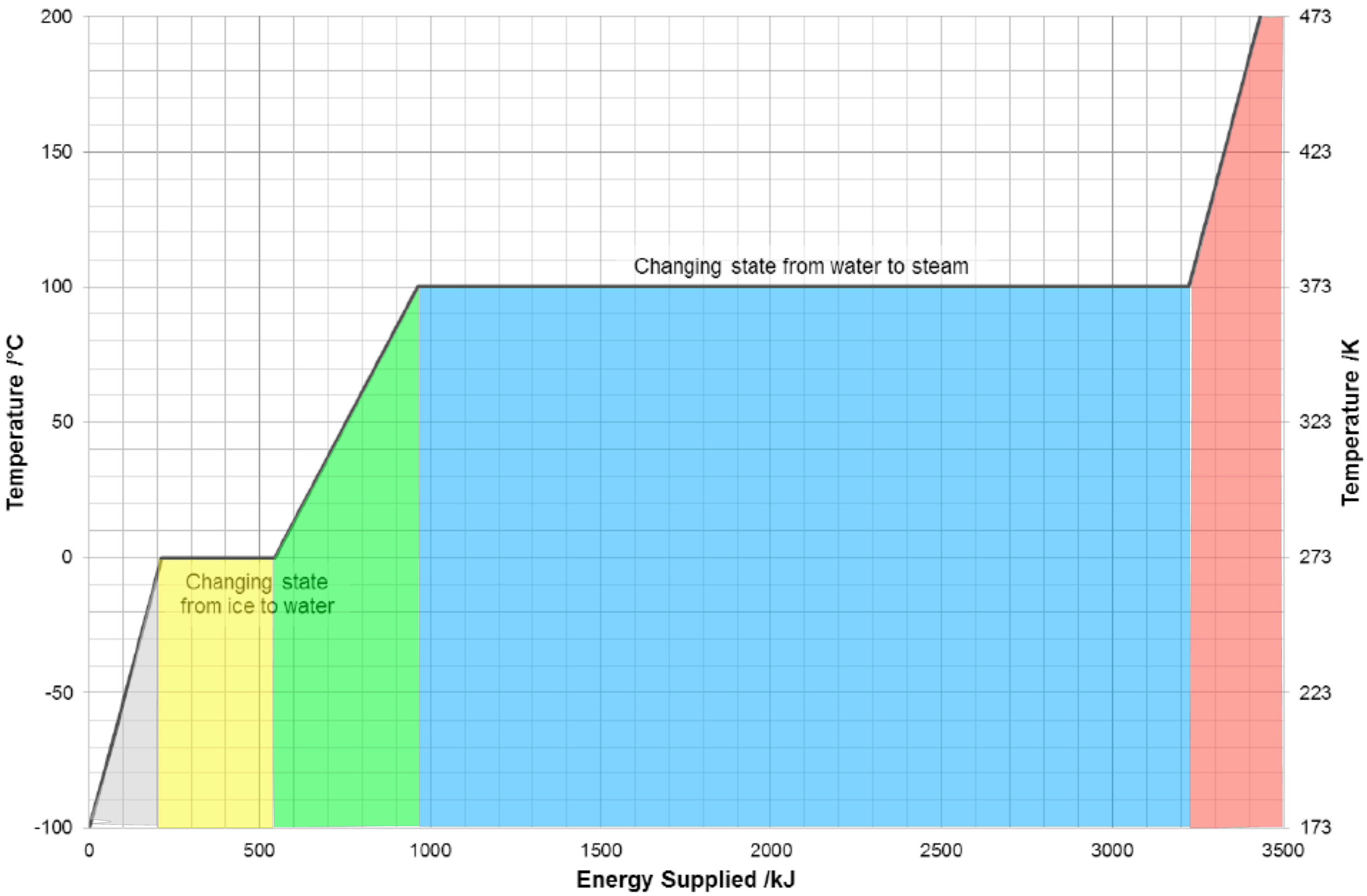
Heat and Calorimetry

Warmup Question

A service technician is working on a piece of high-tech manufacturing equipment, when a high temperature line suddenly ruptures. The skin of her arm is sprayed with 10 g of water at a temperature of 100°C. Will it make any difference to her injuries whether the water is in a liquid or gaseous state (i.e., steam)? Explain. (Please note: No service technicians were killed or maimed in the production of this question)


Changing state from water to steam
Changing state
from ice to water
Temperature /°C
Temperature /K
Energy Supplied /kJ
200
150
100
50
0
-50
-100
473
423
373
323
273
223
173
0
500
1000
1500
2000
2500
3000
3500

ANS: Her injuries will be much worse if she is hit by 100°C steam. In both cases, heat will transfer to her skin and the water will lose heat. In the case of liquid water, it will immediately drop in temperature as it loses heat. In the case of steam, the steam will condense to liquid water as it loses heat. She will absorb a lot of heat as that steam condenses before it even becomes liquid water at 100°C.

Warmup Question

Which of these is a mechanism for transferring thermal energy?

1. conduction
2. radiation
3. convection
4. all of the above

ANS: **4**—All are recognized mechanisms.

Conduction occurs when bodies are in thermal contact with each other.

Convection occurs when fluid currents (like wind) carry away heated or cooled fluid or move it around the room.

Every object that has a temperature (on an absolute scale) will radiate energy, and everything but an ideal reflector (which doesn't actually exist) will absorb some radiant energy.

One object has a mass ten times greater than another, but they both start out at the same temperature. If the same amount of heat is added to both, which ends up with the higher final temperature?

1. the more massive object
2. the less massive object
3. they have the same final temperature
4. more information is needed

ANS: **4**—More information is needed.

We do not know anything about the material composition of the objects. In particular, we don't know anything about the specific heats of the two objects.

If they have the same specific heat (for example if they are made of the same material) then the less massive object will have the lower heat capacity and undergo the greatest change in temperature.

If, on the other hand, the less massive object has ten times the specific heat of the more massive object, they will have the same heat capacity and therefore the same increase in temperature.

The lighter object might actually have more than ten times the specific heat of the heavier object, which would mean that the heavier object would have less heat capacity and actually heat up more.

The specific heat of water is roughly nine times the specific heat of iron. If you fill an iron skillet at 30°C with an equal mass of water at 20°C, the final temperature of the skillet and water at thermal equilibrium is approximately

1. 20°C
2. 21°C
3. 25°C
4. 29°C
5. 30°C

ANS: **2**—The final temp will be 21°C.

They have the same mass, so the water will have a greater heat capacity than the iron. The pan loses as much heat as the water gains, so the drop in the pan's temperature will be greater than the gain in the water's temp, making the final temperature closer to the initial water temperature than to the initial pan temperature.

In fact, the water's heat capacity will be 9 times the pan's heat capacity. Therefore, the loss in the pan's temp will be nine times greater than the gain in the water's temperature:

$$m_\mathrm{w} c_\mathrm{w} \Delta T_\mathrm{w} + m_\mathrm{p} c_\mathrm{p} \Delta T_\mathrm{p} = 0 \quad \rightarrow \quad \frac{\Delta T_\mathrm{p}}{\Delta T_\mathrm{w}} = -\frac{m_\mathrm{w} c_\mathrm{w}}{m_\mathrm{p} c_\mathrm{p}} = -9\,.$$

This makes the final temperature 21°C.

You pour your favorite drink into a glass. If specified mass of one of the following is added and they come to thermal equilibrium, which is likely to cool it to the lowest temperature?

1. ice at 0°C
2. water at 0°C
3. stone cubes at -25°C with the same specific heat as ice
4. Either 1 or 2
5. Either 1 or 3
6. Either 2 or 3
7. All of the above are equal

ANS: 1—Ice at 0°C will cool the beverage the most.

The ice must first melt (change phase) before it becomes water at 0° C. The beverage will cool significantly as the ice melts. After that point, we have water at 0° C cooling a beverage that is already cooler than it started. So the ice will certainly cool more than the water.

The specific heat of ice is roughly half the specific heat of water, so the stone cubes with the same specific heat as ice will not cool the beverage as much as the water would. Plus, there would be no phase change in the plastic.

Remember: it's not the specific heat of ice that makes it do such a good job of cooling your beverage. It's the latent heat absorbed as the ice melts.

A guy in a bar offers you the following bet for a large sum. He bets you can’t burn a hole in a dollar bill stretched across your forearm using the lit end of a cigarette.

Can you win the bet?

1. No, it can’t be done without serious injury.
2. Sure, what’s a little pain?
3. It can be done, but I won’t do it because bars, cigarettes, and betting are all against my principles.

ANS: **1**—You will burn yourself badly long before the bill ignites.

A dollar bill is very thin, so the part of the bill exposed to the flame will have very little mass. It won’t take much heat to raise the temperature of the bill high enough to ignite. If you hold the bill in the air and touch it with a flame, the bill ignites easily.

However, when the bill is in contact with your arm, heat will be conducted away from the bill and into your arm. The flame will heat up the bill, but heat will readily flow from the hot bill to your cooler arm. The heat capacity of your arm will be much greater than that of the dollar bill, and will readily absorb the heat. You will have to keep holding the flame to the bill and slowly heat up both the bill and your arm. Sadly, your arm will sustain quite a bit of damage before the bill gets hot enough to ignite.

You may have seen a physics demonstration where you can boil water in a paper cup over a flame that will readily burn the empty cup. The explanation is the same.

Liquid water above 0° is combined with ice below 0° in a thermally isolated container. You calculate the following thermal energy requirements:

• Heat to cool the liquid water to 0°C	28 kJ
• Heat required to freeze the liquid water	17 kJ
• Heat required to warm the ice to 0°C	13 kJ
• Heat required to melt the ice	10 kJ

What is the final state after thermal equilibration?

1. All liquid water above 0°C
2. All liquid water at 0°C
3. A mixture of ice and water at 0°C
4. All ice at 0°C
5. All ice below 0°C
6. More information is needed

The answer is **1.** The first thing that will happen is an exchange of heat between the ice and water till one of them reaches 0°C. When 13 kJ is exchanged, the ice will be entirely at 0°C, while the water would have to lose another 15 kJ before it got there. More heat is exchanged which further cools the water while melting the ice. Once 10 kJ of heat are exchanged, all the original ice is melted into water, but the original water has still not reached 0°C, as it would still have to lose another 5 kJ to reach zero. The final equilibration temperature will be below the temperature the water had reached but above 0°C.

Problems like this are solved by bookkeeping. Here, the relevant energies are given to you, but more generally you'd be required to calculate the energy associated with each process before figuring out what the final state would be.

The following data are all for water:

- $c_{\text{ice}} = 2.11\,\text{kJ/kg°C}$
- $c_{\text{liquid}} = 4.19\,\text{kJ/kg°C}$
- $c_{\text{vapor}} = 2.08\,\text{kJ/kg°C}$
- $L_{\text{fusion}} = 334\,\text{kJ/kg}$
- $L_{\text{vaporization}} = 2256\,\text{kJ/kg}$

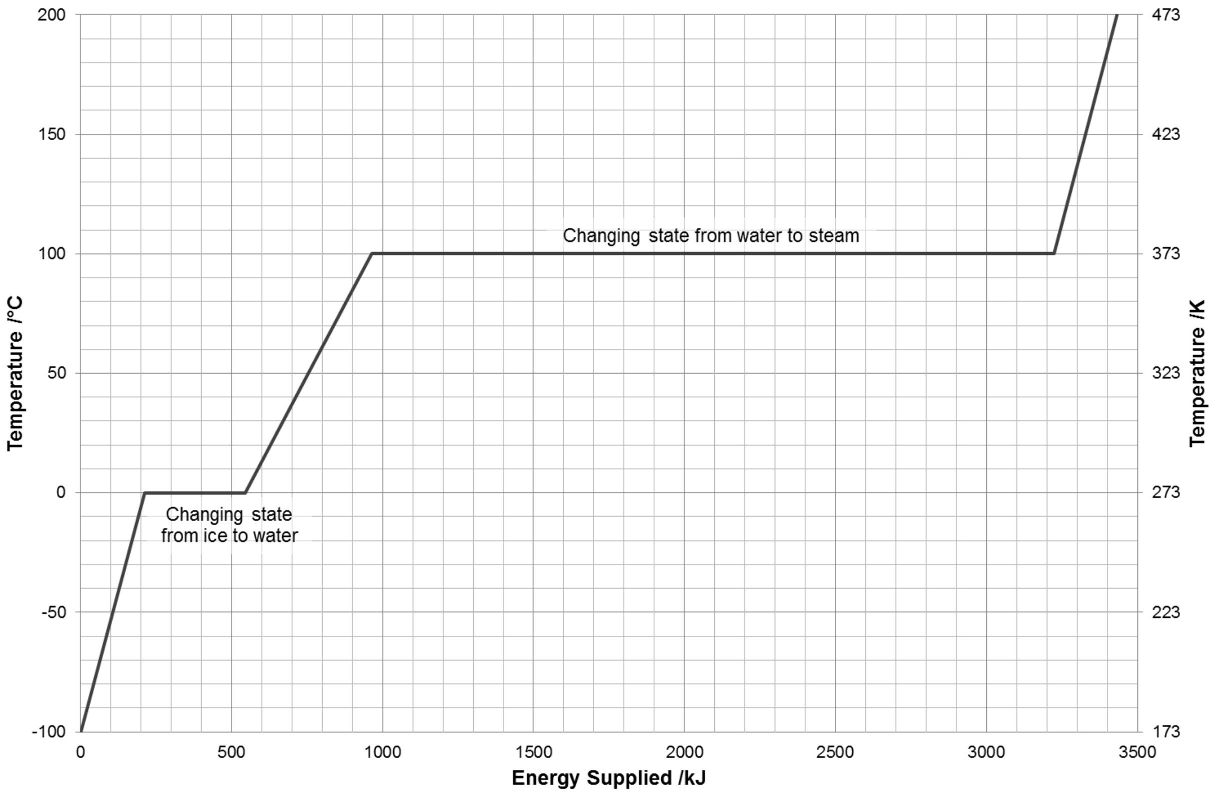
For a given mass of water, which 10°C temperature change requires the most heat?

1. −15°C → −5°C
2. −5°C → 5°C
3. 5°C → 15°C
4. 85°C → 95°C
5. 95°C → 105°C
6. 105°C → 115°C
7. They are all the same

ANS: **5**—The temperature change $95°C \rightarrow 105°C$ requires the most heat.

This should be immediately obvious. The mass does not matter, as long as it is the same in each case, so let's just take the mass to be 1 kg for simplicity. Then the amount of heat to raise the temperature 10°C *with no phase change* is anywhere from around 21 kJ (for ice and vapor, choices 1 and 6) to around 42kJ for water (choices 3 and 4).

This is nowhere near the heat required in the cases with phase changes, where 336 kJ is required just to melt the ice (choice 2) and 2256 kJ is required to just boil the water (choice 5). This does not even count the heat required to raise the temperature of the water before and after the phase changes!


200
150
100
50
0
-50
-100
473
423
373
323
273
223
173
Temperature /°C
Temperature /K
Changing state from water to steam
Changing state
from ice to water
0
500
1000
1500
2000
2500
3000
3500
Energy Supplied /kJ