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Topic 9.11: Electrolysis and Faraday's Law

Worksheet · AP Chemistry

UNIT 9 · THERMODYNAMICS AND ELECTROCHEMISTRY

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How to Use This Worksheet

Work the questions in order, and do not look at the answer key until you have attempted every question. Section A checks the pipeline, the electron counts, and the product rules that the whole topic rests on. Section B practices the calculations: masses from currents, times from masses, gas volumes, series cells, and a current from a target mass. Section C combines them the way exam questions do, with a mass comparison, a water electrolysis pair, and a long plating run worked backward.

Reference facts. F = 96,485 C mol^{-1}; molar volume at STP = 22.4 L mol^{-1}; Cu molar mass = 63.55 g mol^{-1}, Ag = 107.9 g mol^{-1}, Al = 27.0 g mol^{-1}, Ni = 58.69 g mol^{-1}, Zn = 65.38 g mol^{-1}, Cr = 52.00 g mol^{-1}. Mass per mole of electrons is molar mass divided by n: Cu 31.78 g, Ag 107.9 g.

Use the same working order every time. First, write the balanced half reaction and read n, the electrons per mole of the substance asked about. Second, convert every time to seconds before touching current. Third, walk the chain below, with F = 96,485 C mol^{-1}, then mass or volume.

$Q = I \times t$

$\text{mol } e^- = Q / F$

$\text{mol substance} = \text{mol } e^- / n$

Fourth, for a backward question, run the same chain in reverse and check it by running forward from your answer back to the stated mass or volume.

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Three slip points deserve a deliberate pause. Dividing by F gives moles of electrons, not moles of product: the division by n comes after, and skipping it is the most expensive single error in the topic. Hydrogen needs 2 electrons per molecule and oxygen needs 4, so the same charge never gives equal gas volumes. And series cells share charge, not moles of product: the same coulombs pass through each cell, but each cell's product amount follows its own half reaction.

A miniature chain, to fix the order before you start. A current of 2.00 A for 10.0 min through a Cu^{2+} cell: time is 600 s, so Q = (2.00)(600) = 1200 C; moles of electrons are 1200 / 96,485 = 0.01244 mol; copper needs 2 electrons per ion, so moles of copper are 0.01244 / 2 = 0.006219 mol; mass is 0.006219 × 63.55 = 0.395 g. Every question in this worksheet is the same chain with different numbers, run forward or backward, so if a working ever feels unfamiliar, return to this example and match its steps one by one.

Section A: Recall and Concepts

A1. State the four steps of the Faraday's law chain in order, with the equation for each step and the units of every quantity. State the value of Faraday's constant and what it means in one sentence.

A2. A current of 4.0 A flows for 5.0 min. (a) Calculate the charge passed and the moles of electrons that flow. Show the time conversion explicitly. (b) How long, in minutes, would the same 4.0 A current need to flow to pass 0.0500 mol of electrons?

A3. For each half reaction, state how many moles of electrons are transferred per mole of the substance named: (a) $Zn^{2+} + 2e^- \rightarrow Zn$, per mole of zinc; (b) $Fe^{3+} + 3e^- \rightarrow Fe$, per mole of iron; (c) $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$, per mole of oxygen gas.

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A4. (a) In the electrolysis of aqueous sodium chloride, state the product at each electrode and explain, for the cathode, why sodium metal does not form. (b) State the product at each electrode for molten sodium chloride, and explain why the two cases differ. (c) State the two half reactions for the electrolysis of water, name the product at each electrode, and state the volume ratio of the two gases for the same charge.

A5. Two electrolysis cells are connected in series: one containing Ag^{+} and one containing Al^{3+}. If 0.50 mol of electrons passes through both, (a) how many moles of metal form in each cell, and (b) what mass of metal forms in each cell? Explain why the amounts differ although the charge is the same. (Ag molar mass = 107.9 g/mol; Al molar mass = 27.0 g/mol)

Section B: Core Practice

B1. A current of 2.50 A flows for 40.0 min through a Cu^{2+} electroplating cell. (a) What mass of copper is deposited? (b) How long, in minutes, would a current of 5.00 A need to flow to deposit the same mass? (Cu molar mass = 63.55 g/mol)

B2. How long does it take to deposit 8.00 g of nickel using a current of 3.00 A? ($Ni^{2+} + 2e^{-} \rightarrow Ni$; Ni molar mass = 58.69 g/mol) Give the time in minutes.

B3. A current of 1.20 A flows for 25.0 min through an acidic water electrolysis cell. (a) What volume of H_2 gas is produced at STP? (b) What volume of O_2 gas is produced at the anode in the same run at STP? ($2H^{+} + 2e^{-} \rightarrow H_2$; $2H_2O \rightarrow O_2 + 4H^{+} + 4e^{-}$; molar volume 22.4 L/mol)

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B4. A current of 2.00 A flows for 2.00 h through a water electrolysis cell. (a) What volume of O_2 gas forms at the anode at STP? (b) What volume of H_2 gas forms at the cathode in the same run at STP, and what is the ratio of the two volumes? ($2H_2O \rightarrow O_2 + 4H^+ + 4e^-$; $2H^+ + 2e^- \rightarrow H_2$; molar volume 22.4 L/mol)

B5. Two cells in series carry 0.200 mol of electrons: one with Ag^+ and one with Zn^{2+}. Calculate the mass of metal deposited in each cell. (Ag molar mass = 107.9 g/mol; Zn molar mass = 65.38 g/mol)

B6. What current is needed to deposit 12.0 g of copper in 45.0 min? ($Cu^{2+} + 2e^- \rightarrow Cu$; Cu molar mass = 63.55 g/mol)

Section C: Exam Style

C1. The same charge is passed through a Cu^{2+} cell and an Ag^+ cell. (a) Calculate the mass of metal deposited per mole of electrons in each cell. (b) State the ratio of the copper mass to the silver mass for the same charge. (c) A student calculates 8.00 g of copper and 8.00 g of silver for the same charge. Explain, using your ratio, why at least one of those masses must be wrong. (d) Calculate the actual mass of each metal deposited by 0.300 mol of electrons, and confirm that their ratio matches part (b).

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C2. A current of 5.00 A flows for 1.00 h through a water electrolysis cell. (a) Calculate the volume of H_2 gas produced at STP. (b) Calculate the volume of O_2 gas produced at STP. (c) State the ratio of the two volumes and explain it from the two half reactions. (d) How long, in hours, would the same 5.00 A current need to flow to produce 5.00 L of H_2 gas at STP?

C3. Chromium is plated from Cr^{3+} solution ($Cr^{3+} + 3e^- \rightarrow Cr$; Cr molar mass = 52.00 g/mol). (a) How long, in hours, does it take to deposit 25.0 g of chromium using a current of 4.00 A? (b) Verify your answer by running the chain forward from your time back to the stated mass.

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Answer Key

A1. Step 1: Q = I × t, current in amperes times time in seconds, giving charge in coulombs. Step 2: mol e^- = Q / F, charge divided by Faraday's constant. Step 3: mol substance = mol e^- / n, with n from the balanced half reaction per mole of that substance. Step 4: mass = mol × molar mass, or gas volume at STP = mol × 22.4 L mol^{-1}. No step can be reordered: charge must come before moles of electrons, and moles of electrons before moles of product. Faraday's constant is F = 96,485 C mol^{-1}, the charge carried by one mole of electrons.

A2. (a) Time is 5.0 × 60 = 300 s. Charge is Q = (4.0)(300) = 1200 C. Moles of electrons are 1200 / 96,485 = 0.01244 mol. The time conversion comes first: using 5.0 min directly would give 20 C, fifty times too small. (b) Charge needed is 0.0500 × 96,485 = 4824 C. Time is 4824 / 4.0 = 1206 s, which is 20.1 min.

A3. (a) $Zn^{2+} + 2e^- \rightarrow Zn$: n = 2 mol e^- per mole of zinc. (b) $Fe^{3+} + 3e^- \rightarrow Fe$: n = 3 mol e^- per mole of iron. (c) $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$: n = 4 mol e^- per mole of oxygen gas. In each case n is read from the coefficient on the electrons in the balanced half reaction, matched to the substance named.

A4. Aqueous NaCl: hydrogen gas at the cathode, chlorine gas at the anode. Water is reduced more easily than Na^+, so H_2 forms at the cathode and Na^+ stays in solution; chloride is oxidized at the anode to Cl_2. Molten NaCl: sodium metal at the cathode, chlorine gas at the anode. The cases differ because molten NaCl contains no water, so there is no competing water reduction at the cathode and Na^+ is reduced directly. (c) Cathode: $2H^+ + 2e^- \rightarrow H_2$, hydrogen gas. Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$, oxygen gas. The volume ratio H_2:O_2 is 2:1 for the same charge, because hydrogen needs 2 electrons per molecule and oxygen needs 4.

A5. (a) Silver: 0.50 mol e^- / 1 = 0.50 mol of Ag. Aluminum: 0.50 mol e^- / 3 = 0.167 mol of Al. (b) Silver mass = 0.50 × 107.9 = 54 g. Aluminum mass = 0.167 × 27.0 = 4.5 g. The charge is the same because the cells are in series, so the same moles of electrons pass through both. The amounts differ because each silver ion needs 1 electron while each aluminum ion needs 3, so the same electrons make fewer moles of aluminum, and aluminum is also the lighter metal.

B1. (a) Time is 40.0 × 60 = 2400 s. Q = (2.50)(2400) = 6000 C. Mol e^- = 6000 / 96,485 = 0.06219 mol. Mol Cu = 0.06219 / 2 = 0.03109 mol. Mass = 0.03109 × 63.55 = 1.98 g of copper. (b) The same mass needs the same charge, 6000 C. Time at 5.00 A is 6000 / 5.00 = 1200 s, which is 20.0 min: double the current, half the time, as the chain requires.

B2. Mol Ni = 8.00 / 58.69 = 0.1363 mol. Mol e^- = 0.1363 × 2 = 0.2726 mol. Q = 0.2726 × 96,485 = 26,304 C. Time = 26,304 / 3.00 = 8768 s, which is 146 min. Forward check: 8768 s at 3.00 A gives 26,304 C, 0.2726 mol e^-, 0.1363 mol Ni, 8.00 g.

B3. (a) Time is 25.0 × 60 = 1500 s. Q = (1.20)(1500) = 1800 C. Mol e^- = 1800 / 96,485 = 0.01866 mol. Mol H_2 = 0.01866 / 2 = 0.009328 mol. Volume = 0.009328 × 22.4 = 0.209 L of H_2 at STP. (b) The same

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0.01866 mol e^- gives mol O_2 = 0.01866 / 4 = 0.004664 mol. Volume = 0.004664 × 22.4 = 0.104 L of O_2 at STP, exactly half the hydrogen volume.

B4. (a) Time is 2.00 × 3600 = 7200 s. Q = (2.00)(7200) = 14,400 C. Mol e^- = 14,400 / 96,485 = 0.1493 mol. Mol O_2 = 0.1493 / 4 = 0.03731 mol. Volume = 0.03731 × 22.4 = 0.836 L of O_2 at STP. (b) Mol H_2 = 0.1493 / 2 = 0.07463 mol. Volume = 0.07463 × 22.4 = 1.67 L of H_2 at STP. Ratio H_2:O_2 = 1.67:0.836 = 2:1, as the 2-electron and 4-electron half reactions require.

B5. Silver: 0.200 mol e^- / 1 = 0.200 mol of Ag, mass = 0.200 × 107.9 = 21.6 g. Zinc: 0.200 mol e^- / 2 = 0.100 mol of Zn, mass = 0.100 × 65.38 = 6.54 g. The same charge passes through both cells, but zinc needs 2 electrons per ion and has a smaller molar mass, so its deposit is much lighter. The series rule is the whole explanation: the charge is identical, so the difference comes entirely from the 1-electron versus 2-electron half reactions and the two molar masses.

B6. Mol Cu = 12.0 / 63.55 = 0.1888 mol. Mol e^- = 0.1888 × 2 = 0.3777 mol. Q = 0.3777 × 96,485 = 36,438 C. Time is 45.0 × 60 = 2700 s. Current = 36,438 / 2700 = 13.5 A. Forward check: 13.5 A for 2700 s gives 36,450 C, 0.3778 mol e^-, 0.1889 mol Cu, 12.0 g to the precision carried.

C1. (a) Copper: 63.55 / 2 = 31.78 g per mole of electrons. Silver: 107.9 / 1 = 107.9 g per mole of electrons. (b) Ratio Cu/Ag = 31.78 / 107.9 = 0.295. For the same charge, the copper deposit weighs 0.295 times the silver deposit. (c) Equal masses cannot both be right, because the ratio must be 0.295: if the silver mass were 8.00 g, the copper mass would be 8.00 × 0.295 = 2.36 g, and if the copper mass were 8.00 g, the silver mass would be 8.00 / 0.295 = 27.1 g. At least one of the two 8.00 g values contradicts the half reaction stoichiometry. (d) Copper: 0.300 mol e^- / 2 = 0.150 mol, mass = 0.150 × 63.55 = 9.53 g. Silver: 0.300 mol e^- / 1 = 0.300 mol, mass = 0.300 × 107.9 = 32.4 g. Ratio = 9.53 / 32.4 = 0.294, matching part (b) to rounding.

C2. (a) Time is 3600 s. Q = (5.00)(3600) = 18,000 C. Mol e^- = 18,000 / 96,485 = 0.1866 mol. Mol H_2 = 0.1866 / 2 = 0.09328 mol. Volume = 0.09328 × 22.4 = 2.09 L of H_2 at STP. (b) Mol O_2 = 0.1866 / 4 = 0.04664 mol. Volume = 0.04664 × 22.4 = 1.04 L of O_2 at STP. (c) Ratio H_2:O_2 = 2.09:1.04 = 2:1. The cathode half reaction needs 2 electrons per H_2 molecule while the anode half reaction needs 4 electrons per O_2 molecule, so the same charge makes twice as many moles, and twice the volume, of hydrogen. (d) Mol H_2 needed = 5.00 / 22.4 = 0.2232 mol. Mol e^- = 0.2232 × 2 = 0.4464 mol. Q = 0.4464 × 96,485 = 43,074 C. Time = 43,074 / 5.00 = 8615 s, which is 2.39 h. Forward check: 8615 s at 5.00 A gives 43,075 C, 0.4464 mol e^-, 0.2232 mol H_2, 5.00 L to rounding.

C3. (a) Mol Cr = 25.0 / 52.00 = 0.4808 mol. Mol e^- = 0.4808 × 3 = 1.442 mol. Q = 1.442 × 96,485 = 139,161 C. Time = 139,161 / 4.00 = 34,790 s, which is 9.66 h. (b) Forward check: 34,790 s at 4.00 A gives 139,161 C, 1.442 mol e^-, 0.4808 mol Cr, 25.0 g of chromium. The backward answer returns the stated mass exactly.

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