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Topic 6.5: Energy of Phase Changes

Worksheet · AP Chemistry

UNIT 6 · THERMOCHEMISTRY

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How to Use This Worksheet

Work in order. Section A checks the language of the heating curve: its five segments, the plateau idea, the six changes of state and their signs, and the sizes of the numbers. Section B practises stage-by-stage pricing: single plateaus, two-stage heating paths, cooling paths with negative totals, and a reverse problem that starts from the heat and finds the mass. Section C is exam style: a full five-stage path, five claims to judge, and a heater problem that connects plateau length to enthalpy.

Reference facts, all for water. Specific heat capacities: ice 2.09, liquid water 4.18, steam 2.01 J g^{-1} $°C^{-1}$. ΔH_{fus} = 6.01 kJ mol^{-1}. ΔH_{vap} = 40.7 kJ mol^{-1}. Molar mass 18.02 g mol^{-1}. Warming stages are priced by $q = mc\Delta T$ with the mass in grams; plateau stages are priced by $q = n\Delta H$, with n = mass ÷ molar mass. Signs are taken from the sample's point of view: heat absorbed is positive, heat released is negative.

Three habits protect every answer. Split the path at every phase boundary before touching a number, and price each stage separately. Convert grams to moles for the plateau stages, and bring joules and kilojoules to one unit before adding anything. Finish by checking the total: its sign must match the direction of the journey, and on any path that boils water the vaporization term should be the largest single term.

Do not look at the answer key until you have attempted every question.

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Section A: Recall and Concepts

A1. (a) List the five segments of the heating curve of water, in order, from ice below 0 °C to steam above 100 °C. (b) State which segments are sloped and which are flat. (c) State the equation that prices each sloped segment, and name what each symbol stands for. (d) State the equation that prices each flat segment. (e) State the temperature of each flat segment for water.

A2. (a) Define the enthalpy of fusion, ΔHfus, and give its value for water. (b) Define the enthalpy of vaporization, ΔHvap, and give its value for water. (c) Write down the enthalpy change for freezing one mole of water, and for condensing one mole of steam. (d) Explain, at the particle level, why ΔHvap is so much larger than ΔHfus.

A3. (a) Ice at 0 °C is heated steadily, yet its temperature does not rise while it melts. State where the added heat goes. (b) State what temperature measures, and use that to explain why the temperature cannot rise during the melting. (c) State what starts to happen to the temperature the moment the last crystal has melted. (d) A student claims the plateau means no heat is being absorbed there. Correct the claim.

A4. (a) Name the six changes of state between solid, liquid and gas. (b) Mark each one as endothermic or exothermic. (c) Pair each change with its exact reverse. (d) Write ΔHsub for water in terms of ΔHfus and ΔHvap, and calculate its value. (e) State the enthalpy change when one mole of water vapour deposits directly as ice.

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A5. Four processes are proposed for exactly 1.00 mol of water: warming the ice by 10 °C; melting the ice; warming the steam by 10 °C; vaporizing the liquid. (a) Calculate the heat absorbed in each process. (b) Rank the four from smallest to largest. (c) State what the ranking shows about where the energy sits in a full heating path. (d) Using the same numbers, explain why the vaporization plateau lasts far longer than the melting plateau when the heat is supplied at a steady rate.

Section B: Core Practice

B1. (a) Calculate the number of moles in 54.1 g of ice. (b) Calculate the heat needed to melt all of it at 0 °C. (c) State why $q = mc\Delta T$ cannot price this step.

B2. 45.0 g of liquid water at 0 °C freezes solid, and the ice then cools to −15.0 °C. (a) Calculate the number of moles of water. (b) Calculate q for the freezing stage. (c) Calculate q for the cooling stage. (d) Calculate the total q for the journey, and state what its sign tells you.

B3. 20.0 g of ice at −20.0 °C is heated until it is liquid water at 0 °C. (a) Name the two stages of the journey. (b) Calculate q for the first stage. (c) Calculate q for the second stage, showing the mole conversion. (d) Calculate the total heat absorbed, in kJ.

B4. 15.0 g of water at 75.0 °C is heated until it is entirely steam at 100 °C. (a) Name the two stages of the journey. (b) Calculate q for the first stage. (c) Calculate q for the second stage, showing the mole conversion. (d) Calculate the total heat absorbed, in kJ. (e) State which stage dominates the total, and explain why.

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B5. 30.0 g of steam at 100 °C is cooled until it is ice at 0 °C. (a) Name the three stages of the journey. (b) Calculate q for each stage. (c) Calculate the total q, in kJ. (d) State the heat needed for the exact reverse journey, ice at 0 °C to steam at 100 °C for the same sample, and justify the answer without recalculating.

B6. (a) How many moles of ice at 0 °C can 25.0 kJ of heat melt? (b) What mass of ice is that? (c) Calculate the heat absorbed when 0.500 mol of ice sublimes. (d) Calculate q for the deposition of 0.500 mol of water vapour as ice, and state whether the surroundings warm or cool.

Section C: Exam Style

C1. 40.0 g of ice at −15.0 °C is heated steadily until it is steam at 120.0 °C. (a) List the five stages of the journey in order. (b) Calculate q for each stage, showing the mole conversion where one is needed. (c) Calculate the total heat absorbed, in kJ. (d) State which stage takes the largest share of the total, and connect that fact to the shape of the heating curve. (e) A student prices the whole journey as $q = mc\Delta T$, using $c = 4.18\ \text{J g}^{-1}\ \text{°C}^{-1}$ and $\Delta T = 135$ °C, and gets 22.6 kJ. Identify the two distinct errors in that working.

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C2. Judge each claim, supporting each verdict with the rule it depends on. (a) "While ice melts, the temperature stays constant because the heater's energy stops entering the sample." (b) "A single q = mcΔT calculation can price a whole heating curve, provided the overall temperature change is used." (c) "Freezing one mole of water releases exactly the amount of heat that melting one mole of ice absorbs." (d) "ΔHvap is larger than ΔHfus mainly because vaporization happens at a higher temperature." (e) "On a cooling curve, the condensation plateau sits at a lower temperature than the boiling plateau on a heating curve."

C3. A 500 W heater supplies 500 J every second, and all of it reaches the sample. It is used on 100 g of ice at 0 °C. (a) Calculate the heat needed to melt all of the ice, and hence the time the melting plateau lasts. (b) Calculate the time the resulting water takes to warm from 0 °C to 100 °C. (c) Calculate the heat needed to vaporize all of the water at 100 °C, and hence the time the boiling plateau lasts. (d) Explain why the two plateau times differ so much, using the values of ΔHfus and ΔHvap. (e) Calculate the total time from ice at 0 °C to steam at 100 °C.

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Answer Key

A1. (a) Ice warming; melting; liquid water warming; vaporization; steam warming. (b) Sloped: the three warmings. Flat: melting and vaporization. (c) $q = mc\Delta T$, where m is the mass of the sample in grams, c is the specific heat capacity of the phase being warmed, and ΔT is the temperature change. (d) $q = n\Delta H$, with ΔH_{fus} at the melting plateau and ΔH_{vap} at the boiling plateau. (e) Melting at 0 °C; vaporization at 100 °C.

A2. (a) The heat absorbed to melt one mole of a solid at its melting point; 6.01 kJ mol^{-1} for water. (b) The heat absorbed to vaporize one mole of a liquid at its boiling point; 40.7 kJ mol^{-1} for water. (c) Freezing: −6.01 kJ mol^{-1}. Condensing: −40.7 kJ mol^{-1}. Each reverse change keeps the magnitude and flips the sign. (d) Melting only loosens the ordered solid: the particles stay in contact and many attractions survive into the liquid. Vaporization pulls the particles completely apart, so every attraction between them must be overcome, and that complete separation costs far more energy per mole.

A3. (a) Into overcoming the intermolecular attractions that hold the particles in the solid: it raises the particles' potential energy. (b) Temperature measures the average kinetic energy of the particles. While the melt lasts, none of the added heat becomes kinetic energy, so the average, and with it the temperature, cannot move. (c) It starts to rise: with no solid left to melt, further heat has nowhere to go except into kinetic energy, and the liquid warms. (d) Heat is being absorbed all through the plateau; that absorption is precisely what drives the change of state. The plateau shows heat being absorbed without a temperature rise, not heat failing to enter.

A4. (a) Melting, freezing, vaporization, condensation, sublimation, deposition. (b) Endothermic: melting, vaporization, sublimation. Exothermic: freezing, condensation, deposition. (c) Melting pairs with freezing; vaporization with condensation; sublimation with deposition. (d) $\Delta H_{sub} = \Delta H_{fus} + \Delta H_{vap} = 6.01 + 40.7 = 46.7$ kJ mol^{-1}. (e) −46.7 kJ mol^{-1}: deposition is the reverse of sublimation, endothermic forward, so the reverse is exothermic with the same magnitude.

A5. (a) Warming the ice: per mole of ice, 18.02 × 2.09 × 10 = 377 J, about 0.38 kJ. Melting: 6.01 kJ. Warming the steam: 18.02 × 2.01 × 10 = 362 J, about 0.36 kJ. Vaporizing: 40.7 kJ. (b) Warming the steam (0.36 kJ), then warming the ice (0.38 kJ), then melting (6.01 kJ), then vaporizing (40.7 kJ). (c) The phase changes hold nearly all the energy, and vaporization holds most of that; the warming stages are small corrections either side of the plateaus. (d) At a steady supply rate, a plateau's length in time is set by the energy it must deliver per mole. Vaporization needs 40.7 kJ for every mole against melting's 6.01 kJ, about 6.8 times as much, so its plateau lasts about 6.8 times longer.

B1. (a) $n = 54.1 \div 18.02 = 3.00$ mol. (b) $q = n\Delta H_{fus} = 3.00 \times 6.01 = 18.0$ kJ, absorbed. (c) During melting the temperature does not change, so $\Delta T = 0$ and $q = mc\Delta T$ would return zero; the energy

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goes into potential energy against the intermolecular forces, and only a per-mole price, nΔH, captures it.

B2. (a) n = 45.0 ÷ 18.02 = 2.497 mol. (b) Freezing: q = −nΔHfus = −2.497 × 6.01 = −15.0 kJ, that is −15,008 J. (c) Cooling the ice: q = mcΔT = 45.0 × 2.09 × (−15.0) = −1,411 J, that is −1.41 kJ. (d) Total: −15,008 + (−1,411) = −16,419 J, about −16.4 kJ. The negative sign says the sample releases heat overall: the journey is exothermic from the sample's point of view, and the surroundings receive 16.4 kJ.

B3. (a) Warm the ice from −20.0 °C to 0 °C, then melt it at 0 °C. (b) q = mcΔT = 20.0 × 2.09 × 20.0 = 836 J. (c) n = 20.0 ÷ 18.02 = 1.110 mol, so q = nΔHfus = 1.110 × 6.01 = 6,670 J. (d) Total: 836 + 6,670 = 7,506 J = 7.51 kJ absorbed.

B4. (a) Warm the liquid from 75.0 °C to 100 °C, then vaporize it at 100 °C. (b) q = mcΔT = 15.0 × 4.18 × 25.0 = 1,568 J. (c) n = 15.0 ÷ 18.02 = 0.832 mol, so q = nΔHvap = 0.832 × 40.7 = 33,879 J, that is 33.9 kJ. (d) Total: 1,568 + 33,879 = 35,447 J, about 35.4 kJ absorbed. (e) Vaporization, by a wide margin: 33.9 kJ of the 35.4 kJ. Warming moves particles faster within the liquid, but vaporizing has to separate every particle from all of its neighbours, and complete separation is priced per mole at 40.7 kJ.

B5. (a) Condense the steam at 100 °C; cool the liquid from 100 °C to 0 °C; freeze it at 0 °C. (b) n = 30.0 ÷ 18.02 = 1.665 mol. Condensing: q = −nΔHvap = −1.665 × 40.7 = −67,758 J. Cooling the liquid: q = mcΔT = 30.0 × 4.18 × (0 − 100) = −12,540 J. Freezing: q = −nΔHfus = −1.665 × 6.01 = −10,006 J. (c) Total: −67,758 − 12,540 − 10,006 = −90,304 J, about −90.3 kJ. (d) +90.3 kJ must be absorbed. Every stage of the reverse journey is the exact reverse of a stage here, and a reverse change keeps its magnitude and flips its sign, so the totals are equal in size and opposite in sign.

B6. (a) n = 25.0 ÷ 6.01 = 4.16 mol. (b) Mass = 4.16 × 18.02 = 75.0 g. (c) ΔHsub = 6.01 + 40.7 = 46.71 kJ mol^{-1}, so q = 0.500 × 46.71 = 23.4 kJ absorbed. (d) q = −23.4 kJ: deposition releases the heat that sublimation absorbs. Released heat flows into the surroundings, so the surroundings warm.

C1. (a) Warm the ice, −15.0 °C to 0 °C; melt at 0 °C; warm the water, 0 °C to 100 °C; vaporize at 100 °C; warm the steam, 100 °C to 120.0 °C. (b) The sample is n = 40.0 ÷ 18.02 = 2.220 mol throughout. Warm the ice: q = 40.0 × 2.09 × 15.0 = 1,254 J. Melt: q = 2.220 × 6.01 = 13,341 J. Warm the water: q = 40.0 × 4.18 × 100.0 = 16,720 J. Vaporize: q = 2.220 × 40.7 = 90,344 J. Warm the steam: q = 40.0 × 2.01 × 20.0 = 1,608 J. (c) Total: 1,254 + 13,341 + 16,720 + 90,344 + 1,608 = 123,267 J, about 123 kJ absorbed. (d) Vaporization: 90,344 J of the 123,267 J, roughly 73 percent. On the heating curve that is the long flat stretch: the boiling plateau stretches far beyond the melting plateau because separating the particles completely costs the most energy per mole. (e) First, a single mcΔT term prices only warming and captures none of the energy absorbed at the two plateaus, where most of the true total sits. Second, it applies the liquid's specific heat capacity to all five stages, but the ice stage needs 2.09 and the steam stage 2.01 J g^{-1} $°C^{-1}$. Both errors shrink the answer, which is why 22.6 kJ lands far below the true 123 kJ.

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C2. (a) False. The heater's energy enters the sample continuously through the plateau; it is spent raising potential energy against the intermolecular forces rather than kinetic energy, which is why the temperature, the measure of average kinetic energy, stays fixed. (b) False. The plateau stages absorb large amounts of heat while ΔT is zero, and they are priced per mole by q = nΔH. A single warming term can never include them, whatever overall ΔT is inserted. (c) True. Freezing is the exact reverse of melting: same magnitude, opposite sign, −6.01 kJ released against +6.01 kJ absorbed per mole for water. (d) False. The difference is the separation achieved: melting loosens the particles while they stay in contact, vaporization separates them completely. The boiling point temperature is where the change happens, not the reason it costs more. (e) False. Condensation and boiling are the same phase boundary crossed in opposite directions, so both plateaus sit at 100 °C for water at the same pressure; the cooling curve mirrors the heating curve.

C3. (a) n = 100 ÷ 18.02 = 5.549 mol, so melting needs q = 5.549 × 6.01 = 33,352 J. At 500 J per second, the plateau lasts 33,352 ÷ 500 = 66.7 s. (b) Warming the water needs q = mcΔT = 100 × 4.18 × 100 = 41,800 J, taking 41,800 ÷ 500 = 83.6 s. (c) Vaporizing needs q = 5.549 × 40.7 = 225,860 J, taking 225,860 ÷ 500 = 451.7 s. (d) Both plateaus serve the same 5.549 mol at the same supply rate, so each plateau's time is proportional to its per-mole price. Vaporization separates the particles completely at 40.7 kJ per mole, while melting only loosens them at 6.01 kJ per mole, so the boiling plateau lasts about 6.8 times longer than the melting plateau. (e) Total: 66.7 + 83.6 + 451.7 = 602 s, about ten minutes, most of it spent on the boiling plateau.

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