1. (8 points) In the 1800’s it was recognized that temperatures in mines and caves increased with depth. Listed below are some measurements taken in a rather deep mine. Assume steady-state equilibrium and,

   a) Graph the temperature versus depth using an excel spreadsheet.

   b) Either by hand or using excel’s linear trend line, draw the best fit straight line through your points and determine the thermal gradient from the slope.

   c) Determine the average thermal conductivity from the values given.

   d) Use the results from (b) and (c) to determine the heat flux through the surface in this region.

   e) How many milliWatts per square meter are there in 1 HFU?

   f) Convert the result from (d) into $\frac{\text{calories}}{\text{cm}^2 \cdot \text{sec}}$ and also convert it into HFU.

<table>
<thead>
<tr>
<th>Depth (Km)</th>
<th>Temperature (°C)</th>
<th>Conductivity (Watts/(m-°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>11.0</td>
<td>2.41</td>
</tr>
<tr>
<td>0.5</td>
<td>23.0</td>
<td>2.45</td>
</tr>
<tr>
<td>1.0</td>
<td>36.0</td>
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<td>1.5</td>
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<td>2.52</td>
</tr>
<tr>
<td>2.0</td>
<td>61.5</td>
<td>2.49</td>
</tr>
<tr>
<td>2.5</td>
<td>74.0</td>
<td>2.47</td>
</tr>
<tr>
<td>3.0</td>
<td>85.5</td>
<td>2.60</td>
</tr>
<tr>
<td>3.5</td>
<td>99.0</td>
<td>2.55</td>
</tr>
<tr>
<td>4.0</td>
<td>110.0</td>
<td>2.58</td>
</tr>
</tbody>
</table>

Recall:
1 Watt = 1 Joule/sec
1 calorie = 4.2 Joules
1 HFU = $10^{-6}$ calories/cm$^2$-sec
2. (17 points) Let’s use the heat equation to find an expression relating temperature to depth within the Earth. Assuming a steady-state equilibrium (e.g., no change with respect to time), ∂T/∂t = 0, so the heat equation becomes,

\[ 0 = k \frac{d^2T}{dy^2} + \rho H. \]

Given that we know the heat flux (q = −qs) through the Earth’s surface and the temperature (Ts) at the surface as well,

a) Integrate the heat equation with respect to y to determine the heat flow as a function of depth. Recall that you will need to use the surface heat flux to solve for the constant of integration.

b) Integrate the result from (a) to determine the relation of temperature with depth inside the Earth to show that,

\[ T(y) = T_s + \frac{qs}{k} y - \frac{\rho H}{2k} y^2. \]

Again, you will need the surface temperature to evaluate the constant of integration.

c) Use,

\[ q_s = 70 \text{ milliWatts m}^{-2}, \quad \rho = 3 \text{ g/cm}^3, \]

\[ H = 10^{-10} \text{ W/kg}, \quad k = 4 \text{ Watts m}^{-1} \text{ °C}^{-1}, \]

and \[ T_s = 10^\circ \text{C}, \]

to determine the temperature profile of the upper 200 km within the Earth. Plot these points on the following page.

d) Also shown on the graph paper are the liquidus (the line separating the liquid phase (or magma) of a rock from the partially molten phase) and the solidus (the line separating the solid phase of the rock from the partially molten phase), for a peridotite.

i) Determine the depth where the mantle starts to melt.

ii) Does this depth correspond with any other observational attribute of the mantle?

iii) At what depth is the mantle entirely liquid?

iv) What observations tell us that the mantle does not heat up to such temperatures?

v) How is such melting prevented by the mantle?

e) Using the parameters listed in part (c), find the temperature in the crust at 5, 10, and 15 km by varying your assumption about the heat generation in crustal rocks:

i) assume H = 0; no heat is generated in the rock.

ii) assume H = 10^{-9} \text{ watts/kg}. 

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3. (8 points) For a planet with radius $a$ and surface temperature zero, temperature as a function of radius is given by

$$T(r) = \frac{\rho H (a^2 - r^2)}{6k}$$

where $\rho$ is density, $H$ is heat production, and $k$ is thermal conductivity.

a) Show that this solution satisfies the heat equation for a spherical planet

$$0 = \frac{k}{r^2} \frac{d}{dr} \left( r^2 \frac{dT}{dr} \right) + H \rho.$$

b) Assuming that $k = 4 \text{W/m} \cdot \text{°C}$, $H = 10^{-10} \text{ W/kg}$, $\rho = 5.5 \text{ gm/cm}^3$ find the temperature at the centers of planets with radii 10 km, 100 km, 1000 km. (Be careful with units!)

c) How large must such a planet be before it melts in the center, assuming melting occurs at 1000°C?
4. (5 points) Estimate the total energy in ergs per year flowing from the earth’s interior, assuming a surface heat flow of 1 HFU (1 HFU = 4.184 x 10^{-2} W/m^2). Compare this to the total annual energy per year from solar radiation, assuming an incident solar flux at the Earth’s orbit of 1.36 x 10^3 W/m^2.
5. (4 points) Determine the Rayleigh number as a function of $\Delta T$ for a solid mantle. Use the following physical parameters,

$$\alpha = 2 \times 10^{-5} \, ^\circ C^{-1},$$
$$g = 10 \, m/s^2,$$
$$\rho = 3.5 \times 10^3 \, kg/m^3,$$
$$\kappa = 10^{-6} \, m^2/s,$$
$$\eta = 10^{21} \, kg/m - s.$$

Under what conditions would you expect the solid rock in the mantle to convect?
6. (2 points) To get a feel for different convection styles go to the Geology 202 web page http://www.earth.nwu.edu/people/seth/202 and click the link under the topic Thermal evolution of planets. Then, go to the link A fancier convection "movie". Run both the high-Rayleigh number and low-Rayleigh number versions (requires a *mpeg player). For each, clicking the picture shows the "movie", and clicking the text produces a description. How does the convection differ?
C-1. (6 points) From the heat equation, the time $t$ needed for heat to conduct a distance $y$ is given by $y = \sqrt{Kt}$ where $K$ is the thermal diffusivity. Write an excel spreadsheet to calculate the conductive cooling time (in years) for the given material thickness. Assume $K = 10^{-6} \text{ m}^2/\text{s}$.

a) 1 meter

b) 1 kilometer

c) 6000 kilometers.

The last time is approximately the time needed for the earth to cool down by conduction alone. How does it compare to the age of the earth?