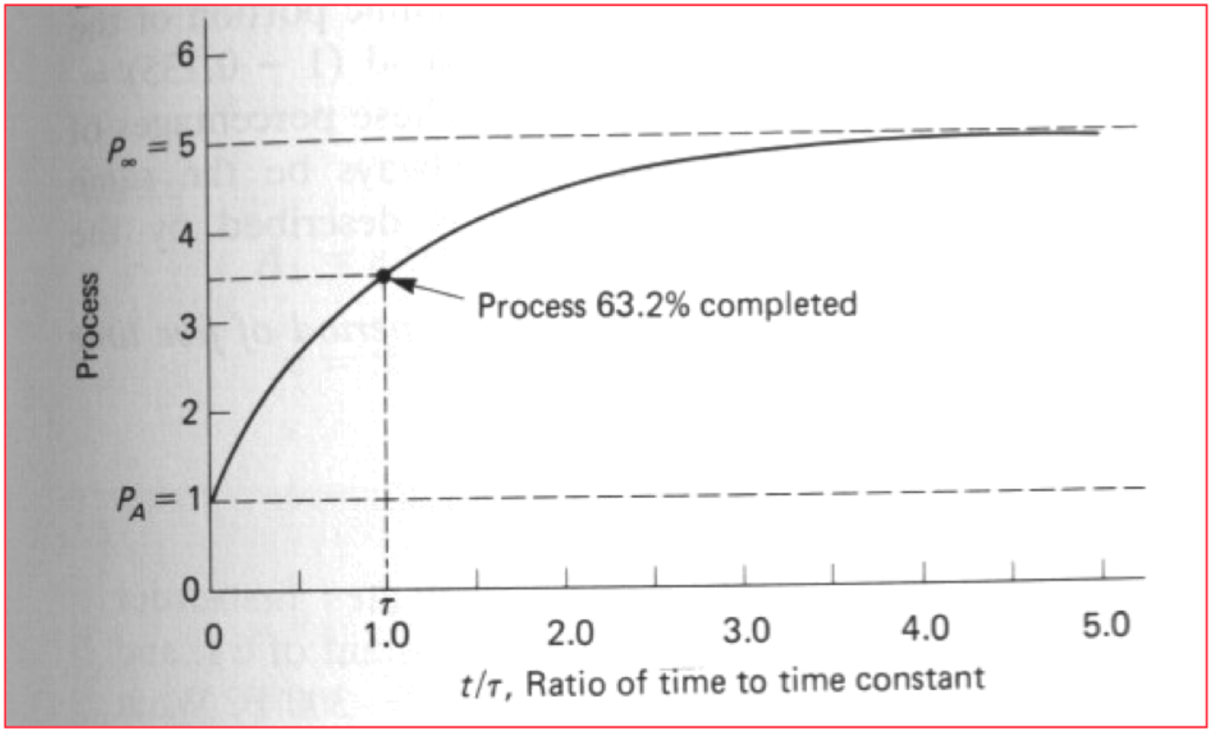
UtahState UNIVERSITY

Mechanical & Aerospace Engineering

Section 6.2 : Heat Transfer and Heat Flux Measurements



Temperature Versus Heat (1)

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

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

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

Temperature Versus Heat (2)

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

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

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

Temperature Versus Heat (3)

- Relationship between temperature and heat transfer

…. Heat flows from “cold to hot”

$$m \cdot c_p \frac{\partial T}{dt} = \frac{\partial q}{dt} \rightarrow$$

$$m \rightarrow mass\ of\ object_{\sim kg}$$

$$c_p \rightarrow specific\ heat\ of\ object_{\sim \frac{J}{kg^\circ K}}$$

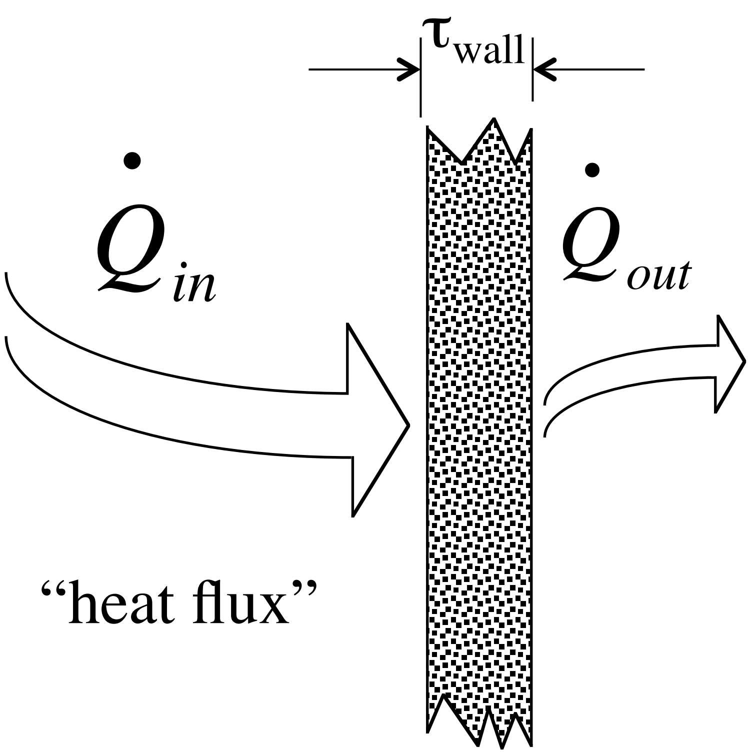
$$T \rightarrow temperature\ of\ object_{\sim^\circ K}$$

$$\frac{\partial q}{dt} \rightarrow rate\ of\ heat\ transfer_{\sim \frac{J}{\mathrm{sec}} \ldots \mathrm{watts}}$$

$$\boxed{m \cdot c_p \longrightarrow \text{“heat capacity”} \sim J/^oK}$$

Temperature Versus Heat (4)

- Example … thin monolithic wall …



$$\frac{1}{A_{surf}}\left[\left(\frac{\partial q}{dt}\right)_{in} - \left(\frac{\partial q}{dt}\right)_{out}\right] = \frac{M\cdot c_p}{A_{surf}}\frac{\partial T}{dt} \rightarrow$$

$$\boxed{\dot{Q}_{in} - \dot{Q}_{out} = \rho\cdot c_p\cdot\tau_{wall}\frac{\partial T}{dt}}$$

$$\rightarrow \dot{Q} \sim \text{"}\mathit{heat\ flux}\text{"}_{\sim\frac{J}{m_2 \sec}}$$

If more heat *goes in* than *goes out* … temperature rises

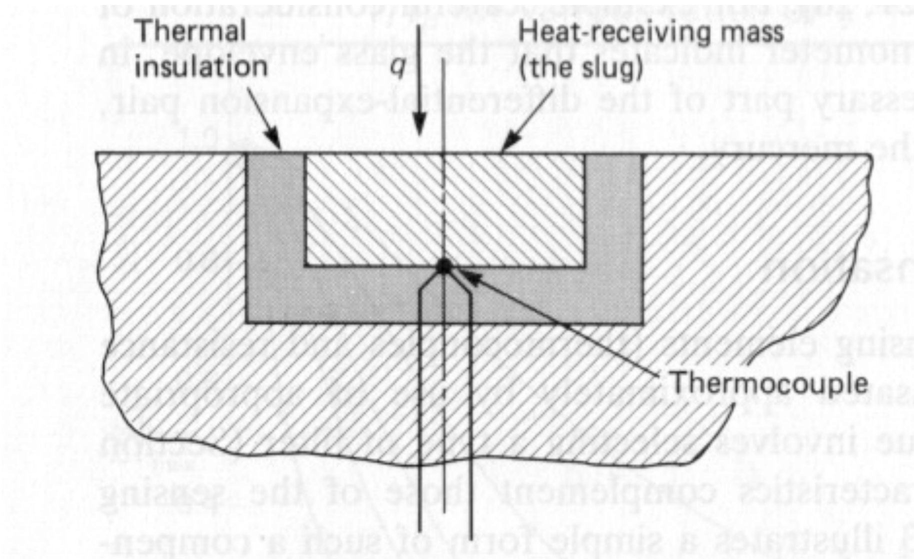
Measurement of Heat Flux

$$q = -k\frac{dT}{dx}$$

We seek to measure

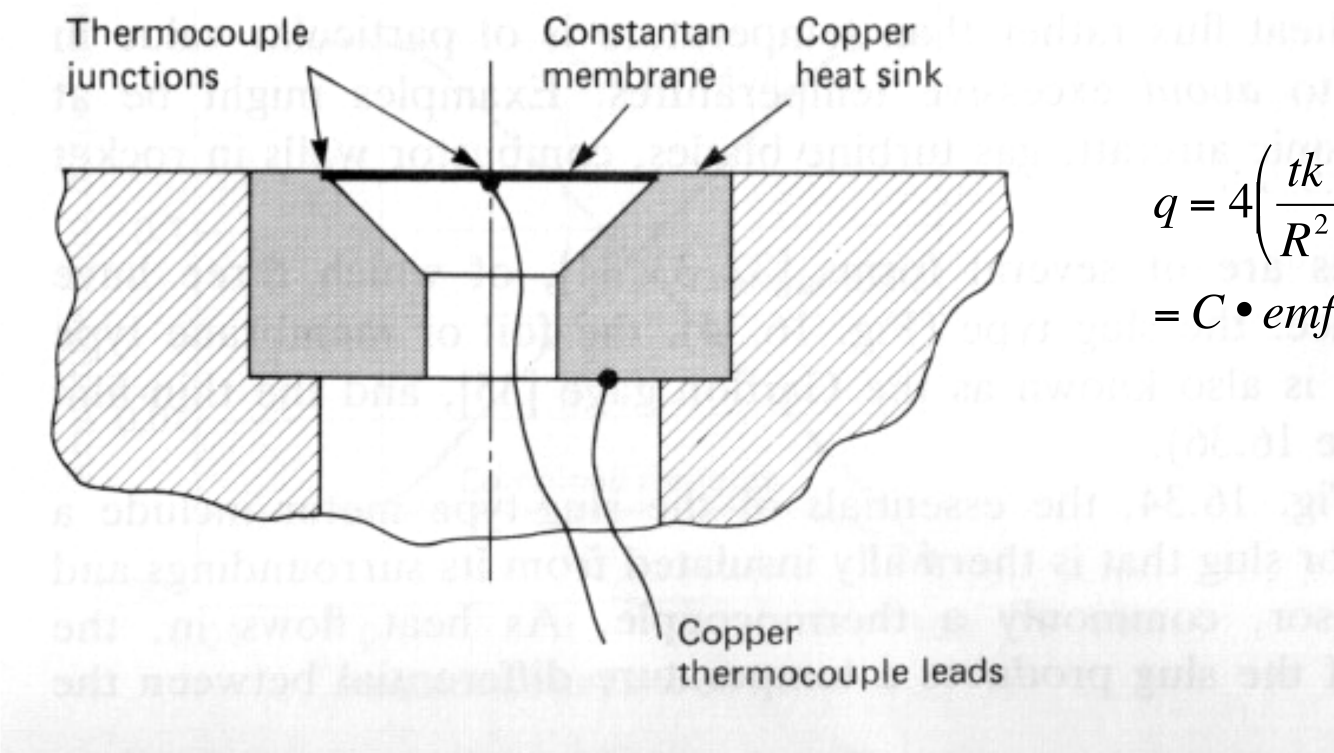
- Slug type
- Foil/Membrane type
- Thin Film Layers type

Heat Flux Measurement: Slug Type



$$q = \frac{Mc}{A}\frac{dT}{dt} + U\Delta T$$

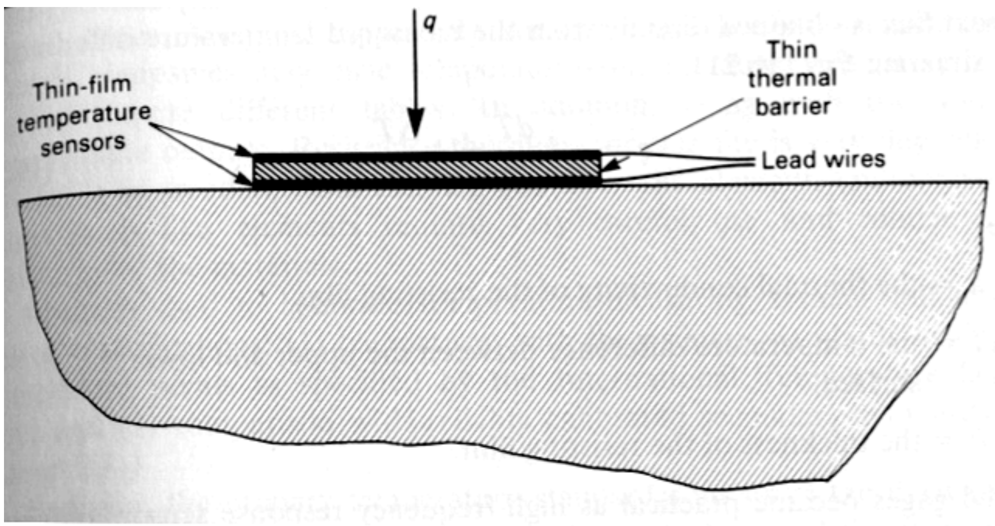
Heat Flux Measurement: Membrane Type



$$q = 4\left(\frac{tk}{R^2}\right)\Delta T$$
$$= C \bullet emf$$

Heat Flux Measurement: Thin-Film Layered Type

$$q = -k\frac{dT}{dx} \approx k\frac{\Delta T}{\delta}$$



Bottom line: create a 1-D heat flow and measure temperature at two known locations.

Temperature Element Response (1)

We've already covered the first part of this in this class (step response to first order systems) and in heat transfer. Since it is so much fun, let's do it again. Say you have a thermocouple that is essentially a sphere with two non-conducting wires protruding from it. You place it in a fluid warmer than the junction. Then the first law says that E_{in} - E_{out} = E_{stored}. No heat comes in, since the bead is cooler than the fluid.

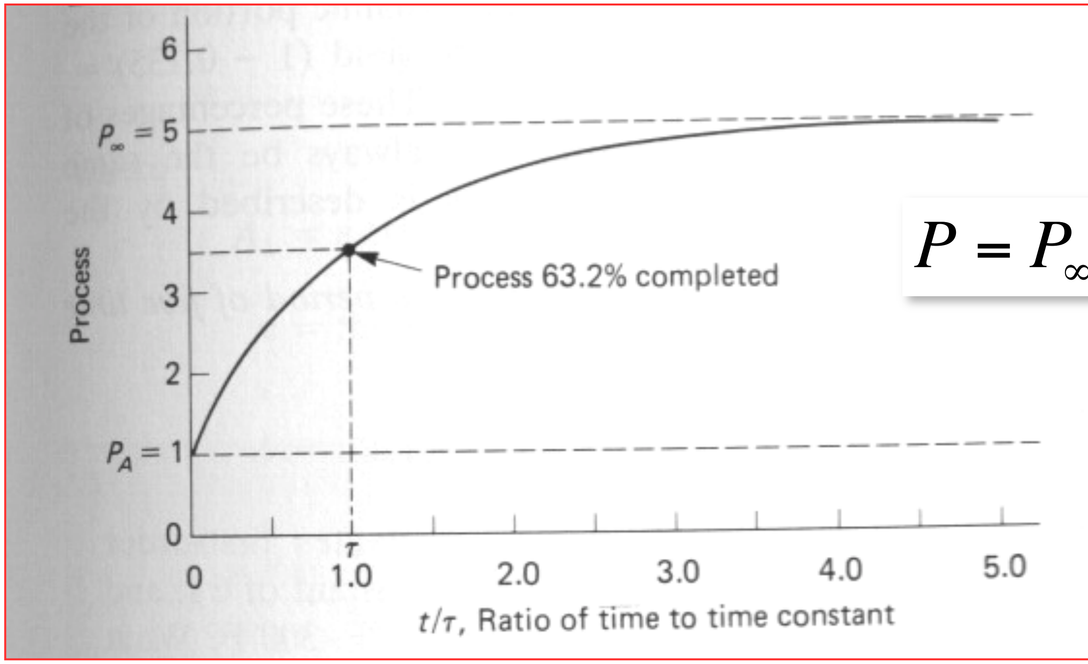
$$mc_p \frac{dT_{probe}}{dt} = hA_{surf}\left(T_{fluid} - T_{probe}\right)$$

$$\frac{dT_{probe}}{dt} + \frac{1}{\tau}T_{probe} = \frac{1}{\tau}T_{fluid} \rightarrow \boxed{\tau = \frac{mc_{probe}}{hA_{surf}}}$$

h -->heat transfer coefficient

Step response essentially first order

Temperature Element Response (2)



$$P = P_\infty + \left[P_A - P_\infty\right]e^{-t/\tau}$$

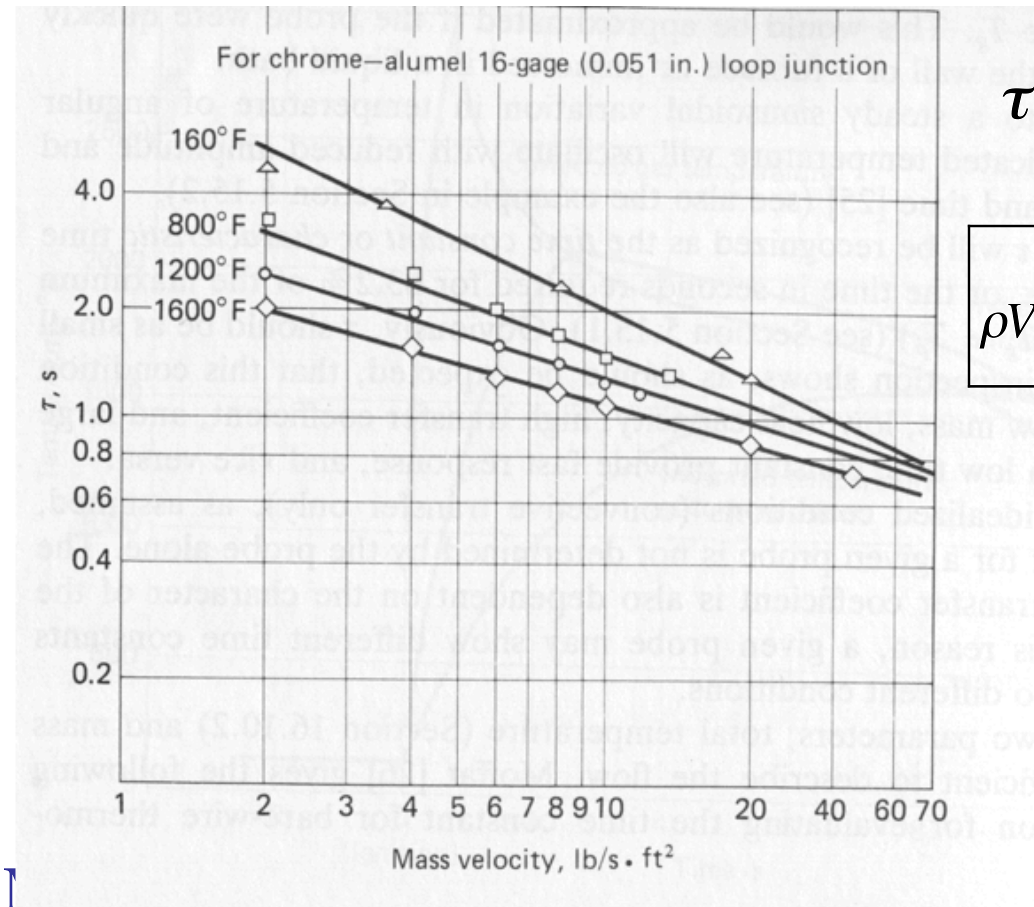
$$T_{probe} - T_0 = \left(T_{fluid} - T_0\right)\left(1 - e^{-t/\tau}\right)$$

$$T_{probe} = \left(T_0 - T_{fluid}\right)e^{-t/\tau} + T_{fluid} - T_0 + T_0$$

$$\boxed{T_{probe} = T_{fluid} + \left(T_0 - T_{fluid}\right)e^{-t/\tau}}$$

In practice

Heat transfer coefficient, h is not always known or easy to compute. TC's are generally calibrated for time response

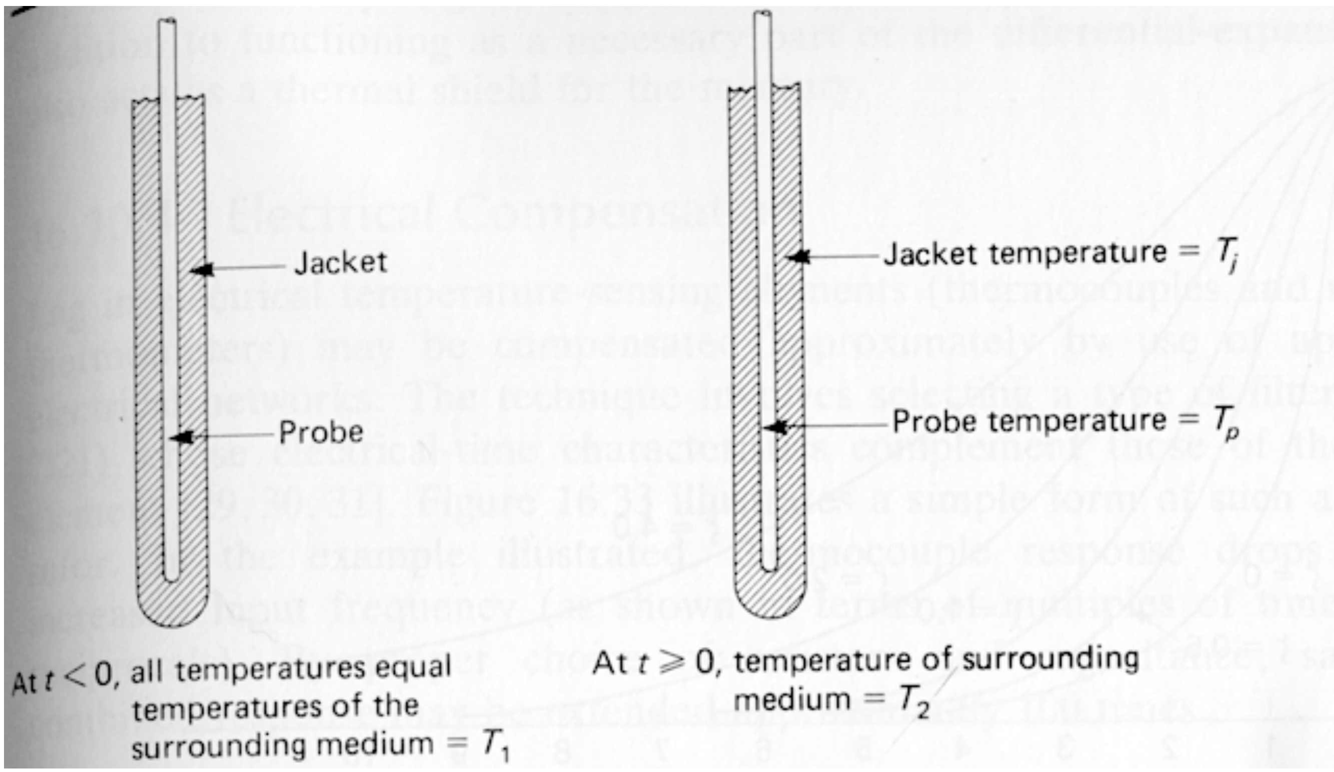


$$\tau = \frac{3500\rho_{tc}c_{tc}d^{1.25}}{T}(\rho V)^{-15.8/\sqrt{T}}$$

$$\boxed{\rho V = \frac{\dot{m}}{A} \rightarrow mass\ velocity\ of\ fluid}$$

Two Time Constant Model (1)

Many (most) times, our temperature sensor is encased in some other material. As a result, the first order response model may not fit well. It is relatively simple to make a richer model that can capture this effect.



Two Time Constant Model (2)

$$m_j c_j \frac{dT_j}{dt} = h_j A_j (T_2 - T_1) - h_p A_p (T_j - T_p)$$ First law on the jacket

$$m_p c_p \frac{dT_p}{dt} = h_p A_p (T_j - T_p)$$ First law on the probe

Rewrite these:

This term is often insignificant. If so, we can combine the two equations.

$$\tau_j \frac{dT_j}{dt} = (T_2 - T_1) - \frac{h_p A_p}{h_j A_j}(T_j - T_p)$$

$$\tau_p \frac{dT_p}{dt} = (T_j - T_p)$$

$$\tau_j \tau_p \frac{d^2 T_j}{dt^2} + (\tau_j + \tau_p)\frac{dT_p}{dt} + T_p = T_2$$

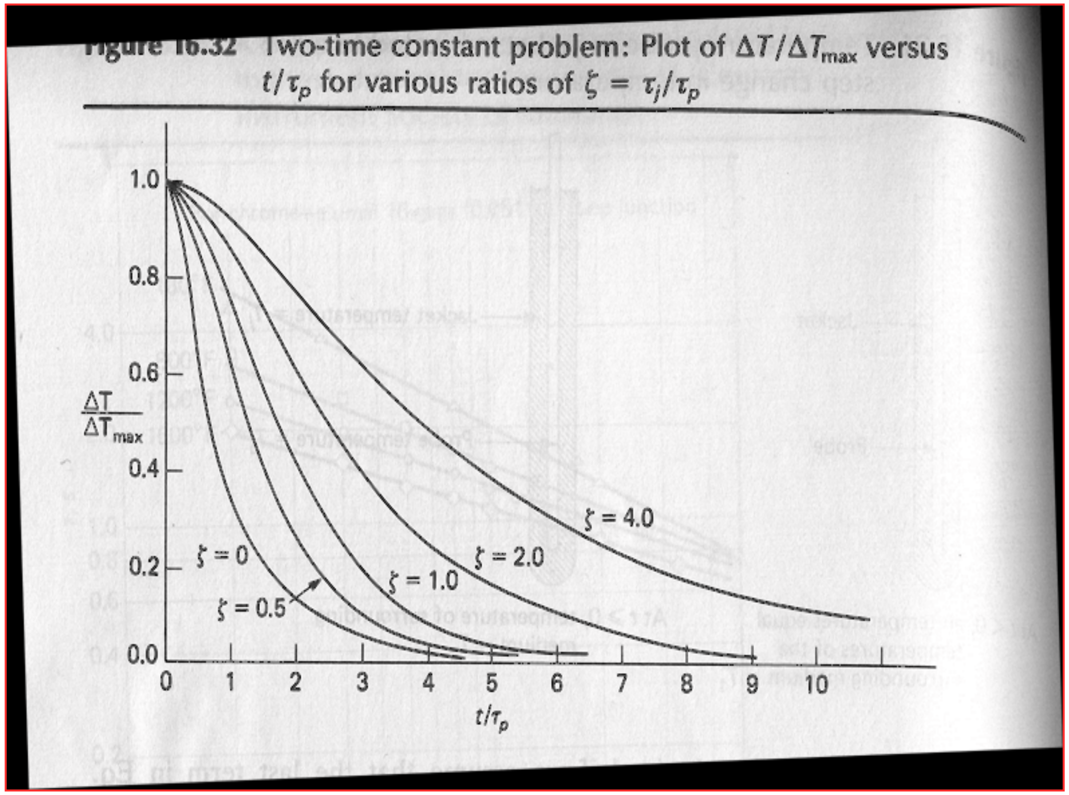
Second Order Response Equation

Two Time Constant Solution (4)

$$\tau_j \tau_p \frac{d^2 T_j}{dt^2} + \left(\tau_j + \tau_p\right)\frac{dT_p}{dt} + T_p = T_2$$

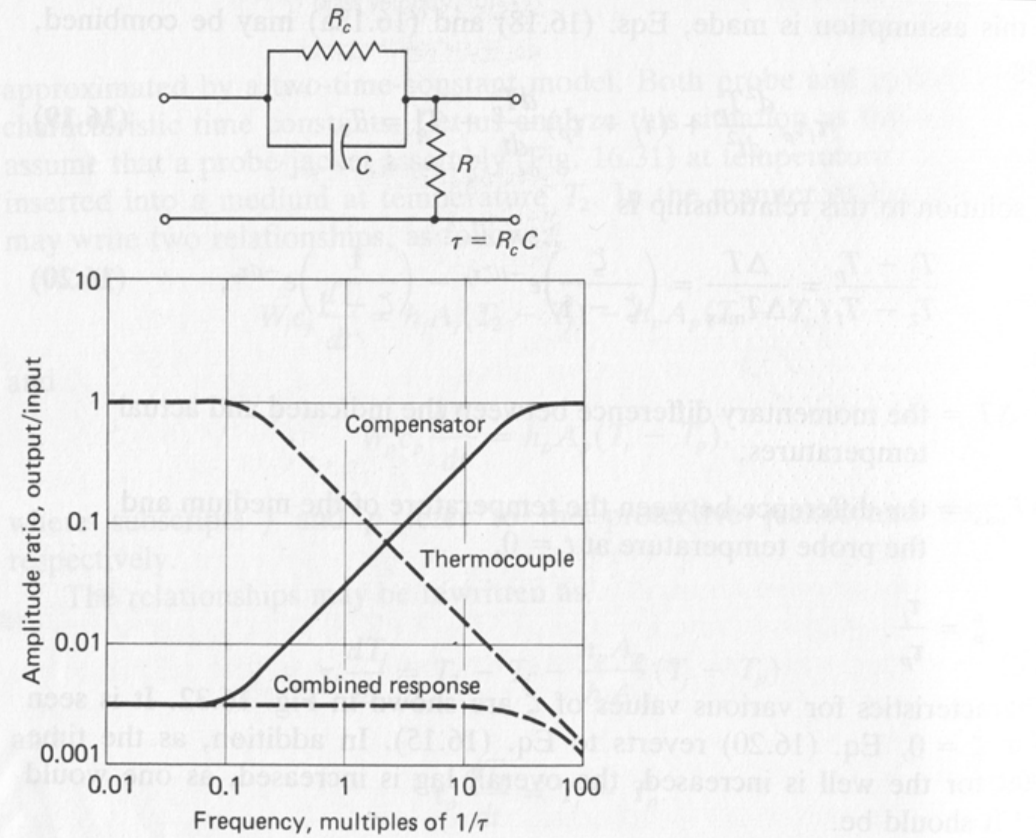
$$\boxed{\begin{aligned} &\frac{T_2 - T_p}{T_2 - T_1} = \frac{\Delta T}{\Delta T_{max}} = \\ &\left(\frac{\zeta}{\zeta - 1}\right) e^{-t/\zeta\tau_p} - \left(\frac{1}{\zeta - 1}\right) e^{-t/\tau_p} \end{aligned}}$$

$$\zeta = \frac{\tau_j}{\tau_p}$$



Compensating Slow Sensors

Figure 16.33 Curves illustrating compensating action of a simple *RC* network (Courtesy: Instrument Society of America)



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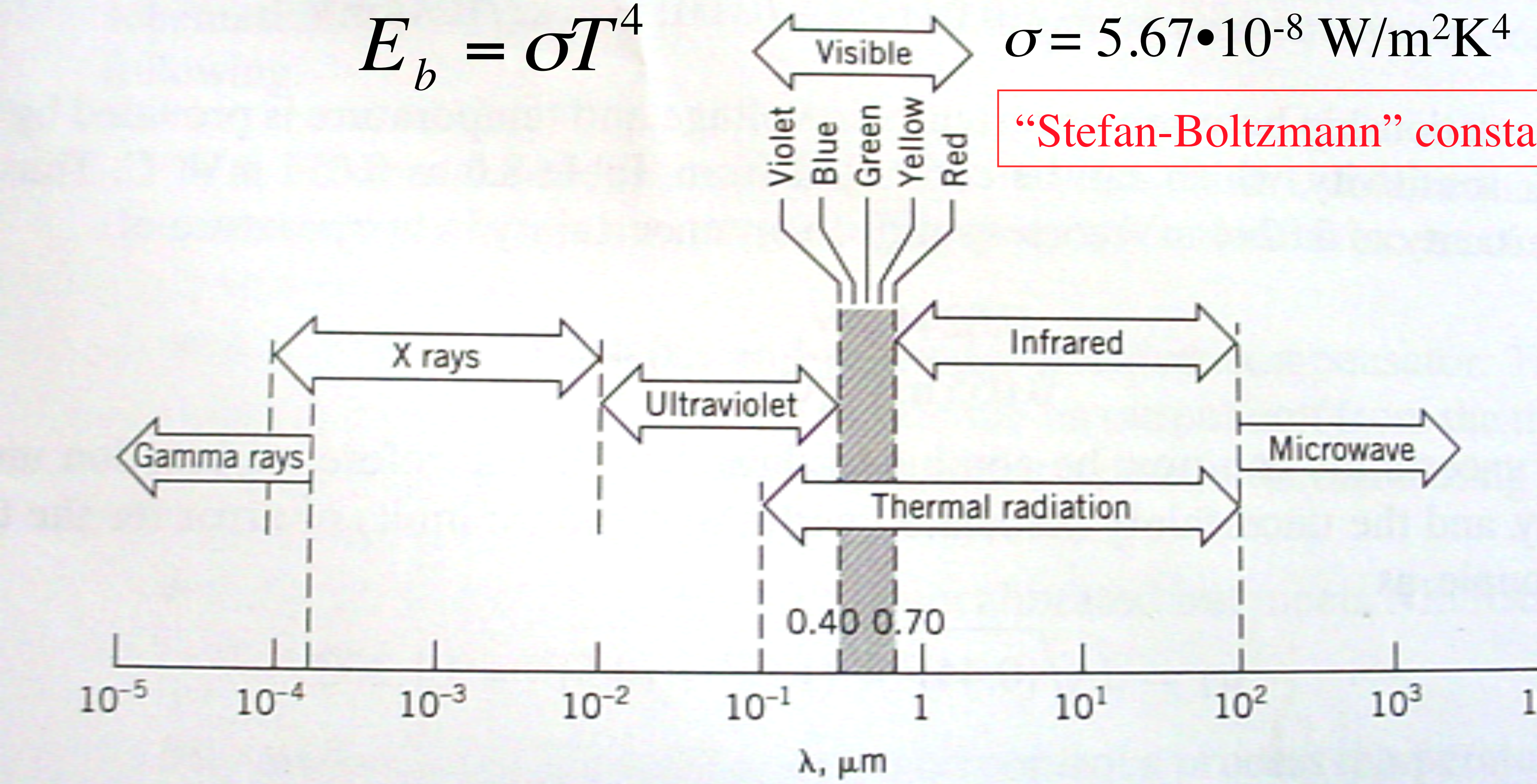
Radiative Temperature Measurements (Pyrometry)

Temperatures greater than 500ºC

$$E_b = \sigma T^4$$

$\sigma = 5.67 \cdot 10^{-8}\ W/m^2K^4$

"Stefan-Boltzmann" constant



Emitted Radiation

- **Emitted Radiant Energy (magnitude)**
  -- as object heats up, it radiates energy back into space

$$\frac{E}{A} = \left\{ \begin{array}{c} \text{emitted energy} \\ \text{per unit area} \\ \text{(all wavelengths)} \end{array} \right\} = \varepsilon\, \sigma\, T^4$$

ε -- emissitivity < 1

σ -- Stefan-Bolzman constant 5.67 x 10^{-8} W/m^2°K^4

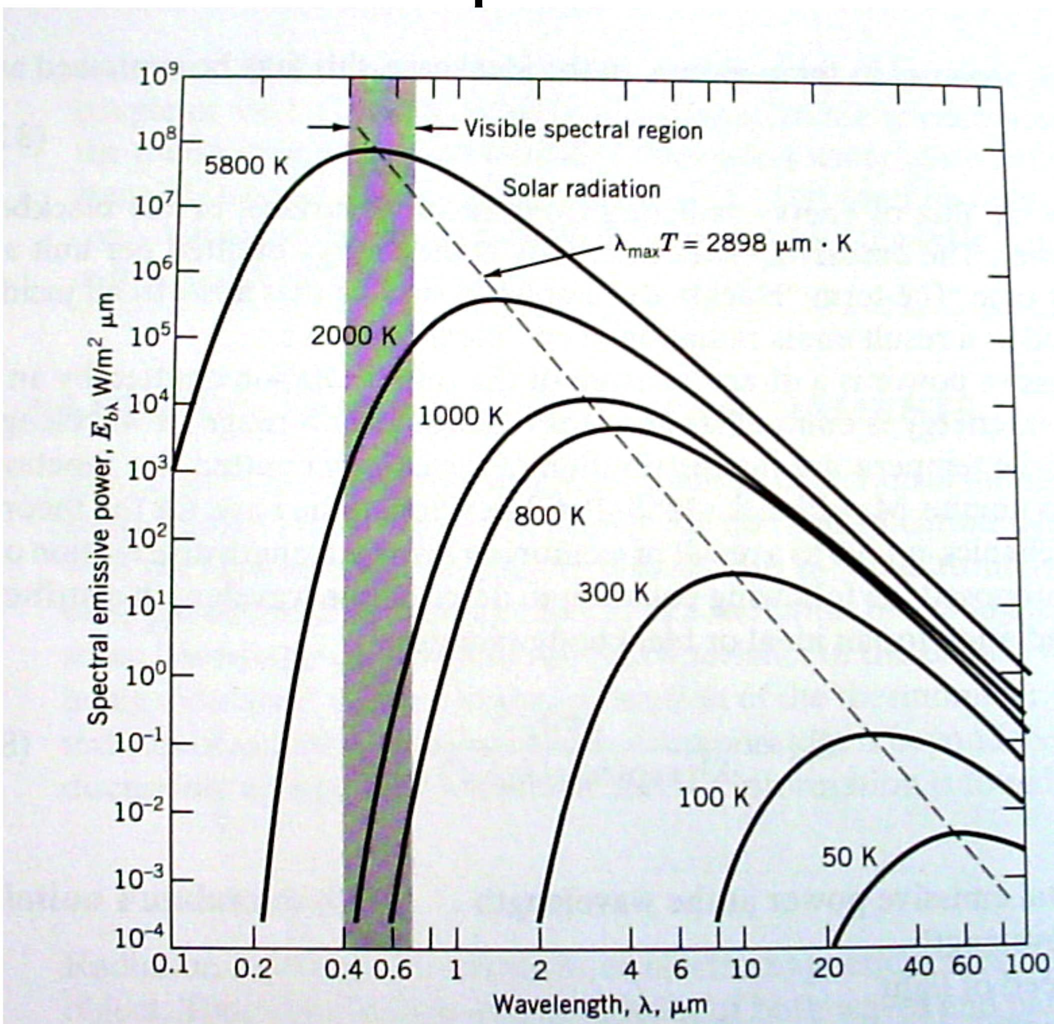
Two Broad Categories

Some radiative temperature measurements are made by detecting photons emitted by the hot source. We'll call these Photon Detectors. There is essentially no difference between this and a CCD camera.

A Thermal Detector produces a rise in temperature at some detector

Thermal Cameras

Radiative Temperature Measurements (1)



Radiative Temperature Measurements (2)

The text's discussion of radiative heat transfer is somewhat "dumbed down." Since most of you are currently Heat Transfer students, I will put this discussion at a more appropriate level. Radiative heat is transferred via photons which travel at the speed of light. When this energy strikes a surface, it can either be absorbed, reflected, or transmitted.

σ is the Stefan-Bolzman constant ($5.6704 \times 10^{-8} \sim \mathrm{J}/°\mathrm{K}^4\text{-m}^2\text{-sec}$), $\{\varepsilon, \alpha\}$ are the emmissivity and absorbtivity of the surface

For a non-ideal radiator, $\alpha + \rho + \tau = 1$

$$E = \sigma \varepsilon T^4$$

The radiative heat transfer between two ideal bodies A and B

$$q = \varepsilon \sigma \left(T_A^4 - T_B^4 \right)$$

Radiative Temperature Measurements (3)

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For a non-ideal radiator, $\alpha + \rho + \tau = 1$

$$E = \sigma \varepsilon T^4$$

The radiative heat transfer between two bodies A and B

$$q = \varepsilon \sigma \left(T_A^4 - T_B^4 \right)$$

Radiative Temperature Measurements (4)

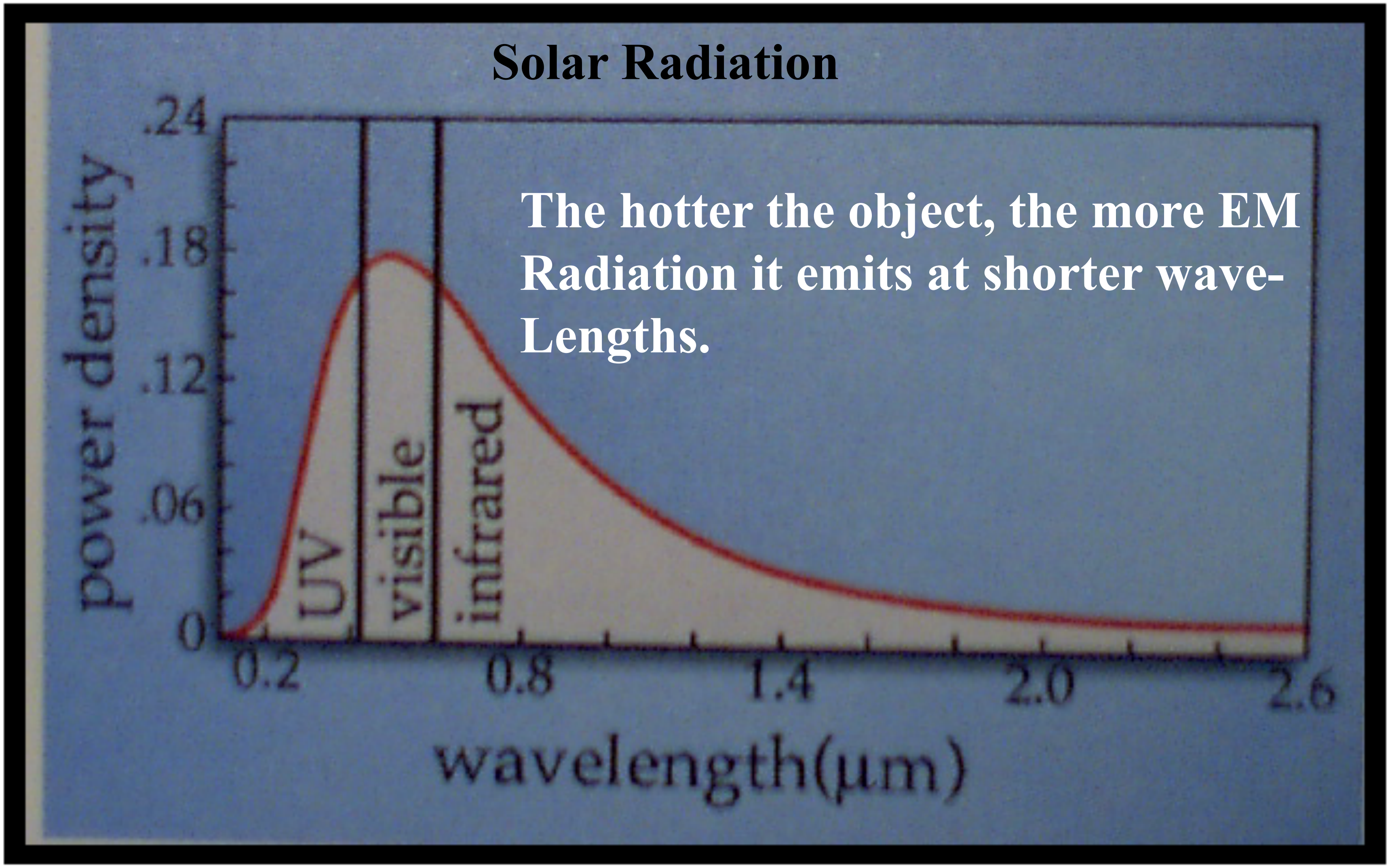
If A is not ideal,

$$q = \varepsilon_A F_{BA} \sigma \left(T_A^4 - T_B^4 \right)$$

In our case, the detecting element will be B, and from this we will determine the heat flux (and thus the temperature) of A.

Calibration is required to account for unknown quantities like the view factor and the body emissivity.

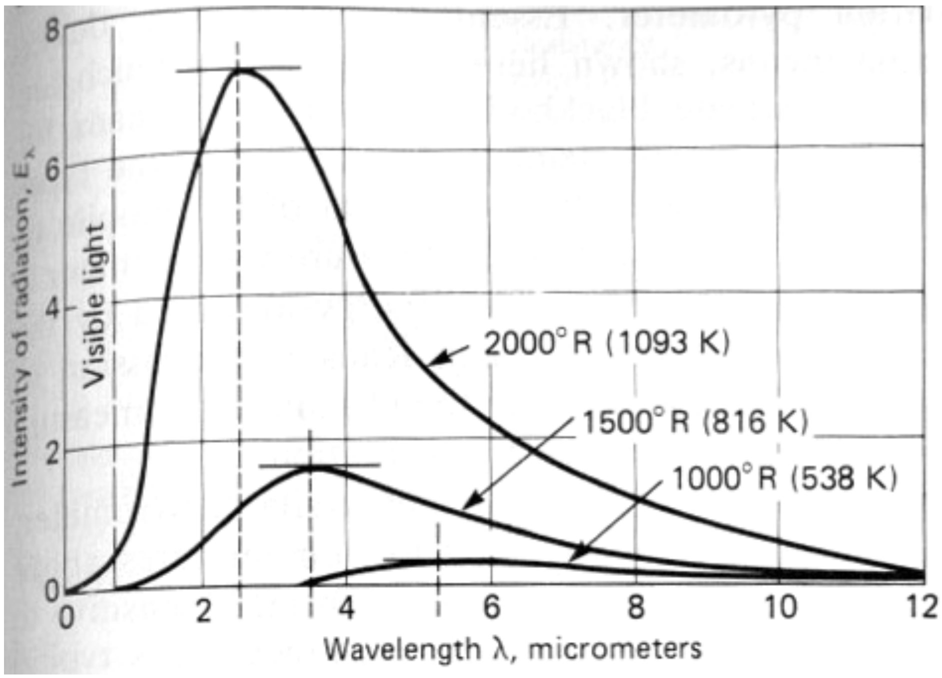
Radiative Temperature Measurements (5)



The hotter the object, the more EM Radiation it emits at shorter wave-Lengths.

Radiative Temperature Measurements (6)

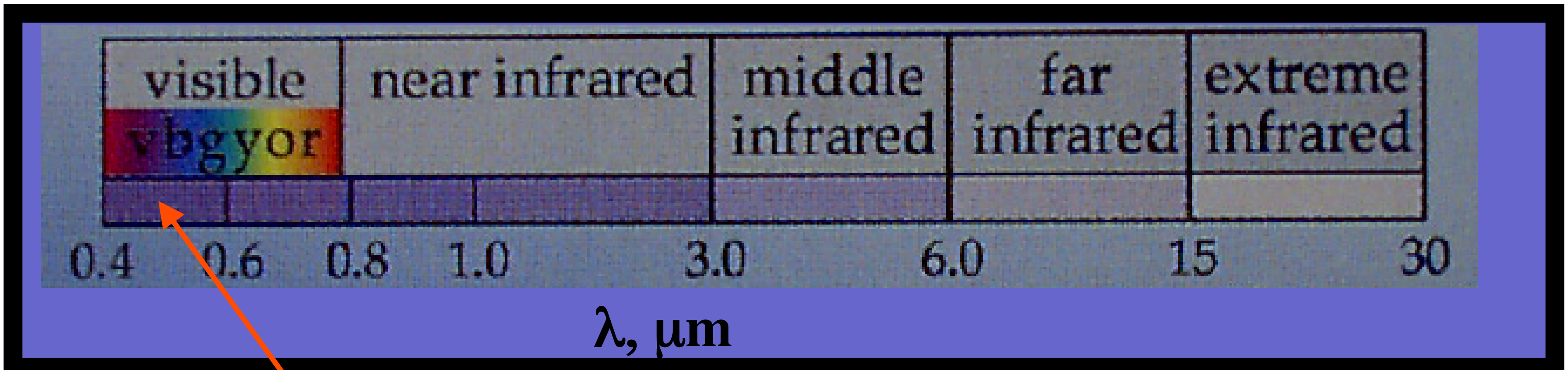
As the body increases in temperature, its emissive power increases, and the peak of the spectrum shifts to higher frequencies (lower wavelengths)



$$E_\lambda = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)}$$

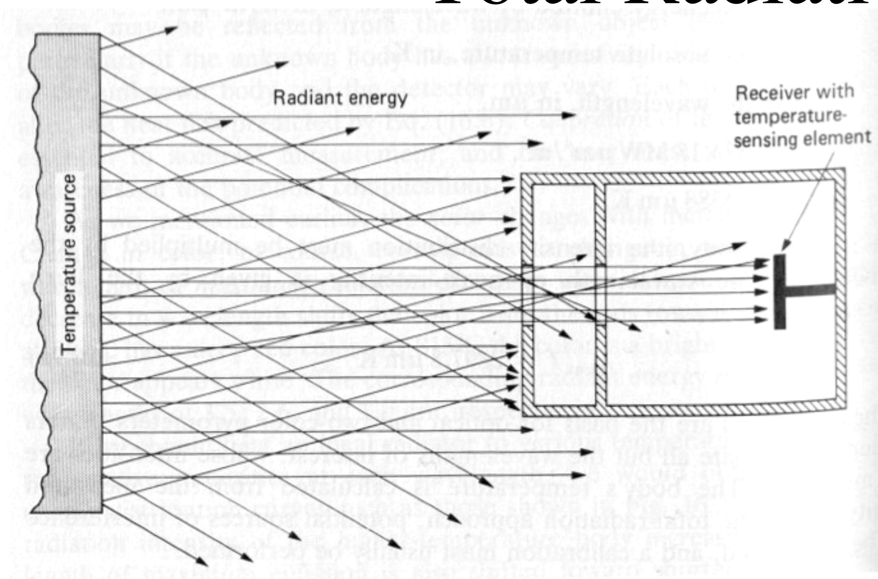
Wien's Displacement Law (radiant frequency)

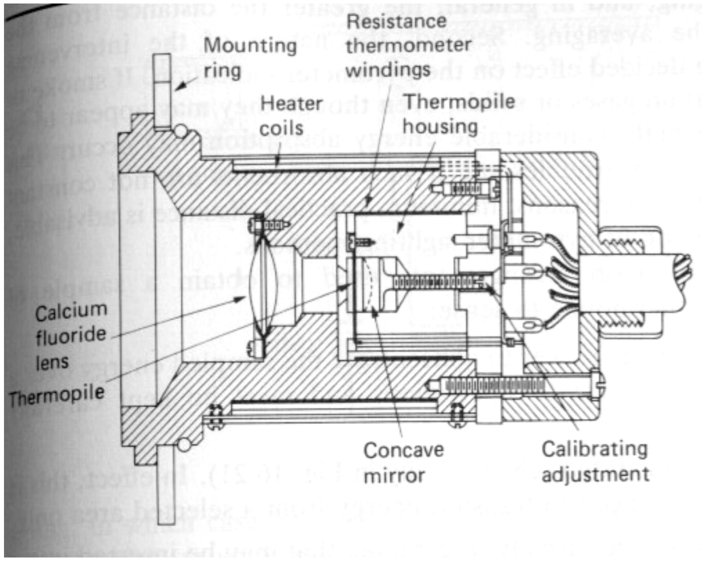
$$\lambda_{max} = \frac{2898}{T} \Rightarrow \left[\begin{array}{l} \lambda_{max} \equiv \text{Wavelength of maximum energy output, } (\mu m) \\ T \equiv \text{Object temperature, deg Kelvin} \end{array} \right]$$



$$\left[\lambda_{max} = \frac{2898}{6000\ °K} \right]_{sun} = 0.483\ \mu m$$

Total Radiation Pyrometry





Optical Pyrometry

One or two wavelengths of light are selected using a series of optical filters. For a photon detector, we can determine the temperature from

$$E_{\lambda} = \frac{C_1}{\lambda^5 \left(e^{C_2/\lambda T} - 1 \right)}$$

If two colors (wavelengths) are examined, the influence of the unknown emissivity of the object, which may be independent of wavelength, can be eliminated.