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Topic 6.8: Enthalpy of Formation

Worksheet · AP Chemistry

UNIT 6 · THERMOCHEMISTRY

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How to Use This Worksheet

Work in order. Section A checks the foundations: the definition, the zero rule, formation equations, and why states and signs behave as they do. Section B practises the full calculation on six reactions, including one back-calculation of an unknown formation value. Section C is exam style: a multi-part ammonia problem, six claims to judge, and a limestone problem that ends in grams and kilojoules.

Reference data. Standard enthalpies of formation, $\Delta H°f$ in kJ mol^{-1} at 298 K, the same table as the revision notes: $CO_2(g)$ −393.5, $H_2O(l)$ −285.8, $H_2O(g)$ −241.8, $CH_4(g)$ −74.8, $CO(g)$ −110.5, $NH_3(g)$ −46.1, $NO(g)$ +90.3, $NO_2(g)$ +33.2, $O_3(g)$ +142.7, $SO_2(g)$ −296.8, $SO_3(g)$ −395.7, $CaCO_3(s)$ −1206.9, $CaO(s)$ −635.1, $NaCl(s)$ −411.2, $HCl(g)$ −92.3, $C_2H_5OH(l)$ −277.7, $C_6H_{12}O_6(s)$ −1273.3. Every element in its standard state has $\Delta H°f = 0$.

Three habits protect every answer. Write the two sums separately, products first, with each value multiplied by its coefficient, before subtracting anything. Match every value to the state printed in the equation, especially water. Finish by checking the sign against the chemistry: combustions must come out negative, and a decomposition of a very stable compound should come out positive.

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

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Section A: Recall and Concepts

A1. (a) Define the standard enthalpy of formation of a compound, giving the conditions. (b) State the amount of compound formed in a formation reaction. (c) State what the reactants in a formation reaction must be. (d) Explain why fractional coefficients, such as $\frac{1}{2}O_2$, appear in formation equations.

A2. (a) State the $\Delta H°f$ of $O_2(g)$, Fe(s) and C(s, graphite), and give the rule that sets them. (b) Diamond is a form of carbon. State whether its $\Delta H°f$ is zero, and explain why. (c) Ozone, $O_3(g)$, has $\Delta H°f = +142.7$ kJ mol^{-1}. Explain what the positive sign tells you about ozone relative to O_2. (d) A compound has $\Delta H°f = -1206.9$ kJ mol^{-1}. State what a large negative value indicates about the compound.

A3. Write the formation equation for each compound, with states, and state its $\Delta H°f$ from the reference table: (a) $H_2O(l)$; (b) $CO_2(g)$; (c) $NH_3(g)$; (d) $CaCO_3(s)$. (e) Explain why $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$ is not a formation equation, even though only elements appear on the left.

A4. (a) Write the formula for $\Delta H°rxn$ in terms of formation enthalpies, including what the coefficient does. (b) State the order of subtraction used with bond enthalpies in Topic 6.7, and explain why the two methods run in opposite orders. (c) Explain why the $\Delta H°f$ of O_2 never changes the result of a calculation, whatever its coefficient. (d) A reaction has $\Delta H°rxn = +178.3$ kJ. State, in terms of the two sums, why the answer is positive.

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A5. (a) $\Delta H°f$ of $H_2O(l)$ is -285.8 kJ mol^{-1} and of $H_2O(g)$ is -241.8 kJ mol^{-1}. Calculate the difference and name the process it prices. (b) Explain why a calculation must use the value matching the state in the equation. (c) Every $\Delta H°f$ in a reaction is negative, yet $\Delta H°rxn$ is positive. Explain how that is possible. (d) State the temperature and pressure at which standard enthalpies of formation are tabulated.

Section B: Core Practice

B1. Ammonia synthesis: $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$. (a) Write the products sum and the reactants sum separately. (b) Calculate $\Delta H°rxn$. (c) State ΔH per mole of ammonia formed, and connect it to $\Delta H°f$ of NH_3.

B2. Limestone decomposition: $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$. (a) Calculate $\Delta H°rxn$. (b) State whether the reaction is exothermic or endothermic, and what that means for a lime kiln. (c) Calculate the heat that must be supplied to decompose 0.50 mol of $CaCO_3$.

B3. Ethanol combustion: $C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$. (a) Write the products sum and the reactants sum separately. (b) Calculate $\Delta H°rxn$. (c) Explain why the $3O_2$ contributes nothing to the reactants sum.

B4. Nitric oxide formation: $N_2(g) + O_2(g) \rightarrow 2NO(g)$. (a) Calculate $\Delta H°rxn$. (b) Calculate ΔH per mole of NO formed. (c) Explain why this reaction's $\Delta H°rxn$ and the $\Delta H°f$ of NO carry the same number per mole, when most reactions' do not.

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B5. Finding an unknown formation value. Burning glucose, $C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$, has $\Delta H°rxn = -2802.5$ kJ. (a) Calculate the products sum. (b) Set up the formation formula with $\Delta H°f$ of glucose as the unknown x. (c) Solve for x. (d) State what the sign and size of x say about glucose relative to its elements.

B6. The state trap. Methane burns two ways on paper: $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$ and $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$. (a) Calculate $\Delta H°rxn$ for the liquid-water version. (b) Calculate $\Delta H°rxn$ for the gas-water version. (c) Calculate the difference between the two answers. (d) Explain the difference using the gap between the two water values and the coefficient of water.

Section C: Exam Style

C1. Ammonia is made by $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$, $\Delta H°f$ of $NH_3(g) = -46.1$ kJ mol^{-1}. (a) Calculate $\Delta H°rxn$, showing both sums. (b) The plant runs the reaction in reverse, decomposing ammonia. State ΔH for $2NH_3(g) \rightarrow N_2(g) + 3H_2(g)$. (c) Calculate the heat released when 0.40 mol of NH_3 is formed. (d) A student calculates $\Delta H°rxn$ as reactants minus products and gets +92.2 kJ. Identify the error and state what the wrong sign would claim about the reaction.

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C2. Judge each claim, supporting each verdict with the rule it depends on. (a) "With formation enthalpies, ΔH°rxn is reactants minus products." (b) "Diamond has ΔH°f = 0 because it is a pure element." (c) "If every ΔH°f in a reaction is negative, the reaction must be exothermic." (d) "Coefficients can be ignored, because ΔH°f is already per mole." (e) "$H_2O(g)$ and $H_2O(l)$ have the same ΔH°f, since both are water." (f) "Ozone cannot exist, because its ΔH°f is positive."

C3. A lime kiln decomposes calcium carbonate: $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$. Use ΔH°f values $CaCO_3(s)$ −1206.9, $CaO(s)$ −635.1, $CO_2(g)$ −393.5 kJ mol^{-1}, and take the molar mass of $CaCO_3$ as 100.09 g mol^{-1}. (a) Calculate ΔH°rxn, showing both sums. (b) Write the formation equation for $CaCO_3(s)$. (c) Calculate the number of moles in 250 g of $CaCO_3$. (d) Calculate the heat that must be supplied to decompose 250 g of $CaCO_3$. (e) Explain why the value in (a) is positive even though $CaCO_3$ has the most negative ΔH°f in the equation.

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Answer Key

A1. (a) The standard enthalpy of formation is the enthalpy change when one mole of a compound forms from its elements in their standard states, at 298 K and 1 atm (1 bar). (b) Exactly one mole. (c) The elements that make up the compound, each in its standard state; no compounds may appear on the reactant side. (d) One mole of product fixes the amounts of the elements, and those amounts are often halves or three-halves of a mole: making one mole of water takes half a mole of O_2. The fraction is part of the definition, not an unbalanced equation.

A2. (a) All three are 0 kJ mol^{-1}. An element in its standard state has $\Delta H°f = 0$ by definition, because forming it from itself involves no change. (b) No. Graphite is the most stable form of carbon at standard conditions, so graphite is the reference; diamond sits slightly higher, at about +1.9 kJ mol^{-1}. (c) Forming ozone from O_2 absorbs 142.7 kJ per mole, so ozone holds more enthalpy than the standard form of oxygen and is less stable than O_2. (d) The compound sits far lower in enthalpy than its elements, so it is stable relative to them: a large amount of energy was released when it formed.

A3. (a) $H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)$; $\Delta H°f = -285.8$ kJ mol^{-1}. (b) $C(s, \text{graphite}) + O_2(g) \rightarrow CO_2(g)$; $\Delta H°f = -393.5$ kJ mol^{-1}. (c) $\frac{1}{2}N_2(g) + 3/2H_2(g) \rightarrow NH_3(g)$; $\Delta H°f = -46.1$ kJ mol^{-1}. (d) $Ca(s) + C(s, \text{graphite}) + 3/2O_2(g) \rightarrow CaCO_3(s)$; $\Delta H°f = -1206.9$ kJ mol^{-1}. (e) It forms two moles of water. A formation equation forms exactly one mole of product, so this equation carries twice $\Delta H°f$, −571.6 kJ, and must be halved to give the formation value.

A4. (a) $\Delta H°rxn = \Sigma\, n\Delta H°f(\text{products}) - \Sigma\, n\Delta H°f(\text{reactants})$, where each $\Delta H°f$ is multiplied by its coefficient n in the balanced equation. (b) Bond enthalpies use broken minus formed: the reactants' bonds are broken first, so the reactant side is priced first. Formation enthalpies price where each species sits relative to the elements, so the products' total is compared against the reactants' total, products first. The orders differ because the two methods price different journeys. (c) Its value is 0, and any coefficient times 0 is still 0, so the term vanishes from the reactants sum however much O_2 the equation uses. (d) The products sum is higher than the reactants sum by 178.3 kJ: the products hold more enthalpy relative to the elements than the reactants do, so the difference must be absorbed from the surroundings.

A5. (a) $-241.8 - (-285.8) = 44.0$ kJ mol^{-1}. It is the enthalpy of vaporization of water at 298 K: the energy needed to convert one mole of liquid water into gas. (b) $\Delta H°f$ is a property of a specific state, because the state itself holds a different enthalpy. Using the gas value where the equation makes liquid water understates the release by 44.0 kJ for every mole of water. (c) $\Delta H°rxn$ is a difference between two sums. If the reactants' total is more negative than the products' total, subtracting it gives a positive result: the reactants sit lower relative to the elements than the products do, so forming the products from the reactants climbs in enthalpy. (d) 298 K and 1 atm (1 bar).

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B1. (a) Products sum: 2(−46.1) = −92.2 kJ. Reactants sum: 0 + 3(0) = 0 kJ, because both reactants are elements in their standard states. (b) ΔH°rxn = −92.2 − 0 = −92.2 kJ. (c) The equation forms 2 mol of NH_3, so per mole: −92.2 ÷ 2 = −46.1 kJ mol^{-1}, which is exactly ΔH°f of NH_3, as it must be: the synthesis equation is the formation equation doubled.

B2. (a) Products sum: −635.1 + (−393.5) = −1028.6 kJ. Reactants sum: −1206.9 kJ. ΔH°rxn = −1028.6 − (−1206.9) = +178.3 kJ. (b) Endothermic. The kiln must be heated continuously: every mole of limestone decomposed absorbs 178.3 kJ from the fuel burning around it. (c) 0.50 × 178.3 = 89.15 kJ, about 89.2 kJ, must be supplied.

B3. (a) Products sum: 2(−393.5) + 3(−285.8) = −787.0 + (−857.4) = −1644.4 kJ. Reactants sum: −277.7 + 3(0) = −277.7 kJ. (b) ΔH°rxn = −1644.4 − (−277.7) = −1366.7 kJ. (c) O_2 is an element in its standard state, so its ΔH°f is 0, and 3 × 0 adds nothing to the sum. The coefficient matters for balancing, not for the total.

B4. (a) Products sum: 2(+90.3) = +180.6 kJ. Reactants sum: 0 + 0 = 0 kJ. ΔH°rxn = +180.6 − 0 = +180.6 kJ. (b) The equation forms 2 mol of NO, so per mole: +180.6 ÷ 2 = +90.3 kJ mol^{-1}. (c) Both reactants are elements with ΔH°f = 0, so the reactants sum vanishes and ΔH°rxn is just the products sum: coefficient times ΔH°f of the one product. Dividing by the coefficient then returns ΔH°f itself. In most reactions the reactants are compounds with nonzero values, so the subtraction changes the number and no such shortcut exists.

B5. (a) Products sum: 6(−393.5) + 6(−285.8) = −2361.0 + (−1714.8) = −4075.8 kJ. (b) ΔH°rxn = products − reactants: −2802.5 = −4075.8 − (x + 6(0)). (c) x = −4075.8 + 2802.5 = −1273.3 kJ mol^{-1}. (d) The large negative value means glucose sits far below its elements in enthalpy: forming it from carbon, hydrogen and oxygen releases a great deal of energy, so it is stable relative to its elements.

B6. (a) Products sum: −393.5 + 2(−285.8) = −965.1 kJ. Reactants sum: −74.8 kJ. ΔH°rxn = −965.1 − (−74.8) = −890.3 kJ. (b) Products sum: −393.5 + 2(−241.8) = −877.1 kJ. Reactants sum: −74.8 kJ. ΔH°rxn = −877.1 − (−74.8) = −802.3 kJ. (c) −802.3 − (−890.3) = 88.0 kJ: the gas version releases 88.0 kJ less. (d) Each mole of water made as gas instead of liquid keeps 44.0 kJ of the vaporization enthalpy, and the equation makes 2 mol of water, so 2 × 44.0 = 88.0 kJ less is released. The products hold that energy as separated gas molecules rather than giving it up on condensing.

C1. (a) Products sum: 2(−46.1) = −92.2 kJ. Reactants sum: 0 + 3(0) = 0 kJ. ΔH°rxn = −92.2 − 0 = −92.2 kJ. (b) Reversing a reaction reverses the sign at the same size: +92.2 kJ. (c) Forming NH_3 releases 46.1 kJ per mole, so 0.40 × 46.1 = 18.44 kJ is released. (d) The student used the bond enthalpy order on formation data. The wrong sign would claim the synthesis is endothermic, absorbing heat, when forming ammonia from its elements actually releases it.

C2. (a) False. Formation enthalpies are subtracted as products minus reactants. Reactants minus products is the shape of the bond enthalpy formula, and it flips the sign of every formation calculation. (b) False. Only the standard state of an element is zero, and carbon's standard state is

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graphite. Diamond is a different, slightly higher-enthalpy form, at about +1.9 kJ mol^{-1}. (c) False. ΔH°rxn is the difference between the products sum and the reactants sum. Limestone decomposition has all-negative values and ΔH = +178.3 kJ, because the reactant's value is more negative than the products' total. (d) False. ΔH°f prices one mole, so each value must be multiplied by its coefficient: the 2 in front of SO_3 doubles its contribution. Ignoring coefficients undercounts every species used more than once. (e) False. They differ by 44.0 kJ mol^{-1}, the enthalpy of vaporization: the gas holds more enthalpy than the liquid, so its formation value is less negative. (f) False. A positive ΔH°f means the compound is less stable than its elements and absorbs energy when it forms; it says nothing about whether the compound can exist. Ozone forms in the upper atmosphere and is detectable there, despite sitting 142.7 kJ mol^{-1} above O_2.

C3. (a) Products sum: −635.1 + (−393.5) = −1028.6 kJ. Reactants sum: −1206.9 kJ. ΔH°rxn = −1028.6 − (−1206.9) = +178.3 kJ. (b) Ca(s) + C(s, graphite) + 3/2O_2(g) → $CaCO_3$(s). (c) 250 ÷ 100.09 = 2.498 mol, about 2.50 mol. (d) Each mole decomposed absorbs 178.3 kJ, so 2.498 × 178.3 = 445.3 kJ, about 445 kJ, must be supplied. (e) ΔH°rxn compares sums, not single values. $CaCO_3$'s −1206.9 kJ mol^{-1} puts the reactant very low, but the products' total, −1028.6 kJ, is higher than that: the products together sit above the carbonate, so reaching them from the carbonate climbs in enthalpy and absorbs heat. A very negative reactant value makes a positive ΔH more likely, not less.

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