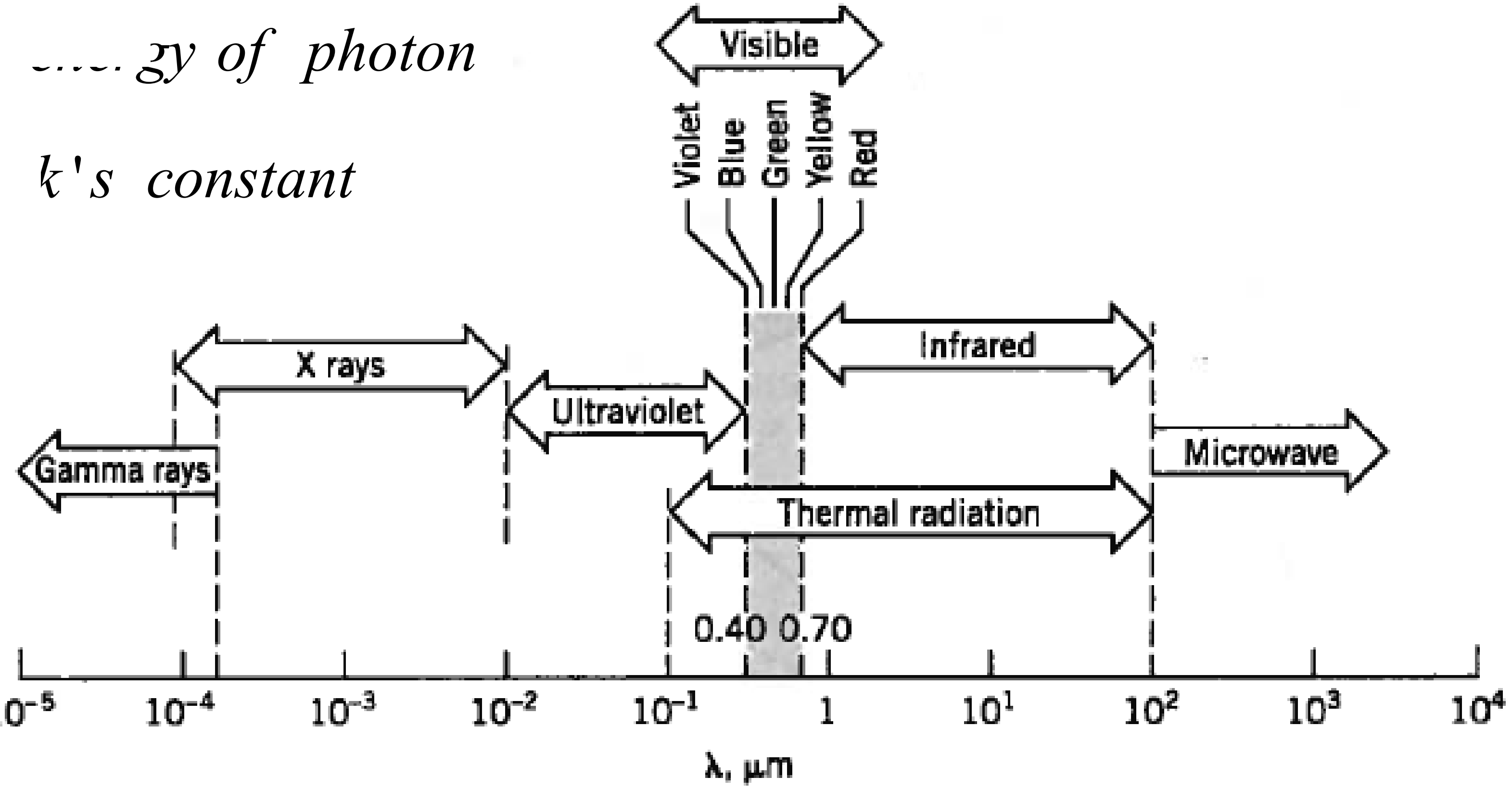
$$emf = \sum_{i=1}^{N} (emf)_i$$

$$emf = \frac{1}{N} \sum_{i=1}^{N} (emf)_i$$

Radiative temperature measurements
Electromagnetic spectrum

$E = \frac{\hbar}{\lambda}$ ... gy of photon

$\hbar$ ... k's constant



Ideal, blackbody radiator

$$E_b = \sigma T^4$$

$$\sigma = emissivity$$

$$E_{b\lambda} = \frac{2\pi h_p c^2}{\lambda^5 \left[\exp\left(h_p c / k_B T\right) - 1\right]}$$

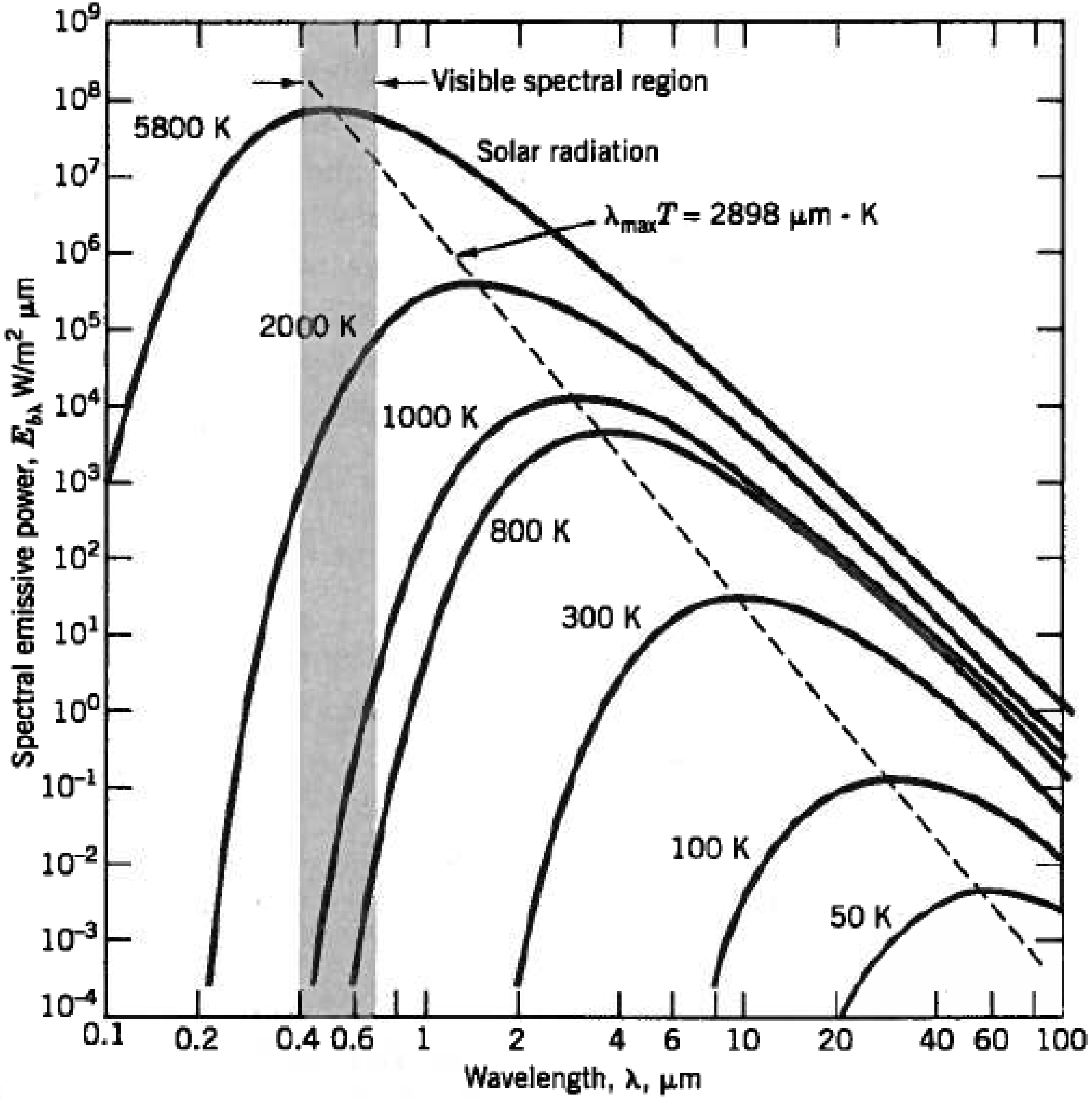
$$= total\ emissive\ power$$

$$\lambda = wavelength$$

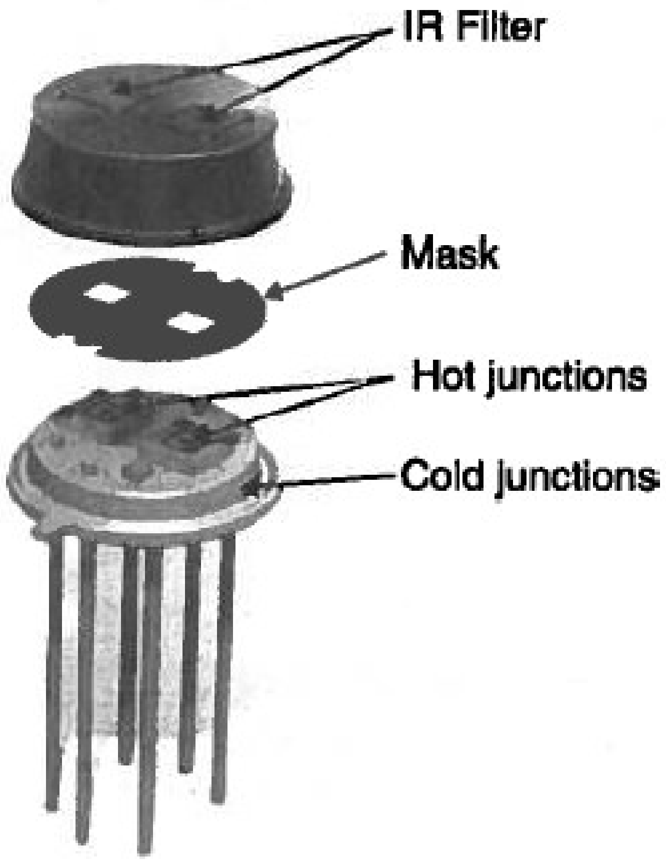
$$c = speed\ of\ light$$

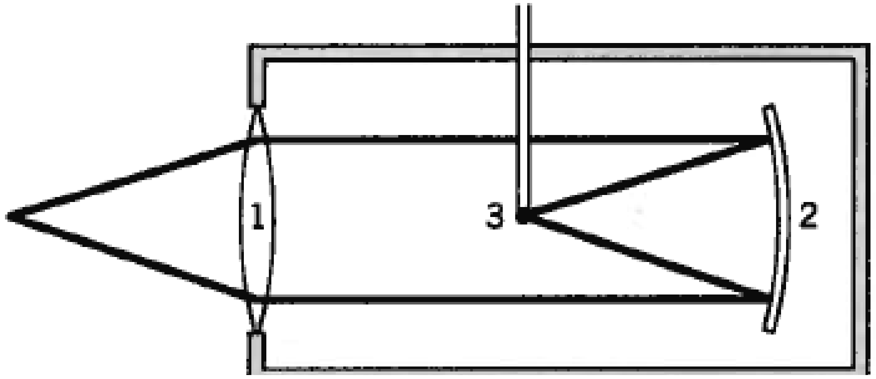
$$h_p = Planck's\ constant$$

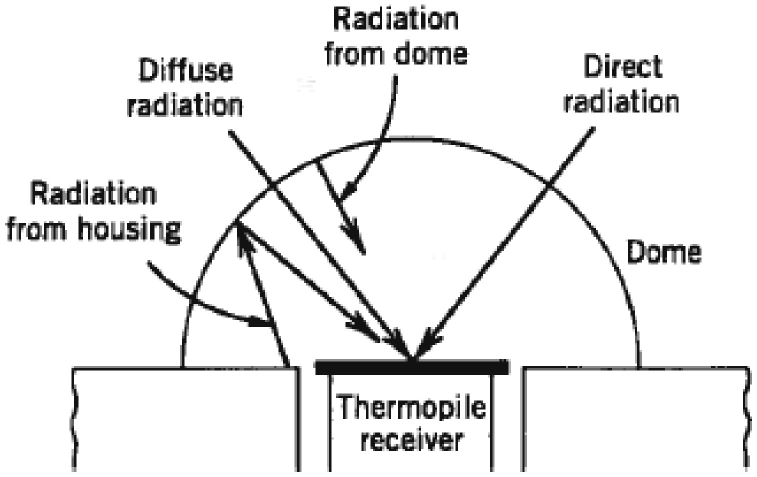
$$k_B = Boltzmann's\ constant$$



Radiometer uses thermopile to measure temperature rise from (optical) radiation hitting hot junction.







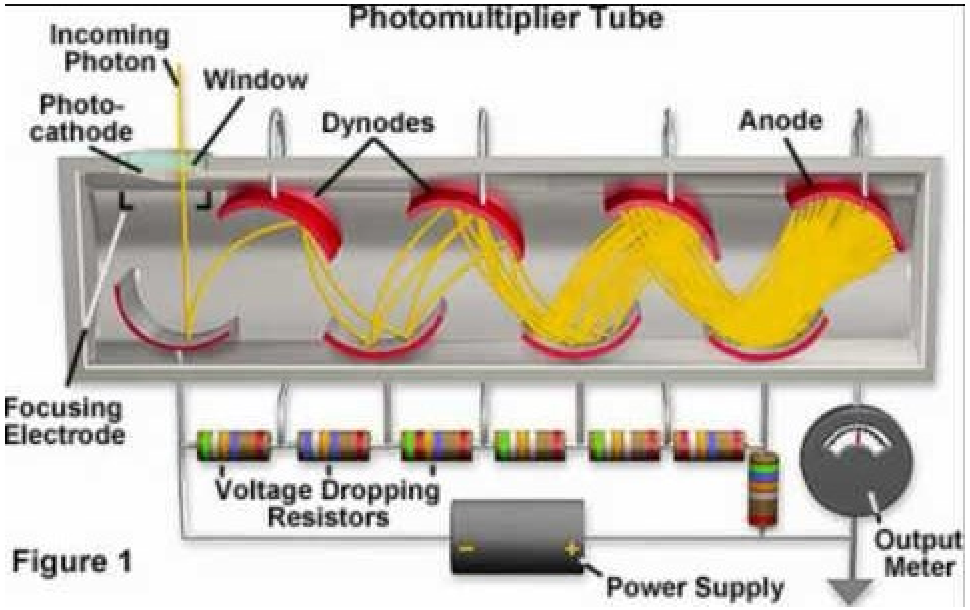
Disappearing-Filament Pyrometer Lamp Superimposed on Target

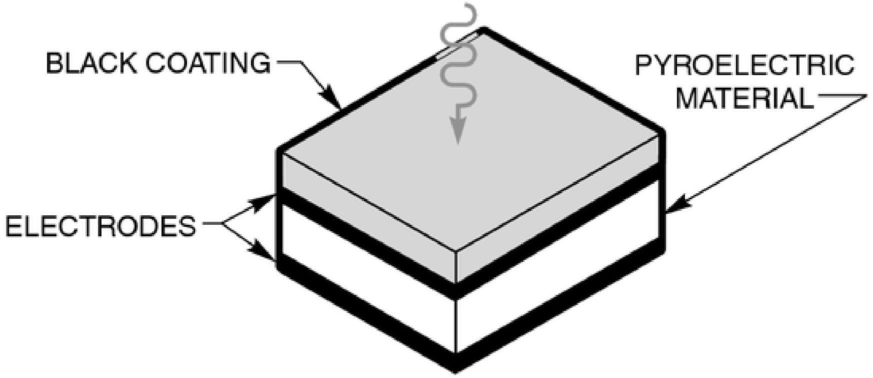
Temperature Reading is Too Low

Correct Temperature Reading

Temperature Reading is Too High

Photomultiplier tubes, semiconductor photovoltaic sensors, pyroelectric sensors





Pyroelectricity is like piezoelectricity except heat generates charge

http://assets.newport.com/web600w-EN/images/2496.gif

IR cameras work just like regular digital cameras but the sensor array is composed of a narrow band gap semiconductor in the IR region or microbolometers – can have 0.1°C resolution

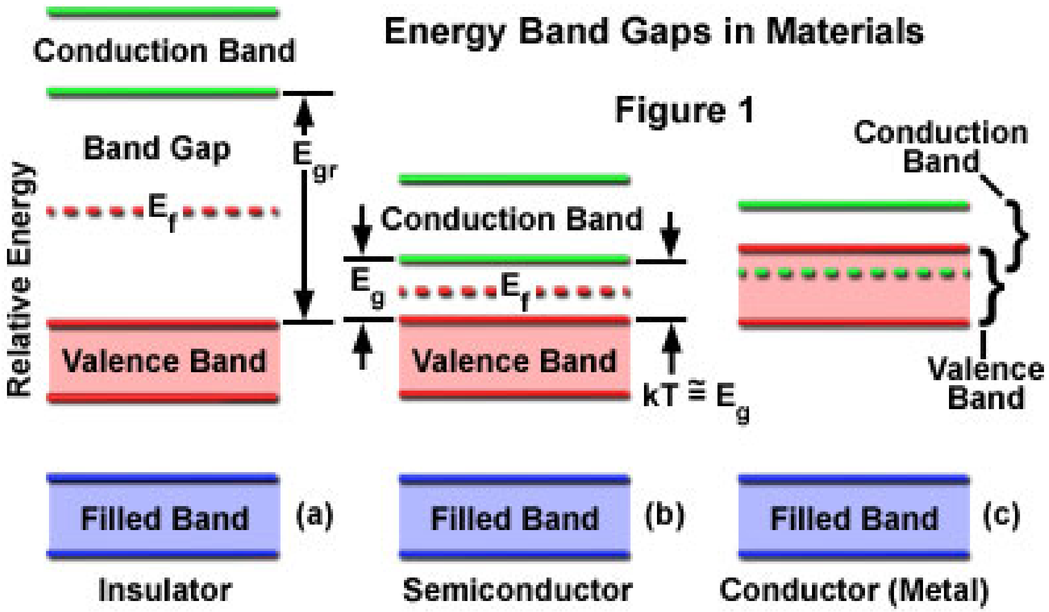
- Sensor types – cooled arrays
  - indium antimonide (3-5 μm)
  - indium arsenide
  - mercury cadmium telluride (MCT) (1-2 μm, 3-5 μm, 8-12 μm)
  - lead sulfide
  - lead selenide

- Sensor types – uncooled arrays
  - vanadium(V) oxide (metal insulator phase change material, for microbolometer arrays)
  - lanthanum barium manganite (LBMO, metal insulator phase change material)
  - amorphous silicon
  - lead zirconate titanate (PZT)
  - lanthanum doped lead zirconate titanate (PLZT)
  - lead scandium tantalate (PST)
  - lead lanthanum titanate (PLT)

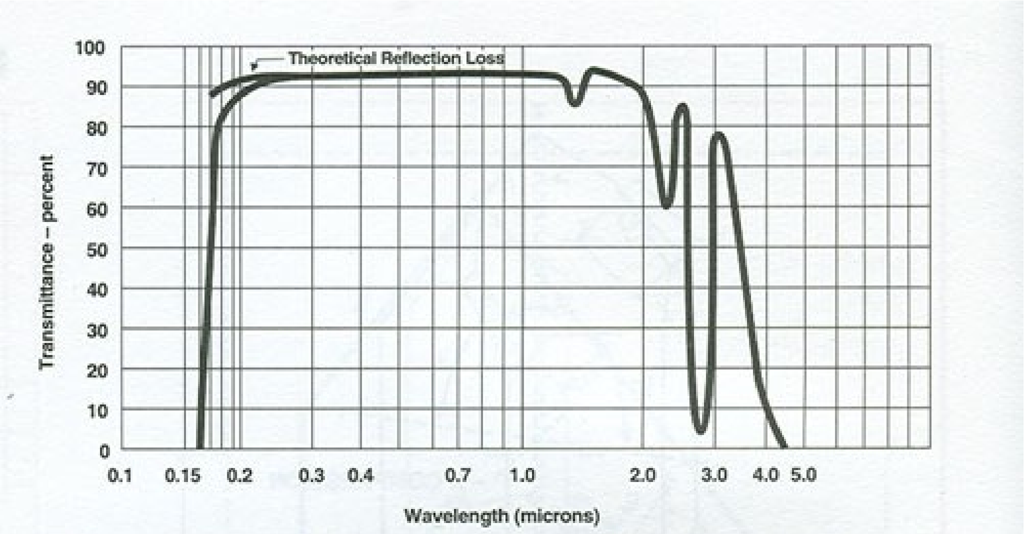
http://en.wikipedia.org/wiki/Thermographic_camera

Narrow band gap means larger wavelength

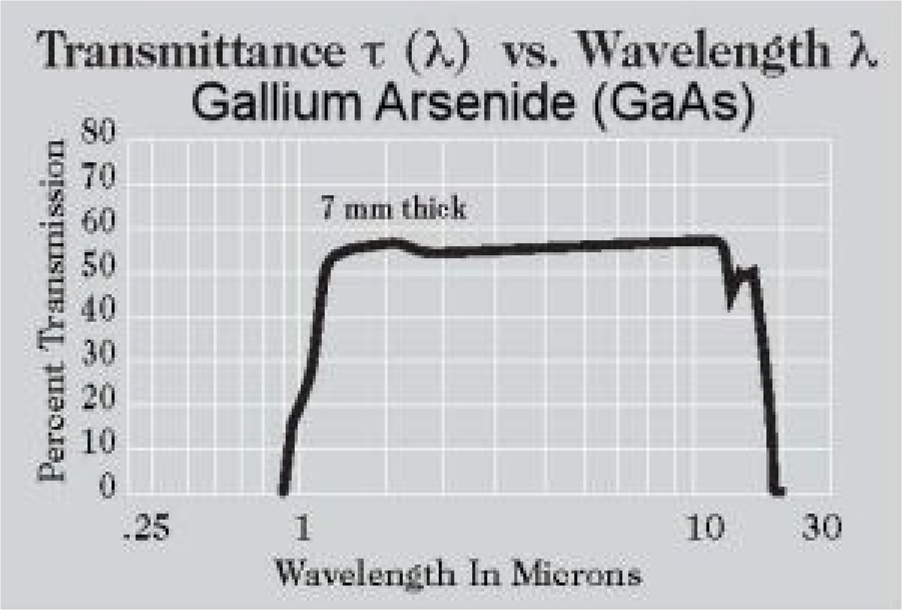
$$E = \cdot\frac{\hbar}{\lambda}$$



Transmittance of different materials in the UV to IR range – IR optics



Transmission through 10mm Thickness of Optical Fused Silica



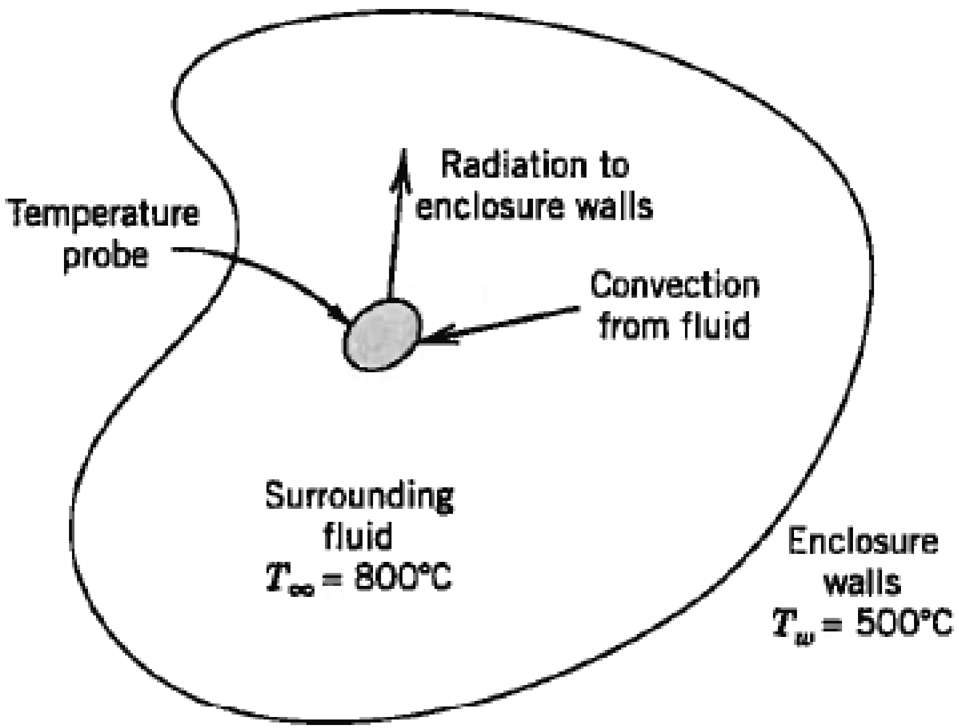
http://www.janis.com/Libraries/Window_Transmissions/GalliumArsenide_GaAs_TransmissionCurve_sm.sflb.ashx

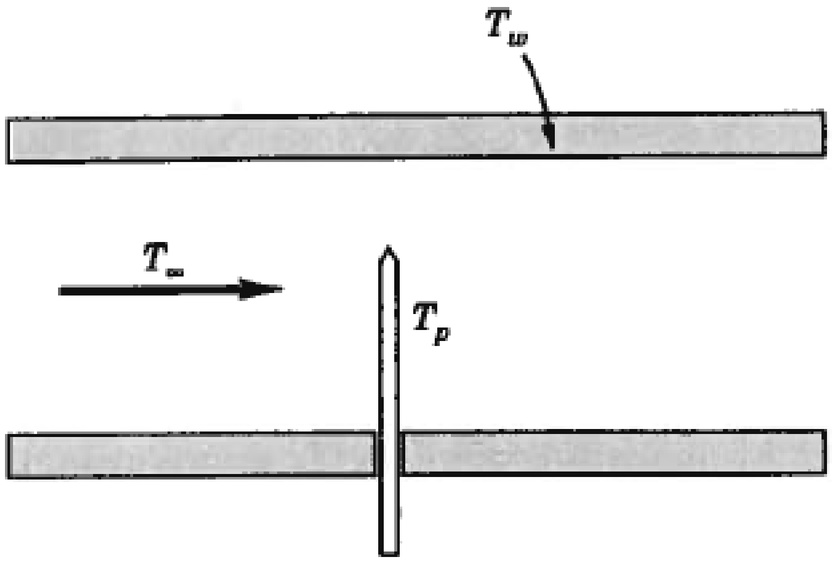
http://www.janis.com/products/AccessoriesandAncillaryEquipment/WindowTransmissionCurves.aspx

Errors in temperature measurement

- Insertion errors
  - Conduction errors – use long, slender probes (L/d>50)
  - Radiation errors – radiation shields
  - Recovery errors – transfer of kinetic energy fluid to create heat
- Effects of plugs and extension wire
  - Non-isothermal connections
  - Loading errors
- Material evolution – sensors age, corrode, get coated
- Ground loops, induced currents from magnetic fields
- Reference junction inaccuracies

Errors in temperature measurement





Exposed thermocouple would read ~640°C for 800 °C fluid. Radiation shield with emissivity of 1 would raise sensor temperature to ~700 °C. Choosing a shield with low emissivity raises sensed temperature to ~770 °C.

Estimating probe temperature for tube with different wall and gas temperatures

From Figliola p. 360-362

Sum of convective heat transfer from gas must equal radiative heat loss to wall when in thermal equilibrium.

$$q_c + q_r = 0$$

$$q_c = hA_s\left(T_\infty - T_o\right) \quad q_r = FA_s\varepsilon\sigma\left(T_w^4 - T^4\right)$$

$$hA_s\left(T_\infty - T_p\right) = FA_s\varepsilon\sigma\left(T_p^4 - T_w^4\right)$$

$$\left(T_p - T_\infty\right) = \frac{F\varepsilon\sigma}{h}\left(T_w^4 - T_p^4\right)$$

$$\sigma = Stefan - Boltzmann\ \ constant = 5.669x10^{-8}\, W\ /\ m^2K^4$$

$$\varepsilon = emissivity$$

$$\mathrm{F = view\ \ factor}$$

$$T_\infty = 800^o\, C$$

$$T_w = 500^o\, C$$

$$\mathrm{h = 100\, W/\ m^2}\ ^o\ C$$

$$F, \varepsilon \sim 1$$

$$T_p = 642.5^o\, C$$

Note that lower emissivity probe or shielding would decrease difference.