Designing a Heat Shield for the Space Shuttle

Submit your answers to the questions found in the shaded boxes of the prelab portion of this handout to the instructor at the beginning of the laboratory. The questions are repeated on the last page for your convenience. You will not be allowed to begin work without having done so. Please include printout from any calculations done using EXCEL or another program.

Objectives
After completing the following exercises you will understand how a calorimeter is based upon the First Law of Thermodynamics. You will use this Law to express an energy balance equation that will enable you to calculate the specific heat capacity of a sample from data collected from a calorimeter. You will understand the difference between heat and temperature.

Goals
- To understand the First Law of Thermodynamics as an expression of the conservation of energy and how this is put to use in a calorimeter.
- To understand the difference between temperature and heat and how the specific heat capacity allows the conversion between the two.
- To construct a calorimeter.
- To collect data using the calorimeter that will allow the calculation of the specific heat capacity of different materials.
- To determine which materials would be suitable for use as a heat shield for the space shuttle.

Lab Summary
You will construct a calorimeter and then calculate its heat capacity. Then you will use the calorimeter to measure the specific heat capacity of several materials using an energy balance equation. The different materials will be evaluated for their suitability for use as a heat shield for the space shuttle using a given design equation and set of parameters.

Temperature, Heat and Energy
Energy is the ability to do work. Energy is measured in units of calories (cal) or Joules (J) (1 cal = 4.184 J). Heat is a form of energy. Heat can be taken and converted into other forms of energy; this is done at electric power plants when the heat in a boiler is used to drive turbines that generate electricity. The heat is transformed into kinetic energy, the motion of the turbine, and then the kinetic energy is transformed into electrical power by the generator. The First Law of Thermodynamics governs energy transformations. The First Law states that energy can be transformed between different forms but cannot be created or destroyed. This will allow us to account for all of the energy that is involved with a process. Since energy is not created or destroyed all the energy going into a process also has to come out of the process in some form or another. This means that energy is conserved.
We will use the letter Q as the symbol for heat. Temperature is proportional to heat; mathematically we can indicate this as:

\[ Q \propto T \text{ or } \Delta Q \propto \Delta T, \]

where \( \Delta \) is the Greek letter delta and is used as the symbol for a change from an initial to a final state (example: \( \Delta T = T_{\text{final}} - T_{\text{initial}} \)). We know that if a material is heated its temperature will rise and if it is cooled or heat is removed its temperature will drop. Observing this phenomenon with many samples of different materials is what saying that temperature is proportional to heat means.

If two different materials are heated from room temperature up to a higher temperature will both materials have the same change in energy since they have the same change in temperature? The answer for this question has been found to be no; the different materials have different changes in energy with the same change in temperature. Scientists doing experiments with calorimeters and calculating energy balances for the events that occurred were able to determine this.

**Calorimetry & Energy Balances**

A calorimeter is essentially just an insulated box and an energy detector. The insulation prevents energy from escaping and allows it to be measured by your detector. An energy balance is a method that allows you to take the measured energy change of the calorimeter and detector and relate it to the energy change of what you put in the calorimeter. Energy balances are based on the First Law of Thermodynamics. This law states that energy can be exchanged between a system and its surroundings or transformed from one form to another, such as converting heat into electrical energy, but no energy can be created or destroyed. Energy is conserved.

What is a scientific Law? It is a description of behavior based on the results of many, many experiments. The First Law of Thermodynamics is a law because no one has encountered a situation where energy is not conserved. In cases where people initially thought that energy was being created further experiments revealed flaws in the original work and theories. We can measure the exchange energy between a system and its surroundings and be confident that we will not have to worry about the creation or destruction of energy.

In our case, the system will be defined as the sample that we place into the calorimeter and the surroundings will be the calorimeter and energy detector. Our calorimeter is made out of Styrofoam cups with a foil lid and the energy detector is a mass of water and a thermometer. The First Law says that energy is conserved; this means that the change in energy of the sample will equal the change in energy of the calorimeter and detector or the Styrofoam cups, mass of water and thermometer. This can be expressed mathematically as:

\[
\Delta E_{\text{sample}} = -\Delta E_{\text{surroundings}}, \text{ or } \\
\Delta E_{\text{sample}} = -(\Delta E_{\text{calorimeter}} + \Delta E_{\text{detector}}), \text{ or } \\
\Delta E_{\text{sample}} = -(\Delta E_{\text{cups}} + \Delta E_{\text{water}} + \Delta E_{\text{thermometer}}).
\]
We now have an energy balance equation that tells us that the energy lost by the sample will be gained by the surroundings, which in this case will be all the components of our calorimeter. Note that there is a minus sign on one side of our equations to indicate that the energy changes are of equal magnitude but are in opposite directions, lost vs. gained. We will always use this sign convention for changes in energy.

**Specific Heat Capacity**

We still have not answered the original question as to whether different materials will have different energy changes for the same temperature change. To answer this question we need to introduce the specific heat capacity \( c_s \). The specific heat capacity allows the conversion of the equation that says a change in temperature is proportional to the change in heat, \( \Delta Q \propto \Delta T \); to a form that says the change in heat is equal to the change in temperature time the specific heat capacity and mass of the sample, \( \Delta Q = c_s m \Delta T \). The specific heat capacity is the proportionality constant for a given material; it has units of J/g - K or J/g - °C and allows the calculation of changes in energy from changes in temperature.

Some examples:

How much energy is required to heat 100 g of water from 0 to 100 °C?  
The specific heat of water is: \( c_s = 4.184 \text{ J/g - K} \)  
0 °C = 273 K and 100 °C = 373 K  
\[ Q = (4.184 \text{ J/g - K})*(100 \text{ g})*(373 \text{ K} – 273 \text{ K}) = 41,840 \text{ J or } 4.18 \times 10^4 \text{ J or } 41.8 \text{ kJ} \]

How much energy is released when 100 g of water is cooled from 100 to 0 °C?  
The specific heat of water is: \( c_s = 1.0 \text{ cal/g - K} \)  
0 °C = 273 K and 100 °C = 373 K  
\[ Q = (4.184 \text{ J/g - K})*(100 \text{ g})*(273 \text{ K} – 373 \text{ K}) = -41,840 \text{ J or } -4.18 \times 10^4 \text{ J or } -41.8 \text{ kJ} \]

Notice how the sign convention works in these two examples and that we convert temperature from Celsius to the Kelvin scale for these problems.

Now to answer the original question; since every different material has its own specific heat capacity the change in energy will be different for the materials with the same change in temperature. Here is an example that shows this and will also explain why hot water can cause such severe burns.
Example: Which would cause more tissue damage, spilling 100 g of hot water at 100 °C onto your lap or dropping 100 g of copper pellets at 100 °C onto your lap? Body temperature is 37 °C and the specific heats of water and copper are 4.184 and 0.385 J/g-K.

We will assume that whatever is dropped or spilled onto our laps will be allowed to cool down from its initial temperature to body temperature.

Energy released from the spilled water:
\[ Q = (100 \text{ g}) \times (4.184 \text{ J/g-K}) \times (310 \text{ K} - 373 \text{ K}) = -26,359 \text{ J or -26.3 kJ} \]

Energy released from dropped copper:
\[ Q = (100 \text{ g}) \times (0.385 \text{ cal/g-K}) \times (310 \text{ K} - 373 \text{ K}) = -2500 \text{ J or -2.5 kJ} \]

The water causes more damage to your body because it stores so much more heat than the copper for a given temperature change. Water is said to have a larger thermal mass than copper.

Our new equation containing the specific heat capacity allows us to use the thermometer to measure temperature changes in our calorimeter and to then calculate the energy changes. We can plug our new equation into the energy balance to get:

\[ m_{\text{sample}} \ C_{\text{sample}} (T_{\text{final}} - T_{\text{init sample}}) = -(m_{\text{H}_2\text{O}} C_{\text{H}_2\text{O}} + C_{\text{cal}}) (T_{\text{final}} - T_{\text{init c}}) \]

Note that the specific heat capacity of the calorimeter has units of cal/K and not cal/g-K and includes the contribution of the cups and thermometer. Realize that the final temperature is the same for the sample and the calorimeter, there will however be different initial temperatures though. This equation can be used to calculate the specific heat capacity of a sample placed into the calorimeter.

**Space Shuttle Heat Shield**

The space shuttle provides a shirtsleeve environment for its crew during orbital flight. This means that the temperature inside the shuttle \( T_{\text{shuttle, init}} \) is kept at 25 °C. The crew needs to be protected from the extreme temperatures that can be encountered during the shuttle's re-entry into the earth’s atmosphere. Hull temperatures \( T_{\text{hull}} \) can reach nearly 1600 °C during the re-entry process.

At approximately 265,000 feet, the shuttle enters a communications blackout, which lasts until the orbiter reaches an altitude of approximately 162,000 feet. Between these altitudes, heat is generated through friction as the shuttle enters the atmosphere and causes reactions among the molecules of oxygen and nitrogen it encounters. Some of the molecules are broken apart into atoms and then the atoms are ionized. The ionized atoms form a temporary layer around the spacecraft. Radio signals between the shuttle and the ground cannot penetrate this sheath of ionized particles, and radio communications are blocked for approximately 16 minutes. The shuttle crew needs thermal protection for only the peak period of heat generation that last for 90 seconds during the 16-minute radio blackout.

The equation below allows you to determine if a material will be useful as a heat shield for the peak period of heat generation. During this period the temperature of the shuttle cannot go above 50 °C. The other terms in the equation are: \( h \), the coefficient of heat transfer for
which a value of 6.0 J-sec\(^{-1}\) m\(^{-2}\) K\(^{-1}\) can be used for all of the materials investigated in the laboratory. A, the surface area of the shuttle for which a value of 100 m\(^{2}\) can be used, C\(_s\), the specific heat capacity of your heat shield material, m, the mass of your heat shield, we are limited to 1200 kg, and t, the time period of peak heat generation

\[ T_{shuttle} = T_{hull} - (T_{hull} - T_{shuttle, initial})e^\left(-\frac{hA}{cm}\right) \]

In the laboratory you will measure the specific heat capacity of several materials and determine if they will make satisfactory heat shields for the space shuttle using the above equation.

Example: We will calculate the final shuttle temperature using a heat shield material with a specific heat of 0.15 J/g-K.

The values we need are: 
- \(T_{hull} = 1600 \, ^\circ C\)
- \(T_{shuttle, initial} = 25 \, ^\circ C\)
- \(h = 6.0 \, \text{J-sec}^{-1}\) m\(^{-2}\) K\(^{-1}\)
- \(A = 100 \, \text{m}^{2}\)
- \(C_s = 0.15 \, \text{J/g-K}\)
- \(M = 1,200,000 \, \text{g}\)
- \(t = 90 \, \text{secs}\)

Then the equation gives us:

\[ T_{shuttle} = 1600 \, ^\circ C - ((1600 \, ^\circ C - 25 \, ^\circ C)*\exp(-6.0 \, \text{J-sec}^{-1}\text{m}^{-2}\text{K}^{-1}*100 \, \text{m}^{2}*90 \, \text{sec}/0.15 \, \text{J/g-K}*1,200,000 \, \text{g})) \]

Note: \(\exp(some \, numbers)\) is one way to indicate an exponential function. This is how you would do it using EXCEL. Some calculators have an \(e^x\) button that accomplishes the same thing.

In the exponential term, J’s, m\(^2\)’s, sec’s, K’s and g’s cancel.

\[ = 1600 \, ^\circ C - (1575 \, ^\circ C*\exp(-0.3)) \]
\[ = 1600 \, ^\circ C - (1575 \, ^\circ C*0.741) = 433 \, ^\circ C \]

This would not be a good material to use; the astronauts are roasted during the reentry process.
Prelab Questions
1) A 450 g block of lead is heated from 25 to 78 °C. How much energy is required if the 
cs is 0.13 J/g-K?

2) A 200 g block of lead absorbs 500 J from its surroundings. If it was initially at
100 °C, what is its final temperature?

3) A 100 g sample of a new material is placed into a calorimeter and heated. It is observed
that the temperature of the material rises from 25 to 28 °C when 300 Joules are added to
the calorimeter. What is the specific heat capacity of the new material?

4) 50 g of water at 75 °C is placed into a calorimeter that contained 50 g of water at
25 °C. The final temperature of the system is 40 °C. What is the specific heat of the
calorimeter?

5) What are the units of the product: \( \frac{hA}{cm}t \)?

6) What would the shuttle temperature be after the peak re-entry time if the heat shield was
composed of aluminum, cs = 0.899 J/g-K. Use the values given in the text above for all
the other variables. What would the temperature be if the mass of the aluminum heat
shield was 1500 kg? Was 900 kg?