



C&R TECHNOLOGIES

TFAWS 2014 Short Course

Non-Grey and Temperature Dependent Radiation Analysis Methods

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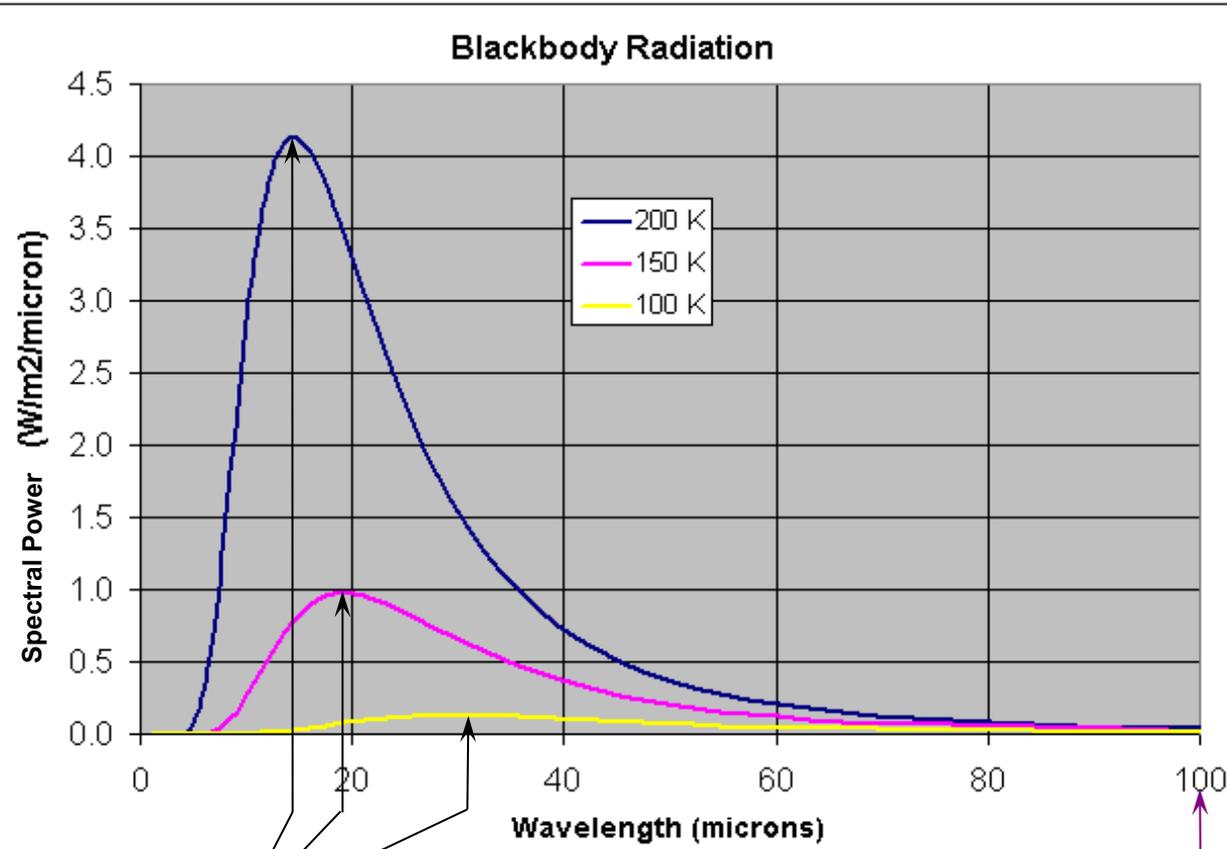


Course Outline

- Review of optical property definitions
 - ↙ emissivity, absorptivity, total, spectral, directional, hemispherical, intensity, power
- Conditions for grey/non-grey radiation analysis
 - ↙ Consider spectral distributions of emitted and incident radiation
- Procedure to implement non-grey analysis in Thermal Desktop
- Examples



Spectral Distribution of Blackbody Emissive Power



- Planck's Radiation Law:
 $E(\lambda, T) = (2\pi hc^2/\lambda^5)/(e^{hc/\lambda kT} - 1)$
- Flux (Q_{bb}) = area under curve
- $Q_{bb, T} = \sigma T^4$
 $\sigma = 5.6697 \times 10^{-8}$
[W/m²-K⁴]
- Curves have similar shapes
 λ_{\max} is proportional to $1/T$



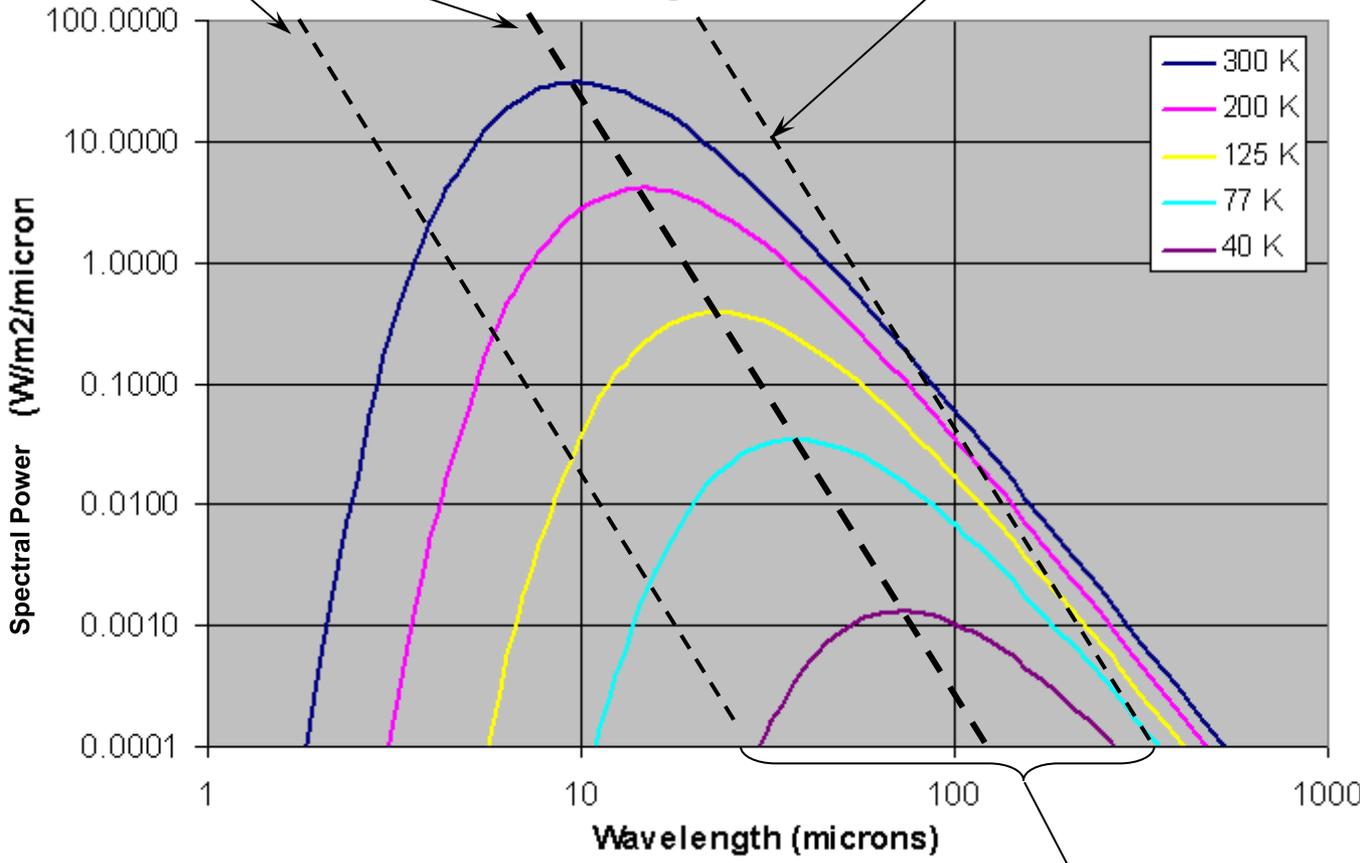
Blackbody Spectral Power: Log Plot

$$\lambda T = 1448 \mu\text{-K}$$

$$\lambda_{\text{max}} T = 2897 \mu\text{-K}$$

$$\lambda T = 22917 \mu\text{-K}$$

Blackbody Radiation

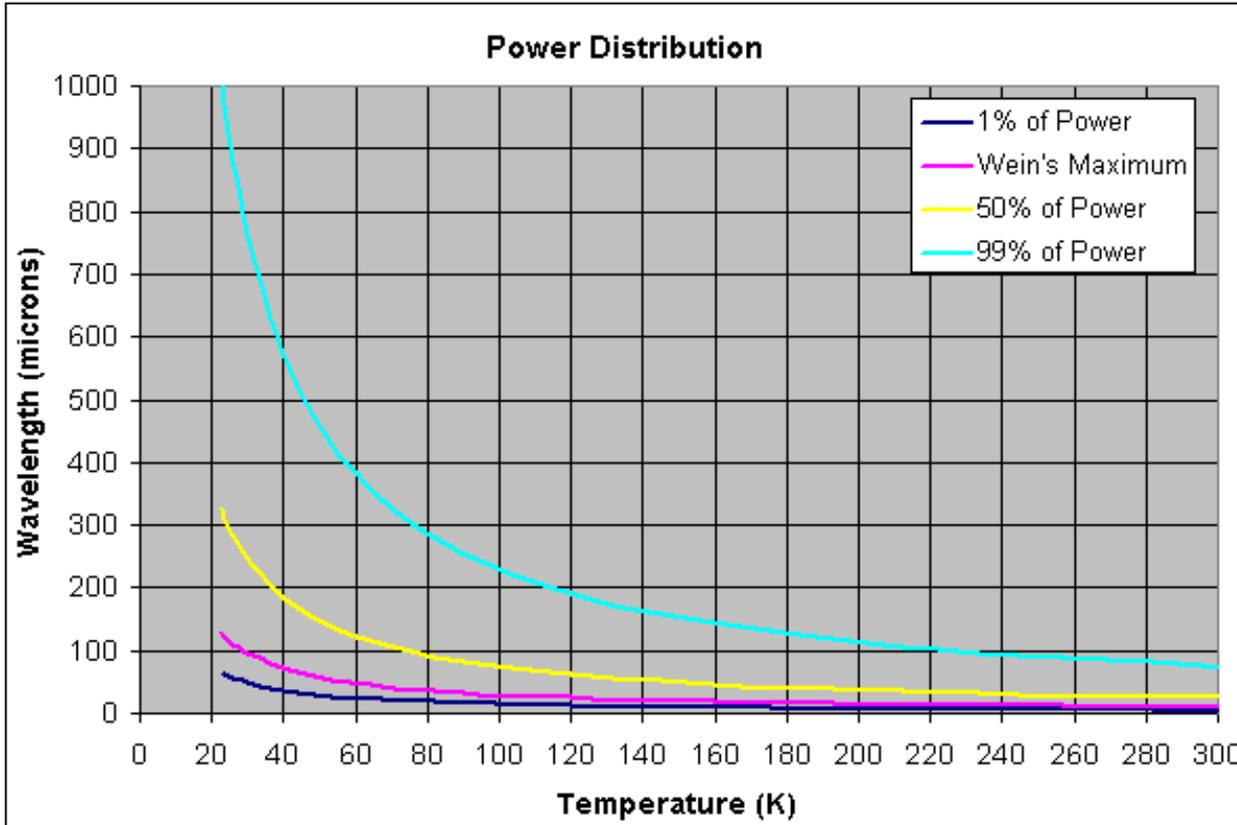


98% of power

- Everything shifts proportional to $1/T$
- Max power occurs at longer wavelengths at lower temperatures
- Curve for a lower temperature is less than curve for a higher temperature at all wavelengths
- At low temperatures, power spreads over a wider range of wavelengths



Percent Power vs Wavelength



1% of power at λ less than $1448/T$

Maximum power at λ of $2897/T$, Also 25%/75% split

50% of power either side of λ of $7393/T$

99% of power at λ less than $22,917/T$



Characterization of Real Surface Behavior

- Materials are characterized by comparing their behavior with respect to the ideal black body
 - ↙ Nothing can emit more than a black body
 - ↙ Given by Planck's Radiation Law
 - ↙ Equal intensity in all directions
 - ↙ Intensity is Watts per projected area, per solid angle, per wavelength interval
 - ↙ Nothing can absorb more than a black body
 - ↙ A blackbody absorbs all incident radiation



Directional Spectral Emissivity

- Dependent on wavelength, direction, and surface temperature

$$\varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) = \frac{i_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) dA \cos \theta \sin \theta d\theta d\varphi d\lambda}{i_{\lambda b}(\lambda, T_{emitter}) dA \cos \theta \sin \theta d\theta d\varphi d\lambda}$$

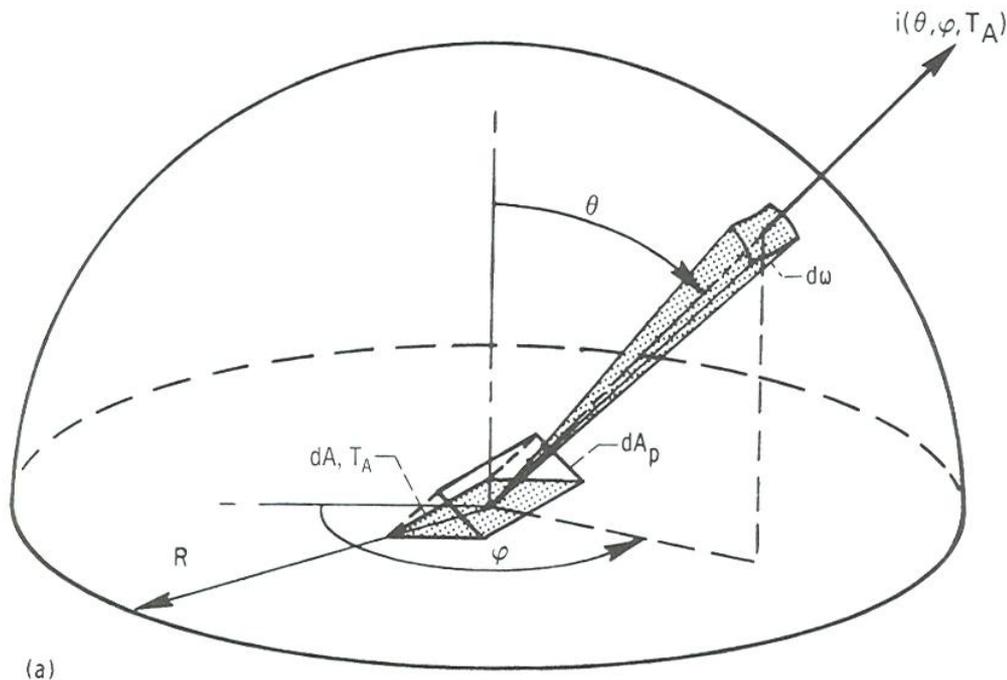
$$\varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) = \frac{i_{\lambda}(\lambda, \theta, \varphi, T_{emitter})}{i_{\lambda b}(\lambda, T_{emitter})}$$

- ✚ Power vs Intensity
- ✚ Subscripts: lambda, b
- ✚ Thermal Radiation Heat Transfer 4th Edition, Siegel and Howell



Directional Emissivity Graphic

Emissivity compares actual energy leaving a surface in a given direction, through a given solid angle, to that of a black body





Power vs Intensity

- Power is really a power flux:
 - ↙ Spectral Hemispherical Emissive Power: $[W/m^2/\mu m]$
 - ↙ Total Hemispherical Emissive Power: $[W/m^2]$
- Directional Intensity is power per unit projected area, per solid angle:
 - ↙ Directional Spectral Intensity: $[W/m^2/\mu m/ster]$
- When integrated over all directions:
 - ↙ $E = \pi I$



Hemispherical Spectral Emissivity

- Directional spectral emissivity averaged over the enclosing hemisphere

$$\varepsilon_{\lambda}(\lambda, T_{emitter}) = \frac{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} i_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) \cos \theta \sin \theta d\theta d\varphi d\lambda}{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} i_{\lambda b}(\lambda, T_{emitter}) \cos \theta \sin \theta d\theta d\varphi d\lambda}$$

$$\varepsilon_{\lambda}(\lambda, T_{emitter}) = \frac{i_{\lambda b}(\lambda, T_{emitter}) \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) \cos \theta \sin \theta d\theta d\varphi}{i_{\lambda b}(\lambda, T_{emitter}) \pi}$$

$$\varepsilon_{\lambda}(\lambda, T_{emitter}) = \frac{1}{\pi} \int_{hemi} \varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) \cos \theta d\omega$$

- ✚ dA, dλ cancels, black body intensity is constant in all directions, substitute directional spectral emissivity definition
- ✚ new notation for hemispherical integration, $E = \pi * i$



Hemispherical Total Emissivity

- Integrate hemispherical spectral emissivity over all wavelengths

$$\varepsilon(T_{emitter}) = \frac{\int_0^{\infty} \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} i_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) \cos \theta \sin \theta d\theta d\varphi d\lambda}{\int_0^{\infty} \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} i_{\lambda b}(\lambda, T_{emitter}) \cos \theta \sin \theta d\theta d\varphi d\lambda}$$

$$\varepsilon(T_{emitter}) = \frac{\int_0^{\infty} i_{\lambda b}(\lambda, T_{emitter}) \int_{hemi} \varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{emitter}) \cos \theta d\omega d\lambda}{\pi \int_0^{\infty} i_{\lambda b}(\lambda, T_{emitter}) d\lambda}$$

$$\varepsilon(T_{emitter}) = \frac{\int_0^{\infty} \varepsilon_{\lambda}(\lambda, T_{emitter}) \pi i_{\lambda b}(\lambda, T_{emitter}) d\lambda}{\sigma T_{emitter}^4}$$



Terminology

Directional Spectral (basic fundamental definition):

$$\varepsilon_{\lambda}(\lambda, \theta, \varphi, T)$$

Directional Total (integrate over all wavelengths):

$$\varepsilon(\theta, \varphi, T)$$

Hemispherical Spectral (integrate over all directions):

$$\varepsilon(\lambda, T)$$

Hemispherical Total (integrate over all directions & wavelengths):

$$\varepsilon(T)$$



Absorptivity

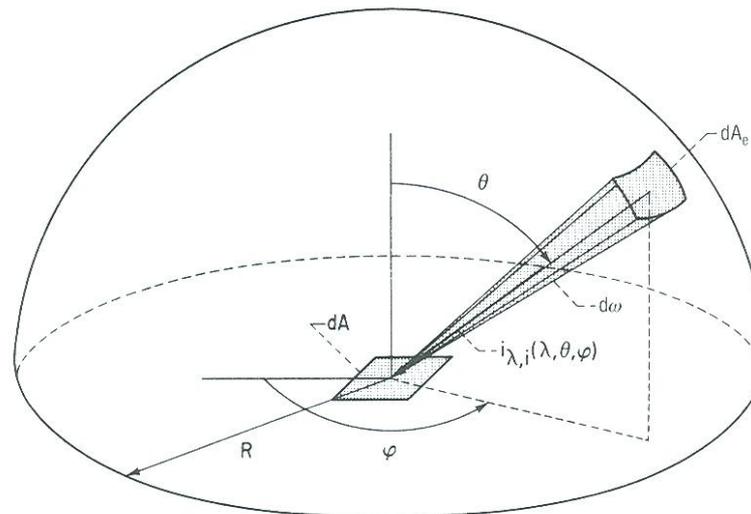
- Defined as the fraction of energy incident on a body that is absorbed by the body
- Incident radiation depends on the source
 - ↪ Spectral distribution of the source is independent of the temperature of the absorber
- More complex than emissivity, since directional and spectral characteristics of the source must be included
- Relations exist between emissivity and absorptivity



Directional Spectral Absorptivity

$$\alpha_{\lambda}(\lambda, \theta, \varphi, T_{\text{absorber}}) = \frac{\text{energy absorbed}}{\text{energy incident}}$$

$$\alpha_{\lambda}(\lambda, \theta, \varphi, T_{\text{absorber}}) = \frac{d^2 Q d\lambda}{i_{\lambda,i}(\lambda, \theta, \varphi) dA \cos \theta d\omega d\lambda}$$

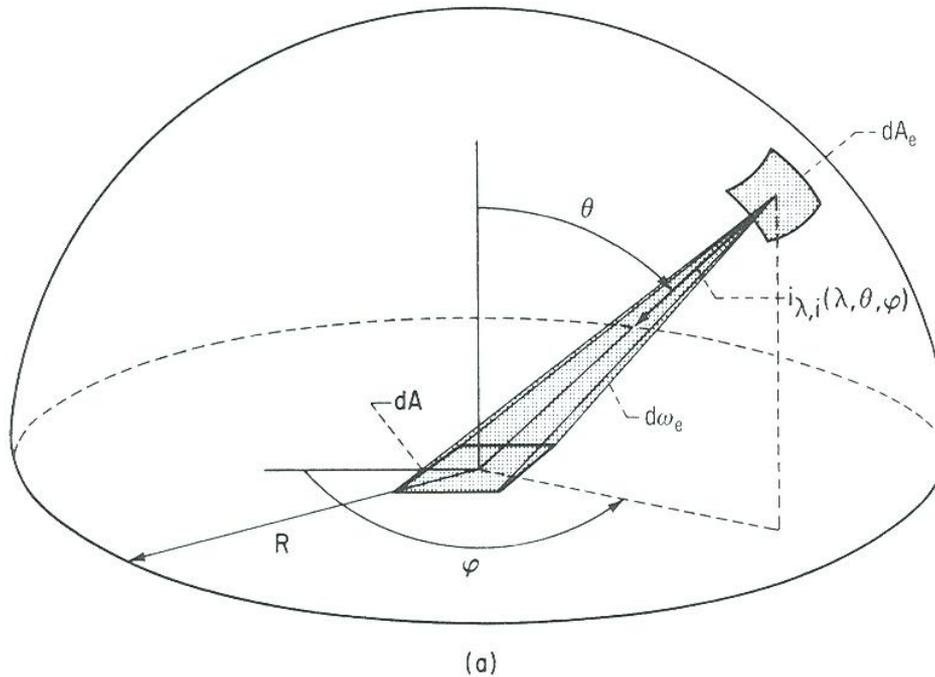


(b)



Equivalent view of Absorptivity

$$dA_e \frac{dA \cos \theta}{R^2} = \frac{dA_e}{R^2} dA \cos \theta = d\omega_e dA \cos \theta$$





Kirchoff's Law

- Energy emitted by a surface in a particular direction, solid angle, and wavelength interval

$$d^2Qd\lambda = \varepsilon_\lambda(\lambda, \theta, \varphi, T_{emitter}) i_{\lambda b}(\lambda, T_{emitter}) dA \cos \theta d\omega d\lambda$$

- Imagine surface placed in black enclosure at the same temperature.
- The following must be true, otherwise surface temperature would cool or warm on its own.

$$\alpha_\lambda(\lambda, \theta, \varphi, T) = \varepsilon_\lambda(\lambda, \theta, \varphi, T)$$



Hemispherical Spectral Properties (non-directional)

- For the rest of this discussion, we will ignore directional dependence

$$\varepsilon_{\lambda}(\lambda, T_{surface}) = \frac{1}{\pi} \int_{hemi} \varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{surface}) \cos \theta d\omega$$

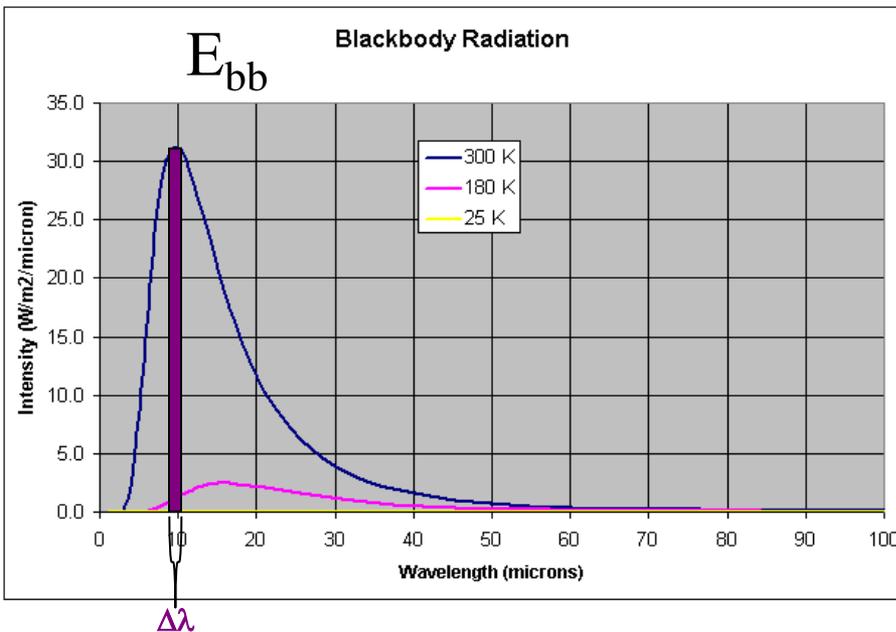
$$\varepsilon_{\lambda}(\lambda, T_{surface}) = \frac{1}{\pi} \varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{surface}) \int_{hemi} \cos \theta d\omega$$

$$\varepsilon_{\lambda}(\lambda, T_{surface}) = \varepsilon_{\lambda}(\lambda, \theta, \varphi, T_{surface})$$

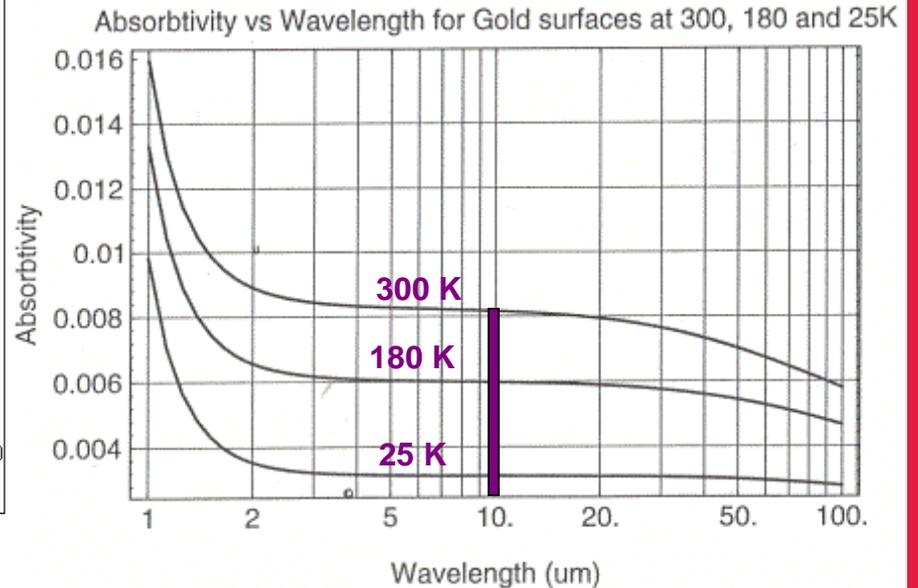
$$\alpha_{\lambda}(\lambda, T_{surface}) = \varepsilon_{\lambda}(\lambda, T_{surface})$$



Total Emissivity Calculations



Wavelength dependent emissivity for UHV evaporated gold



$$\varepsilon(T) = \frac{[\Sigma(E_{bb,\lambda,T})(\varepsilon_{\lambda,T})(\Delta\lambda)]}{\underbrace{\Sigma(E_{bb,\lambda,T})(\Delta\lambda)}_{\sigma T^4}}$$

Temperature dependence has two aspects: Different spectral distribution of blackbody energy, and possible temperature dependent directional spectral emissivity/absorptivity



Total Absorptivity Calculations

Wavelength dependent emissivity for UHV evaporated gold

Solar Engineering of Thermal Processes, Duffie and Beckman

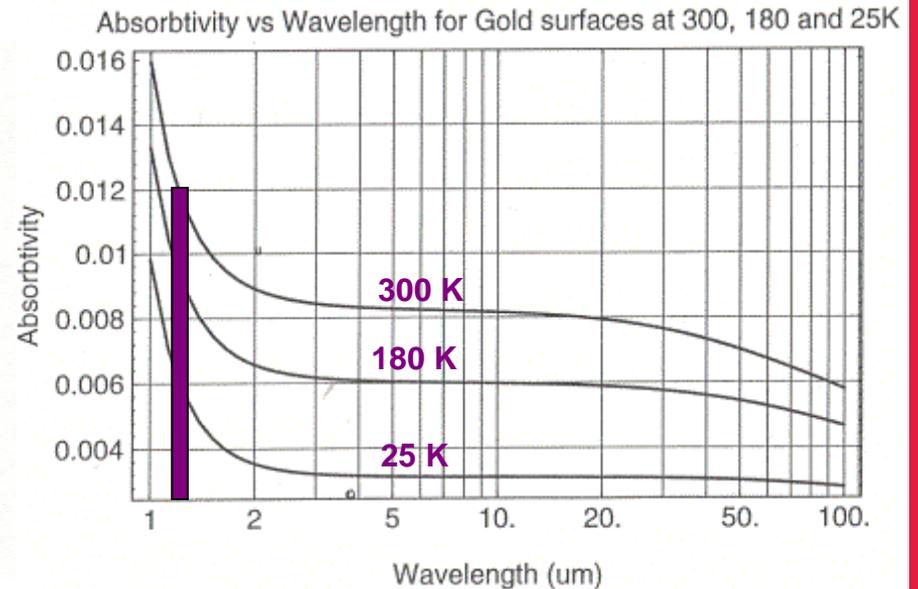
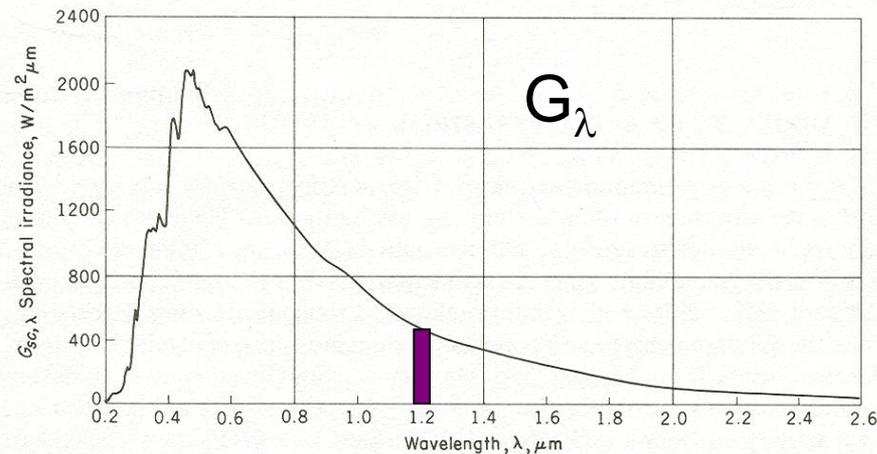


Figure 1.3.1 The NASA/ASTM standard spectral irradiance at the mean sun-earth distance and a solar constant of 1353 W/m².

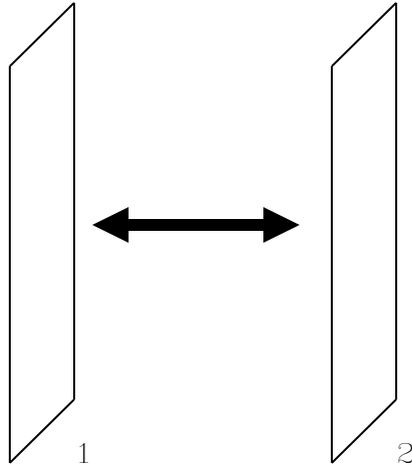
$$\alpha(T) = [\Sigma(G_{\lambda})(\epsilon_{\lambda,T})(\Delta\lambda)] / \Sigma(G_{\lambda})(\Delta\lambda)$$

Total absorptivity is a function of the spectral distribution of the **source**, and possibly the temperature of the absorbing surface.

Note the rise in emissivity of metals at short wavelengths, 3:1 typical between absorptivity in solar and infrared wavelengths



Radiation Exchange



Energy emitted by 1 $\varepsilon_1(T_1)A_1\sigma T_1^4$

Energy incident on 2 $F_{1\rightarrow 2}\varepsilon_1(T_1)A_1\sigma T_1^4$

Energy absorbed by 2 $\alpha_2^{(spectrum_1)}(T_2)F_{1\rightarrow 2}\varepsilon_1(T_1)A_1\sigma T_1^4$

Similarly, for $2 \rightarrow 1$ $\alpha_1^{(spectrum_2)}(T_1)F_{2\rightarrow 1}\varepsilon_2(T_2)A_2\sigma T_2^4$

To put this in the typical, reciprocal, radiation conductor form, where

$$Q_{1\leftrightarrow 2} = K_{1\leftrightarrow 2}\sigma(T_2^4 - T_1^4)$$

The following must hold :

$$\alpha_2^{(spectrum_1)}(T_2)\varepsilon_1(T_1) = \alpha_1^{(spectrum_2)}(T_1)\varepsilon_2(T_2)$$

or

$$\alpha_1^{(spectrum_2)}(T_1) = \varepsilon_1(T_1) \quad \text{and} \quad \alpha_2^{(spectrum_1)}(T_2) = \varepsilon_2(T_2)$$



Reciprocity Conditions

- Absorptivities evaluated using the spectral distribution of ***incoming*** radiation
- Emissivities evaluated using the blackbody radiation from itself.
- Reciprocity holds when emissivities for all surfaces are constant for all wavelengths that dominate the problem (surfaces are grey)
 - ↙ Find smallest wavelength from 98% power of hottest surface
 - ↙ Find longest wavelength from 1% power of coldest surface
 - ↙ 200K to 350K would cover approximately 3 to 100 μm .

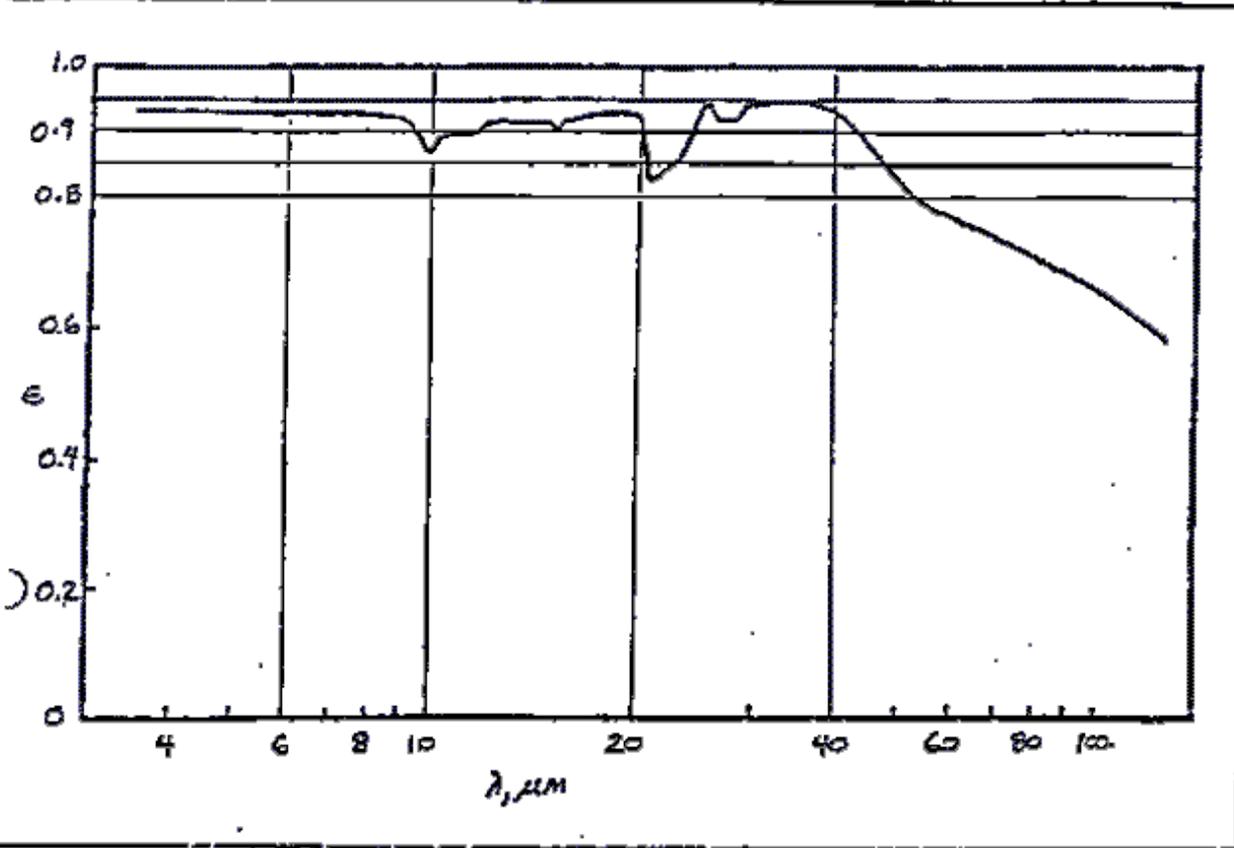


Real Materials

- Lets examine reciprocity and grey/non-grey conditions considering some real world materials
 - ↙ Non-conductors
 - ↙ Conductors
 - ↙ Intentional non-grey



Black Paint



- At a given wavelength, ϵ_λ doesn't vary with temperature
- Total emittance may vary with temperature as the range of wavelengths shifts. $\epsilon(T)$ drops as we get colder

Figure 12. Spectral emittance of Cat-a-Lac black paint at 4.2 K and 77 K. Curve applies to both temperatures as in Figure 11.

Figure 56-4
Spectral Emittance of Cat-A-Lac Black Paint
at 4.2°K and 77°K

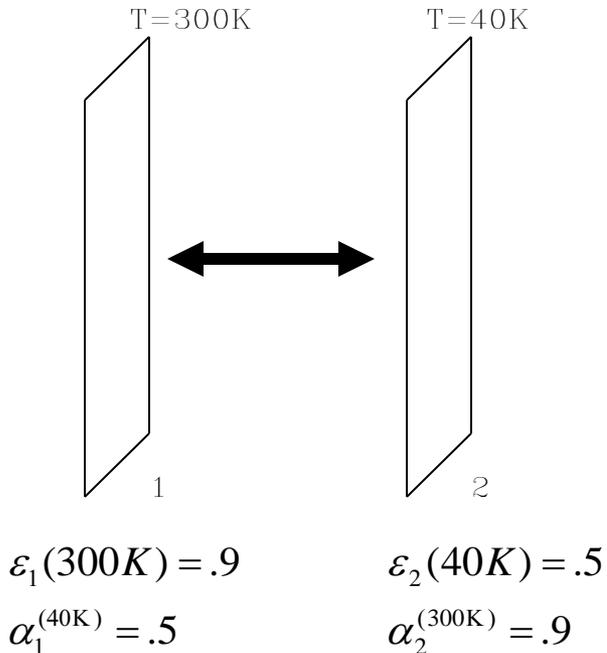


Black Paint Grey/Non-Grey Evaluation

- Suppose all surfaces are around 300K
 - ✦ Peak Wavelength is approximately $10\mu\text{m}$, min is approximately $3\mu\text{m}$, max is approximately $80\mu\text{m}$. (chart 4).
 - ✦ From the data, we see that the emissivity is fairly constant at approximately .9 over that range of wavelengths
- What if we also have some surfaces around 40K?
 - ✦ Peak – $75\mu\text{m}$, min – $30\mu\text{m}$, max – $600\mu\text{m}$
 - ✦ We see from the data that the emissivity varies from .9 to .3 (off chart, best guess)
 - ✦ This analysis should be done using a non-grey method
 - ✦ Total emissivity at this temperature is approximately .5



Non-Grey Radiation Exchange



Using our black paint

$$Q_{1 \rightarrow 2} \propto \varepsilon_1 \alpha_2 \sigma T_1^4 = .9 * .9 * \sigma T_1^4$$

$$Q_{2 \rightarrow 1} \propto \varepsilon_2 \alpha_1 \sigma T_2^4 = .5 * .5 * \sigma T_2^4$$

$$Q_{1 \leftrightarrow 2} \propto .81 \sigma T_2^4 - .25 \sigma T_1^4 \text{ not reciprocal!}$$

Trying to use $\varepsilon_i(T_i) = \alpha_i$, we would get

$$Q_{1 \leftrightarrow 2} \propto .45 (\sigma T_2^4 - \sigma T_1^4)$$

Emissivities for all surfaces are not constant over all significant wavelengths, this problem is non-grey. Heat from 1 to 2 is almost twice as much as grey analysis.

We've also had to assume that 1 illuminates 2 (and vice-versa) with a blackbody "shaped" spectral distribution. Reflections further complicate problem. Absorptivity for surface 2 from 2 to 1 back to 2 is closer to 0.5.



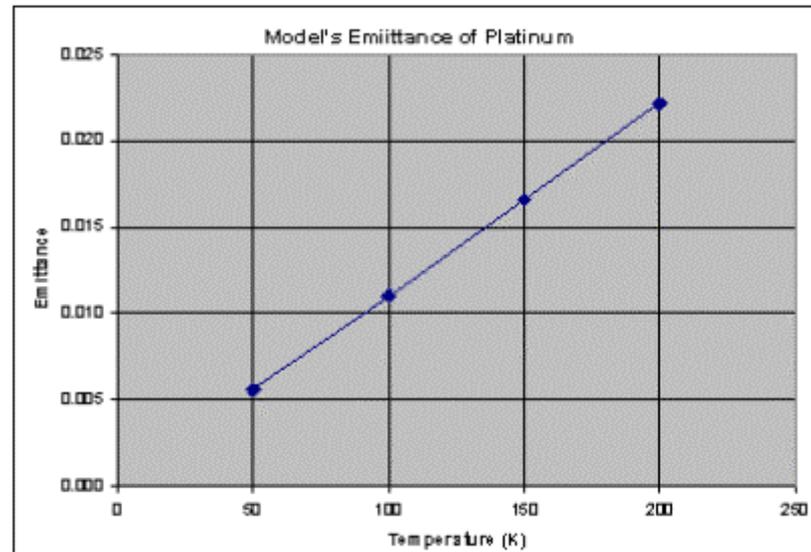
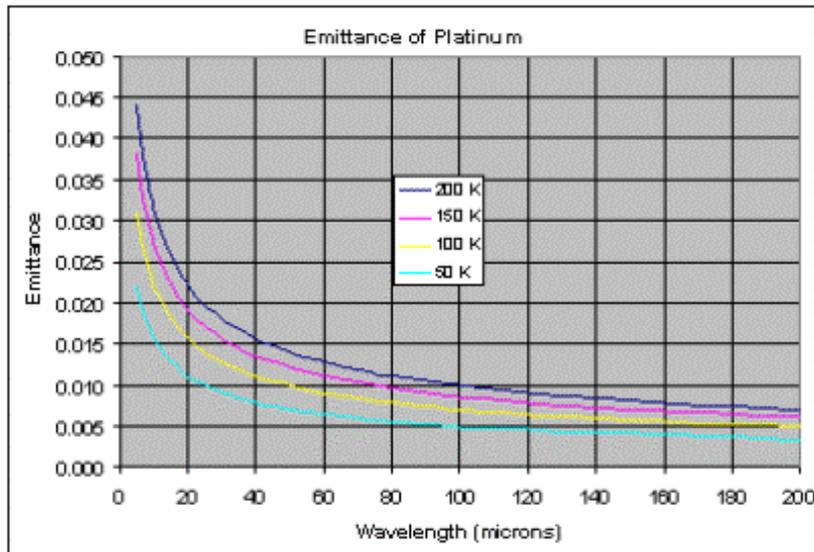
Temperature Dependent Emissivity

- Total Hemispherical Emissivity varies with temperature for two reasons
 - ↙ As temperature changes, spectral distribution of blackbody energy changes. If emissivity vs wavelength is not uniform, total emissivity will change (previous example)
 - ↙ Spectral emissivity, that is, the emissivity at a particular wavelength, may be a function of temperature
 - ↙ Both blackbody shift and wavelength dependence contribute to a total emissivity change with temperature



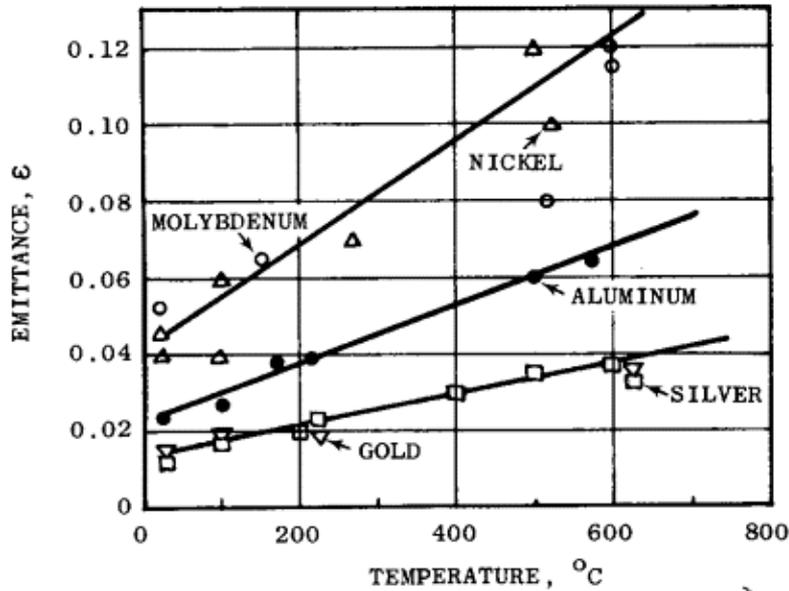
Metals

- For metals, radiation transfer is surface phenomenon
 - All the action takes place within a few hundred angstroms of the surface
 - Only very thin metal foils show any transparency
- For $\lambda > 8 \mu\text{m}$, $\varepsilon_\lambda = 0.00365(r/\lambda)$ (r = electrical resistivity in ohm-cm)
- Since resistivity is proportional to temperature, ε_λ is proportional to $(T/\lambda)^{1/2}$
- Therefore, α_λ is proportional to $(T/\lambda)^{1/2}$, total emittance is proportional to T





More Metals



Emittance of metals varies proportionally to electrical resistance

Best conductors have lowest emittance

Pure metals have lowest electrical resistance

Alloys have higher emittances

Polished surfaces have lower emittance

Usually better than VDA

Annealing reduces electrical resistance



Temperature Dependent Emissivity and Reciprocity

- In order to use reciprocal radiation conductors (radks), greyness must hold. That is, the emissivities of all materials must be constant over the significant range of wavelengths in the problem
- If **total emissivity** is a strong function of T , then most likely your problem is not grey, and a traditional analysis will not work.
- Cases where temperature dependent total emissivity **may** be valid:
 - ↙ Insignificant incident radiation (all goes to space, α 's out of the picture)
 - ↙ Spectral Emissivity is a horizontal line, which just raises or lowers with temperature (still grey!)



Intentional Non-Grey

- So far, the focus has been on typical types of analysis where non-grey conditions may have been neglected
- Some systems are intentionally non-grey
 - ↙ Thermal Photovoltaics
 - ↙ Contains a radiant heat source (600 C), a band gap filter, and a photovoltaic cell that operates in a narrow band
 - ↙ Annealing Processes for Silicon Wafers
 - ↙ Optical properties can also change as a function of time as the wafer grows



Thermal Photovoltaics

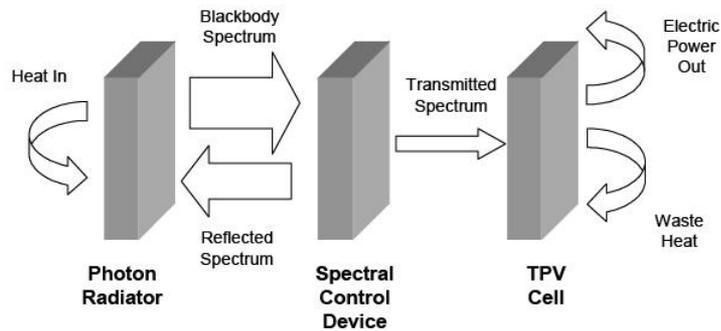
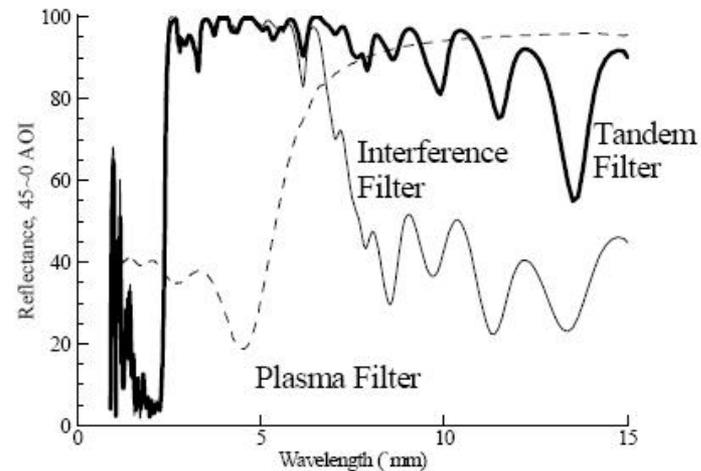


Figure 1. Schematic of TPV conversion components



Definitely Non-Grey!
Band gap is at the peak wavelength of the radiation source



Non-Grey and Spectral Temperature Dependent Methods

- Non-grey problems are handled by breaking the problem up into wavelength bands, such that within each band, the problem becomes grey again.
 - ↙ Banded approach takes care of $\varepsilon(T)$ changes
 - ↙ Even though total emissivity changes with temperature, if the material's spectral distribution is not temperature dependent, no temperature dependent iteration is needed. Energy automatically shifts between the bands.
- If there are temperature dependent spectral emissivities, they must be handled in an iterative matter
 - ↙ New radiation matrices (a matrix for each band) must be computed for new temperatures



Banded Approach

- With one band, we use the total emissivity and radiate using the total emissive power σT^4
 - ↙ We assume that the absorptivity = total emissivity (greyness holds within band)
- With a banded approach, we break the problem up into separate wavelength bands
$$0 \rightarrow \lambda_1, \lambda_1 \rightarrow \lambda_2, \lambda_2 \rightarrow \lambda_3, \dots, \lambda_n \rightarrow \infty$$
 - ↙ We also assume absorptivity = (band averaged) emissivity
 - ↙ Absorptivity will always tend towards emissivity as the bands become narrower
- In each band, each node radiates with the amount of energy in that band, instead of σT^4



Banded Energy Balance

one band

$$Q_{1\leftrightarrow 2} = K_{1\leftrightarrow 2} (\sigma T_2^4 - \sigma T_1^4)$$

multi - band

$$\begin{aligned} Q_{1\leftrightarrow 2} = & K_{1\leftrightarrow 2}^{0\leftrightarrow \lambda_1} (F_{band} (0, \lambda_1, T_2) \sigma T_2^4 - F_{band} (0, \lambda_1, T_1) \sigma T_1^4) + \\ & K_{1\leftrightarrow 2}^{\lambda_1\leftrightarrow \lambda_2} (F_{band} (\lambda_1, \lambda_2, T_2) \sigma T_2^4 - F_{band} (\lambda_1, \lambda_2, T_1) \sigma T_1^4) + \\ & K_{1\leftrightarrow 2}^{\lambda_2\leftrightarrow \lambda_3} (F_{band} (\lambda_2, \lambda_3, T_2) \sigma T_2^4 - F_{band} (\lambda_2, \lambda_3, T_1) \sigma T_1^4) + \\ & \dots + \\ & K_{1\leftrightarrow 2}^{\lambda_n\leftrightarrow \infty} (F_{band} (\lambda_n, \infty, T_2) \sigma T_2^4 - F_{band} (\lambda_n, \infty, T_1) \sigma T_1^4) \end{aligned}$$

$$\sum F_{band} (\lambda_i, \lambda_{i+1}, T) = 1$$



Band Fraction Function

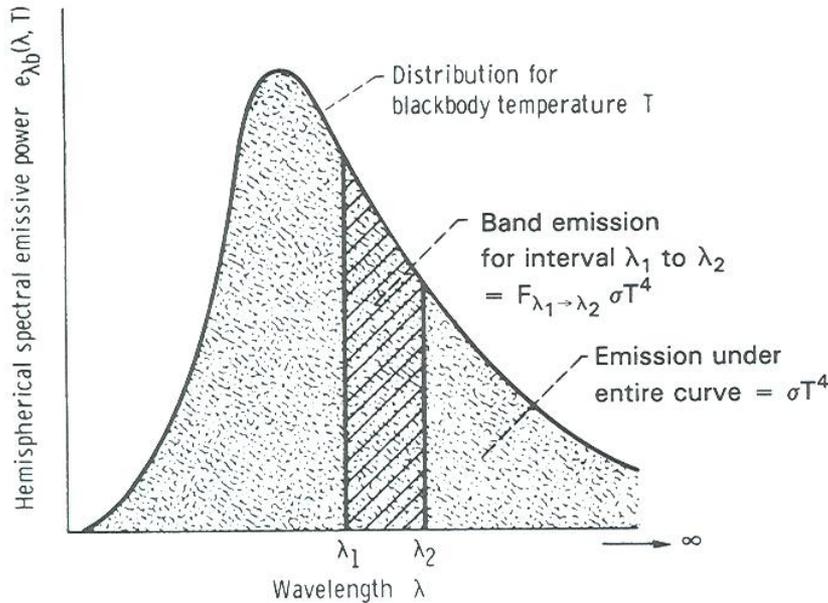


FIGURE 1-11 Emitted energy in wavelength band.

$F_{band}(\lambda_1, \lambda_2, T)$ gives the fraction of energy radiated between λ_1 and λ_2 for a blackbody at temperature T

$$F_{band}(\lambda_1, \lambda_2, T) = \frac{\int_{\lambda_1}^{\lambda_2} E_{\lambda b}(\lambda, T) d\lambda}{\int_0^{\infty} E_{\lambda b}(\lambda, T) d\lambda} = \frac{1}{\sigma T^4} \int_{\lambda_1}^{\lambda_2} E_{\lambda b}(\lambda, T) d\lambda$$

implemented as two integrals

$$F_{band}(\lambda_1, \lambda_2, T) = \frac{1}{\sigma T^4} \left[\int_0^{\lambda_2} E_{\lambda b}(\lambda, T) d\lambda - \int_0^{\lambda_1} E_{\lambda b}(\lambda, T) d\lambda \right]$$

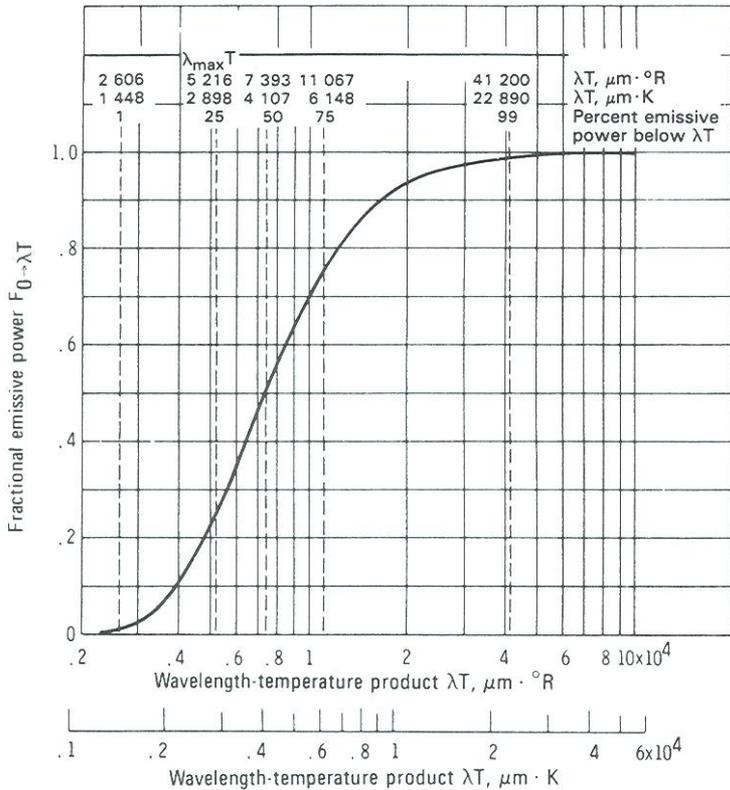
re - arranged in terms of the product λT

$$F_{band}(\lambda_1, \lambda_2, T) = \frac{1}{\sigma} \left[\int_0^{\lambda_2 T} \frac{E_{\lambda b}(\lambda, T)}{T^5} d(\lambda T) - \int_0^{\lambda_1 T} \frac{E_{\lambda b}(\lambda, T)}{T^5} d(\lambda T) \right]$$

$$F_{band}(\lambda_1, \lambda_2, T) = F_{0 \rightarrow \lambda}(\lambda_2 T) - F_{0 \rightarrow \lambda}(\lambda_1 T)$$



Fractional Blackbody Emissive Power Function



$$F_{0 \rightarrow \lambda T}(\lambda T) = \frac{2\pi C_1}{\sigma C_2^4} \int_{\zeta}^{\infty} \frac{\zeta^3}{e^{\zeta} - 1} d\zeta$$

$$\zeta = C_2 / \lambda T$$

$$C_1 = hc^2, \quad C_2 = hc_0 / k$$

$$h = \text{Planck's constant} = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$$

$$k = \text{Boltzmann constant} = 1.3806 \times 10^{-23} \text{ J} / \text{K}$$

$$c_0 = \text{the speed of light} = 2.998 \times 10^8 \text{ m} / \text{s}$$

Both tabular and series form solutions are available

FIGURE I-13 Fractional blackbody emissive power in the range 0 to λT .



Non-Grey Implementation with Grey Radiation Tools

- Manually examine optical properties, pick wavelength bands, and generate emissivities for each band
- Perform separate Radk calculations for each band, using the appropriate set of emissivities
- Use separate submodels and generate “band-radiation” nodes in each radk band (as sink or heater nodes)
 - ✦ For node MAIN.200 generate MAIN_B1.200, MAIN_B2.200, MAIN_B3.200, etc...
- Set the temperature for each band-radiation node so that it matches the emissive power in the band
$$\sigma T_{200-b1}^4 = F_{band}(\lambda_1, \lambda_2, T_{200}) \sigma T_{200}^4$$
- Perform a steady state or transient iteration
- Take the net heat flow into each band-radiation node and sum it into the parent node



Implementation in Thermal Desktop/RadCAD

- Non-grey and temperature varying spectral emissivity analysis automated using Thermal Desktop/RadCAD
- Define wavelength and/or temperature dependent properties using one form, under one optical property name
- Pick bands for radk run using Case Set Manager
- That's it!
 - ↙ RadCAD will recognize banded analysis and automatically compute required optical properties for each band, and automatically compute radks for each band
 - ↙ Sinda contains built-in logic to perform the band-fraction functions and appropriate energy bookkeeping
 - ↙ Dynamic link between Sinda and RadCAD if temperatures change such that new radks are required



Thermal Desktop Optical Property Definition

Edit Optical Property - Cat-A-Lac Black paint

Comment: Set Color...

Use Properties: Wavelength Dependent for Radks, Basic for Heat Rate Calculations

Basic | Wavelength Dependent

Emissivity: Edit Table... Use Table

Transmissivity: Edit Table... Use Table

Specularity: Edit Table... Use Table

Transmissive Specularity: Edit Table... Use Table

Refractive Indices Ratio:

OK Cancel

Tabular Input

Enter Wavelength [micro-m], Emissivity

0.000	0.92
8.000	0.92
10.000	0.85
13.000	0.91
19.000	0.94
20.000	0.82
30.000	0.95
40.000	0.95
60.000	0.78
110.000	0.6
1000.000	0.1

Wavelength [micro-m], Emissivity

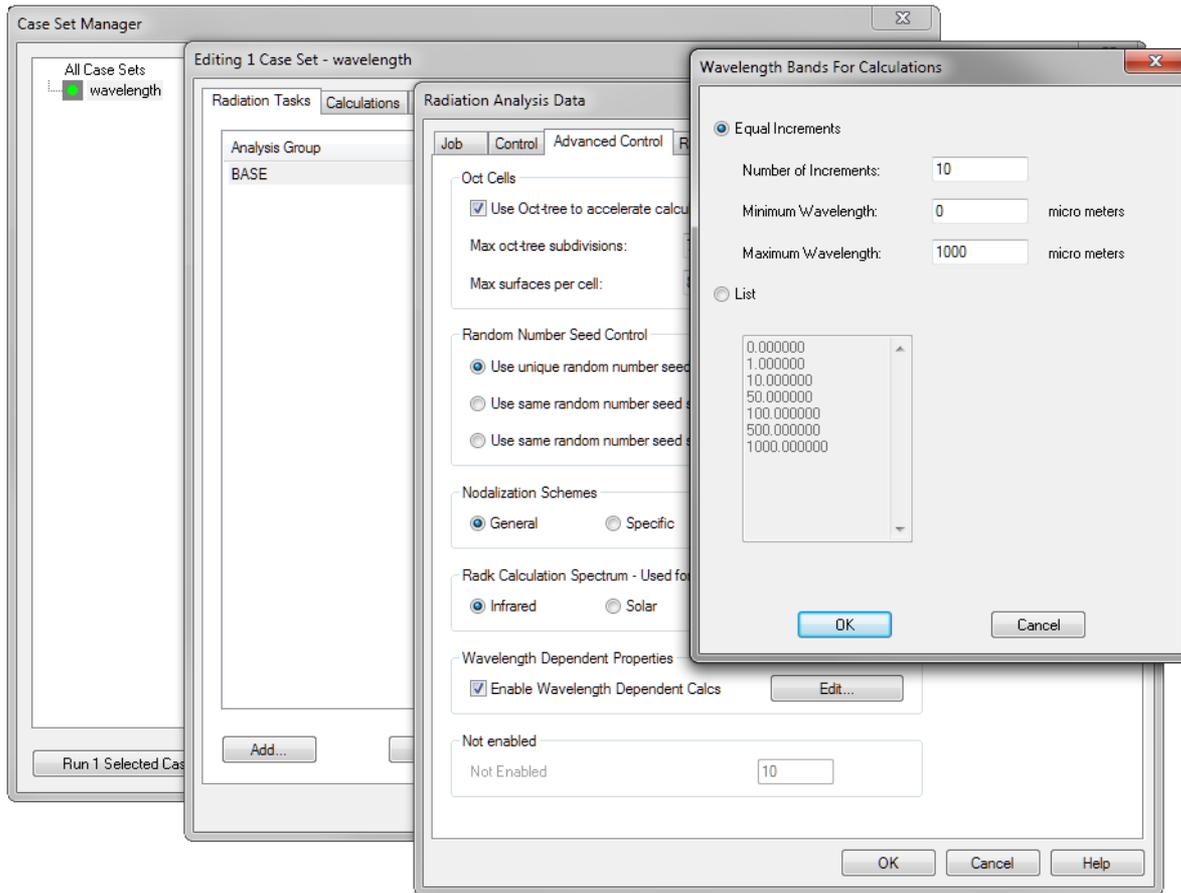
Wavelength [micro-m]

Emissivity

OK Cancel Help



Thermal Desktop Case Set Manager Input



Select Case from Case Set Manager

Edit Radiation Task, selected "Advanced Control"

Edit Wavelength Dependent Properties

Select wavelength bands

TD/RC/SF does the rest



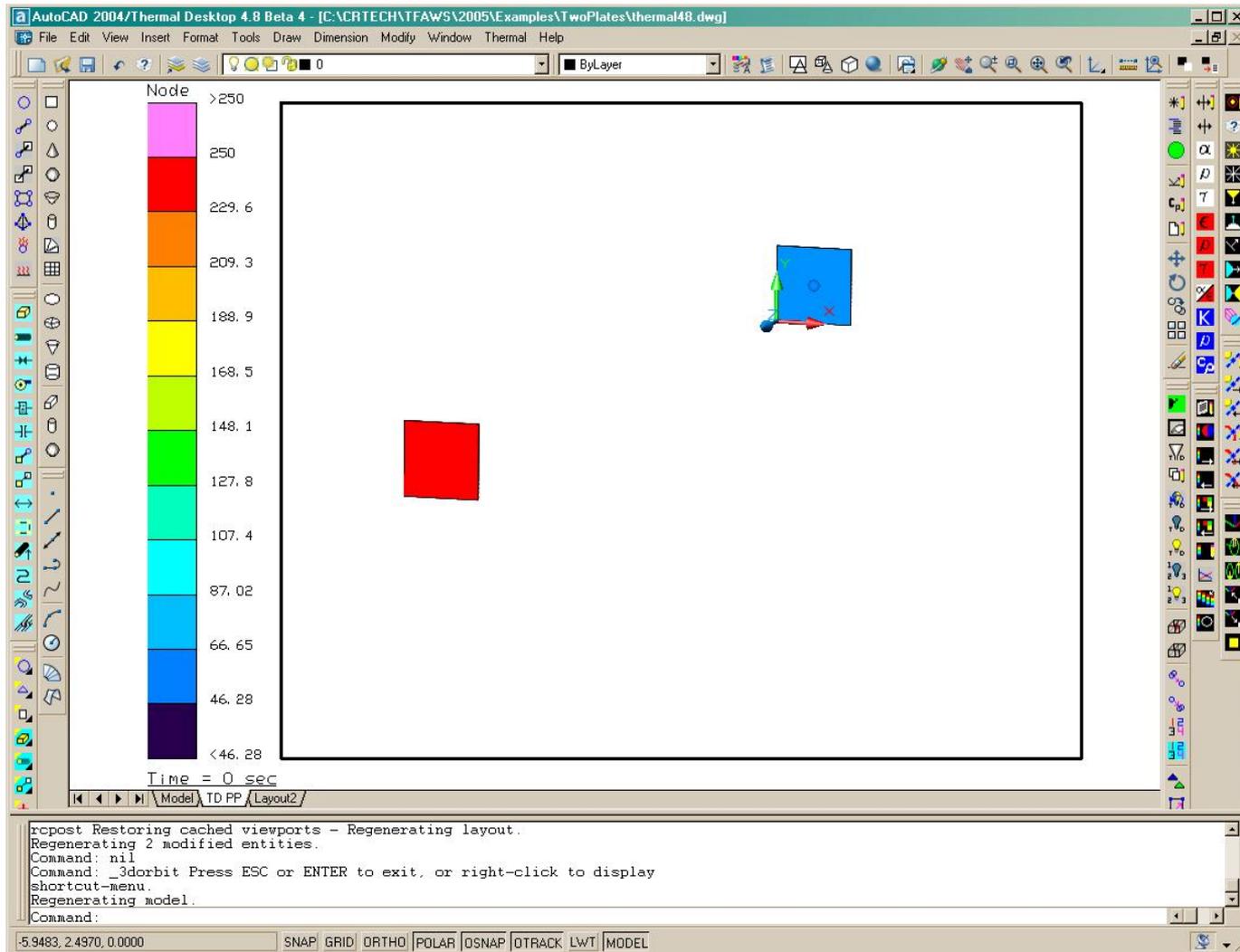
Examples

Demonstration



Example 1

Two Parallel Plates





Problem Description

Two Parallel Plates

- 1x1 rectangles separated by a distance of 16
- One rectangle held at 250 K.
- Spectral Emissivity Data for Cat-A-Lac black paint used for analysis
- 1,000,000 rays per surface
 - ↙ 1st case: constant emissivity of .92 for both surfaces
 - ↙ 2nd case: constant emissivity of .92 for hot surface, constant emissivity of .5 for cold surface
 - ↙ 3rd case: wavelength dependent for both surfaces



Results

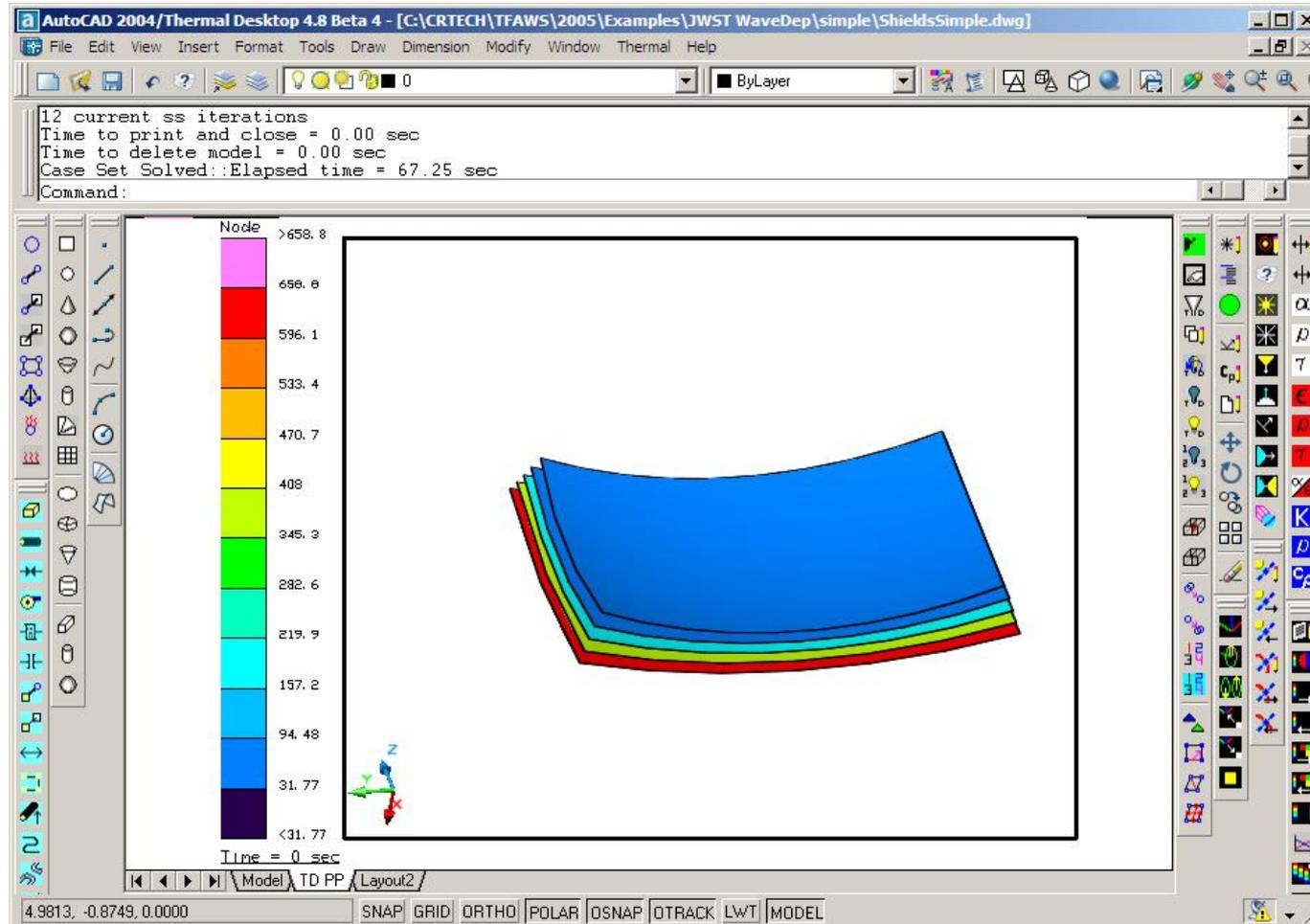
Two Parallel Plates

- Hot surface maintained at 250K
 - ↙ Case 1, .92/.92: Cold surface 46.2 K
 - ↙ Case 2, .92/.5 Cold surface 46.1 K
 - ↙ Case 3, wave/wave Cold surface 42.9 K
- Why the same results for the cold surface for both emissivity equal to .92 and .5 ?
 - ↙ Cold surface comes to equilibrium based on heat absorbed from the hot surface and radiation to space.
 - ↙ Ratio remains essentially the same, at .92 it absorbs more heat from the hot surface, but also radiates more to space. At .5, it absorbs less, but also radiates less.
 - ↙ In reality, the cold surface absorbs at .92, but radiates at .5!
 - ↙ Modeled correctly only using a wavelength dependent analysis



Example 2

Simple Shields





Problem Description

Simple Shield

- 5 spherical shields
- Wavelength/Temperature dependent emissivity using UHV evaporated gold data presented earlier
- Three Cases:
 - ↙ Constant Emissivity
 - ↙ Temperature Dependent *Total Emissivity* (still grey)
 - ↙ Temperature Dependent Spectral Emissivity (non-grey)



Simple Shield Results

	Min Temp	Max Temp
Constant Emissivity	31.55	658.2
Temp dep Total Emissivity	31.77	658.8
Wavelength & Spectral Temp Dep	52.77	617.7

Temperature dependent ***Total Emissivity*** gives the same answers as ***constant*** emissivity, for the same reason as the two parallel plates.

Using total emissivity as a function of temperature is ***not*** a good approximation to a true non-grey analysis



Summary

- Examine optical properties and range of temperatures to determine if problem is non-grey
- Implemented and Automated in Thermal Desktop
 - ↙ Wavelength and temperature dependent optical property input
 - ↙ Automatic breakdown and computation of bands
 - ↙ Dynamic feature for temperature dependent radiation networks



Q&A
