2025 WUCT: Science Fiction Exam

This exam consists of 6 questions and is worth 100 points. You will complete this exam as a pair. You will have 1 hour to take the exam. The only allowed resources for this exam are a calculator and the provided equation sheet. You may NOT use any other notes or books. You must show your work and box your final answer to receive credit for a problem. NOTE: If you get the answer to an early part of a question incorrect but later use that answer for a subsequent part of the question, you can still earn full credit for those subsequent parts. Please write your answer in the designated space on the answer sheet. If you need additional space for a problem, you may use the blank scratch page at the end of the exam. Make sure to clearly indicate in the problem's designated space where the rest of your work can be found. Any work anywhere other than the exam or the scratch page will not be graded. Dark pencil or pen is preferred.

<u>Problem #1</u>: *(21 points)*

You and your team of space explorers are exploring the galaxy on a tricked out rocket! Suddenly your atmospheric scanner starts pinging, signaling that Planet Atomica is nearby. You and your team decide to explore!

a. First, you and your team want to determine the composition of the atmosphere. You collect a 10 gram sample of the atmosphere and run it through your rocket's gas detector. It determines that Planet Atomica's atmosphere is composed of (by mass) 26% carbon dioxide, 37% methane (CH_4), and 37% **unknown diatomic gaseous compound** in a 5:20:2 molar ratio, respectively. What is the identity of the unknown gaseous compound present in Planet Atomica's atmosphere? *Hint: it is a halogen diatomic gas.* ***(4 points)***

Unknown Diatomic Gaseous Compound Identity: ________Br_2________

For a 10 g sample, there must be 2.6 g CO_2, 3.7 g CH_4, and 3.7 g unknown compound

$$\frac{2.6\ g\ CO_2}{1} \times \frac{1\ mol\ CO_2}{44.01\ g} = 0.059\ mol\ CO_2$$

$$\frac{3.7\ g\ CH_4}{1} \times \frac{1\ mol\ CH_4}{16.04\ g} = 0.231\ mol\ CH_4$$ **(+1 point)**

Using the given molar ratio, we can find moles of unknown compound:

$$\frac{0.059\ mol\ CO_2}{1} \times \frac{2\ mol\ unknown}{5\ mol\ CO_2} = 0.0236\ mol\ unknown$$

OR $$\frac{0.231\ mol\ CH_4}{1} \times \frac{2\ mol\ unknown}{20\ mol\ CH_4} = 0.0231\ mol\ unknown$$ **(+1 point)**

$Molar\ Mass\ of\ Unknown = \frac{3.7\ g}{0.0231\ mol}$ (or = $\frac{3.7\ g}{0.0236\ mol}$) = 160.17 g or 156.78 g **(+1 point)**

This most closely corresponds to the halogen Br_2 which has a molar mass of 159.808 g/mol. **(+1 point)**

+1 point for determining the moles of either methane OR carbon dioxide
+1 point for determining the corresponding number of moles of the unknown
+1 point for solving for a molar mass
+1 point for identifying Br_2 as the unknown diatomic halogen gas

b. You and your team take a temperature scan of the outermost atmospheric layer and find that it is 2,000 ℃. ***(4 points)***

i. What is the mean speed (in m/s) of the carbon dioxide molecules? Assume the gas is behaving ideally. ***(2 points)***

Mass of one molecule: $m = \frac{44.01\ amu}{1\ molecule} \times \frac{1.66\times10^{-27} kg}{1\ amu} = 7.31 \times 10^{-26}\ kg/molecule$

$< v > \ = \sqrt{\frac{8k_B T}{\pi m}} = \sqrt{\frac{8\ (1.38\times10^{-23} J/K)\ (2273.15\ K)}{\pi\ (7.31\times10^{-26}\ kg/molecule)}}$ **(+1 point)** $= 1046\ m/s$ **(+1 point)**

+1 point for correct substitution into the correct equation, not including the conversion from mass to mass per molecule

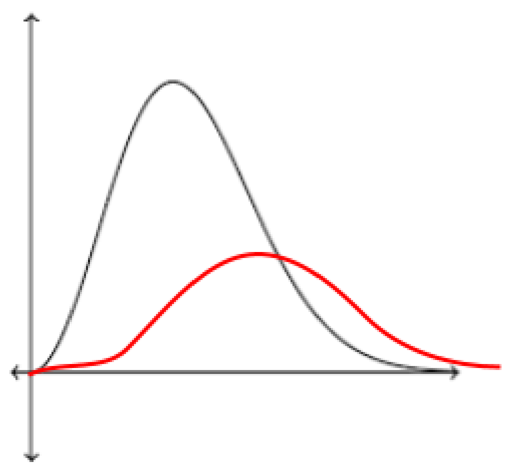
(Note: students can wrongfully plug in 44.01 amu/g/kg and still get this point)

(Note: students can leave k_B as k_B or plug in the value for this point)

(Note: students must explicitly plug in the correct temperature)

+1 point for correct final answer

ii. The following diagram is the Boltzmann distribution for carbon dioxide at room temperature (25˚C). Draw what the Boltzmann distribution would look like at 2,000 ℃. ***(2 points)***



+1 point for a curve shorter and broader than the room temperature plot

+1 point for the peak of the curve being to the right of the room temperature plot

c. The ideal gas law predicts the relationship between the temperature, pressure, volume, and amount of an ideal gas. However, real gases don't behave ideally and these deviations can be predicted using the Van der Waals equation: $P = \frac{RT}{V-b} - \frac{a}{V^2}$, where a is a constant directly related to the strength of intermolecular forces in the gas and b is a constant directly related to the **size** of the gaseous molecule (**not** its weight).

To get an idea of how the pressures on Planet Atomica and Earth differ, you decide to compare the pressures of the most abundant gases in each atmosphere: CH_4 for Planet Atomica and N_2 for Earth.

If both gases were at standard conditions, 298 K, and present in equal amounts, which gas would have the greater pressure, as predicted by the Van der Waals equation? ***(4 points)***

a. CH_4
b. N_2
c. Cannot determine

Provide an explanation for your choice.

CH_4 is a larger molecule than N_2, therefore it will have a larger b value. Both molecules are nonpolar, so the intermolecular forces they experience are London Dispersion Forces (dipole-induced dipole interactions). However, **since CH_4 is the larger molecule, it will therefore experience greater London Dispersion Forces, giving it a larger a value.** Using the Van der Waals equation, a **larger a value would decrease the pressure, while a larger b value would increase the pressure**, therefore without the actual values of the constants for the two gases, it is **impossible to predict** which gas would have the greater pressure.

+1 point for Key Concept 1: some statement that the two molecules experience only LDF or that they both experience the same intermolecular force
+1 point for Key Concept 2: CH_4 is larger, so it experiences more LDF, so its a-value is bigger
+1 point for Key Concept 3: CH_4 is larger in size, so its b-value is bigger
+1 point for Key Concept 4: According to the VdW equation, a larger a-value and a larger b-value creates conflicting trends in pressure AND for circling option C (note: this point cannot be awarded if the student circled anything other than C)

Note: some explanation points can be granted even if the wrong answer was circled.
Note: -1 point for each conceptually incorrect statement made)

d. To make sure your rocket will pass through the planet's atmosphere safely, you decide to reinforce the rocket's heat shield. You and your team have two options for what material to use: alumina (Al_2O_3, Specific Heat Capacity = 0.880 J/g°C) or carbon phenolic (C_6H_5OH, Specific Heat Capacity = 0.938 J/g°C). Provide a brief explanation for which material your team should use. ***(2 points)***

Materials with a **higher heat capacity take more heat to increase in temperature**, requiring more heat to burn away, therefore **dissipating more heat** from the atmosphere. Therefore, your team should choose to reinforce the rocket's heat shield with **carbon phenolic** as it is the material with the higher heat capacity.

+1 point for stating that carbon phenolic is the better material
+1 point for relating a larger heat capacity to better heat dissipation efficiency

e. While running some computations, you accidentally spill coffee on your desk, and decide to clean it with an ethanol (C_2H_5OH) solution. The normal boiling point of ethanol is 78.3 ℃. The standard enthalpy of vaporization of ethanol is 38.56 kJ/mol. Calculate the vapor pressure of the ethanol at room temperature (25˚C). ***(4 points)***

Using the Clausius-Clapeyron equation: $ln(\frac{P_2}{P_1}) = \frac{-\Delta H^\circ_{vap}}{R}(\frac{1}{T_2} - \frac{1}{T_1})$ **(+1 point)**

$ln(\frac{P_2}{1\ atm}) = \frac{-38.56\ kJ/mol}{0.008314\ \frac{kJ}{mol\ K}}(\frac{1}{298.15\ K} - \frac{1}{351.45\ K})$ **(+2 points)**

$P_2 = 0.0945\ atm$ **(+1 point)**

+1 point for choosing to use the Clausius-Clapeyron equation
+2 point for correct substitution, not including the substitution or unit conversion of R (for example, a student could plug in the other value of R or leave it in J/mol K or leave it as "R" and still receive this point)

(note: T_2 must match up with P_2 and T_1 must match up with P_1 to get this point)

+1 point for correct final answer

f. Lastly before you exit the rocket, it is important to think about the reactions that could be occurring in the planet's atmosphere. At high temperatures, methane and water can react. Write out this reaction on the line provided below **and**, based on this reaction, provide a justification as to why it is important that you are equipped with your spacesuit and protective gear before you step out. ***(3 points)***

Reaction: ____

Justification:

____

____

____

____

Reaction: $H_2O + CH_4 \rightarrow CO + 3H_2$ **(+2 points)**

This reaction produces **carbon monoxide** which is toxic to humans if inhaled. **(+1 point)**

+2 points for correct reaction (note: states are not necessary for full credit)

+1 point for a correctly balanced reaction involving water and methane as reactants, but incorrect products (Partial Credit)

+1 point for a valid reason as to why a human would need protective spacegear to step out of a rocket with some connection to the reaction they wrote

<u>Problem #2</u>: *(15 points)*

Congratulations! You and your team of space explorers have successfully landed on the surface of Planet Atomica. But is it safe to leave your rocket?

a. Your space suit is capable of protecting you from UV radiation up to a photon energy of $3.62 \times 10^{-16} J$. The UV radiation emitted from the sun of Planet Atomica ranges from 600 picometers to 50 nanometers. Do your suits protect you and your team as they are, or will additional layers of protection be necessary? Show your work and circle your answer below. ***(3 points)***

The suits are fine as they are. (+1 point) **The suits need to be modified to be safe.**

UV Radiation Wavelengths: $6 \times 10^{-10} m$ to $5 \times 10^{-8} m$

Shortest wavelength → highest energy

$$E_{ph} = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34} Js)(2.998 \times 10^{8} m/s)}{6 \times 10^{-10} m} = 3.311 \times 10^{-16} J$$ **(+2 points)**

Additional work (not technically necessary):

$$E_{ph} = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34} Js)(2.998 \times 10^{8} m/s)}{5 \times 10^{-8} m} = 3.973 \times 10^{-18} J$$

The energy emitted from the Sun is less than the maximum energy your suits can withstand safely, so the suits will protect you and your team as you are.

+2 points for correctly calculating the energy associated with the shortest wavelength (600 pm)

+1 point for circling whatever answer matches the value they got for this energy (note: if the student mistakenly calculates a number that is larger than the maximum given and circles that the suits need modification, they can earn this point)

Note: students may show more work than is required by the key (i.e. a calculation of photon energy associated with the longer wavelength)

b. Your scanners detect that the rock structures nearby are made of polonium and have an average atomic mass of 209.56 amu. Knowing how toxic it is to humans, you must investigate. Determine the isotopic abundances of Polonium-210 and Polonium-209, using the fact that the rock structures are 1.09% Polonium-208 and these are the only three isotopes present. ***(2 points)***

Polonium-210: ___57.09%____________ Polonium-209: ___41.82%____________

(+1 point)

Average atomic mass (amu) = (210 amu)(isotopic abundance of Po-210) + (209 amu)(isotopic abundance of Po-209) + (208 amu)(isotopic abundance of Po-208)

209.56 amu = (210 amu)(x) + (209 amu)($1 - x - 0.0109$) + (208 amu)(0.0109) **(+1 point)**

$$209.56\,amu = 210x + 209 - 209x - 2.2781 + 2.2672$$

$$209.56\,amu = x + 208.9891$$

$$x = 0.5709$$

+1 point for correct substitution into a weighted average calculation (must include the 1 - x - 0.0109 term to earn this point, but they can use any variable)
+1 point for correct final answer of isotopic abundances

<u>Score of 1 out of 2</u> for having two answers in the blanks that add to 98.91% (even if the individual blanks are wrong) (Partial Credit)

c. Through an elemental dating process, the rock structures are determined to be 7.8 billion Earth years old. This is 2.06×10^{10} half lives of the Polonium-210. What is the half life of Polonium-210 in Earth **days**? Round your answer to the nearest day. ***(2 points)***

$$\frac{7{,}800{,}000{,}000\ years}{2.06 \times 10^{10}\ half\ lives} = \frac{0.37864\ years}{1\ half\ life} \times \frac{365\ days}{1\ year} = 138\ days$$ **(+2 points)**

+2 points for correct half life <u>in days</u>
<u>Score of 1 out of 2</u> for a correct half-life in years (0.37864 years)

d. To find how many grams of sample remain after a given number of half-lives, you must multiply the original mass by $(\frac{1}{2})^n$, where n is the number of half-lives.

The sample you and your team obtained of the rock structure was 65 g. Assuming that it was pure Polonium-210, how much time will have elapsed (in Earth days) when only 8% of the sample remains? ***(4 points)***

Original Mass: $65\ g$
Final Mass: $65\ g \times 0.08 = 5.2\ g$

$$Remaining\ Sample\ Mass = Original\ Sample\ Mass \times (\frac{1}{2})^n$$

$5.2\ g = 65\ g \times (\frac{1}{2})^n$ **(+2 points)**

$$\frac{5.2\ g}{65\ g} = (\frac{1}{2})^n$$

$$ln(\frac{5.2\ g}{65\ g}) = n \times ln(\frac{1}{2})$$

$n = 3.644\ half\ lives$ **(+1 point)**

$3.644\ half\ lives \times \frac{138\ days}{1\ half\ life} = 502.85\ days$ **(+1 point)**

+2 points for correct substitution into the equation
+1 point for correctly solving for n
+1 point for correctly converting from number of half lives to days (if conversion involves a wrong answer from part c, i.e. a different number of days than 138, but the math is correct, the student can earn this point)

e. Before leaving the rocket, you and your team need to know how you'll be affected by gravity. You set up an electric field that points upwards and you suspend a droplet charged with the fundamental unit of charge so that the electric force experienced balances out the gravitational force on the droplet.

If the mass of your suspended droplet is 2.8×10^{15} times larger than the mass of a proton (in kg), and the electric field needed to suspend the droplet is 8.73×10^{8} N/C, what is the gravitational constant of Planet Atomica? ***(3 points)***

$F_g = F_E$

$mg = qE$ **(+1 point)**

$m = (1.67 \times 10^{-27} kg) \times (2.8 \times 10^{15}) = 4.676 \times 10^{-12} kg$

$q = 1.602 \times 10^{-19} C$

$E = 8.73 \times 10^{8} N/C$

$(4.676 \times 10^{-12} kg) \cdot g = (1.602 \times 10^{-19} C)(8.73 \times 10^{8} N/C)$ **(+1 point)**

$g = 29.91\, m/s^2$ **(+1 point)**

+1 point for correctly setting the force due to gravity and the force of the field equal
+1 point for correct substitution into the equation, not including the fundamental unit of charge (i.e. can leave as q)
+1 point for correct new value of g

f. Humans can withstand up to around 5 times the strength of Earth's gravity before facing serious health complications. Based on your answer in part (e), how many times stronger is Planet Atomica's gravity than Earth's? ***(1 point)***

$\frac{g_{Planet\ Atomica}}{g_{Earth}} = \frac{29.91\, m/s^2}{9.8\, m/s^2} = 3.05$ times stronger **(+1 point)**

<u>Problem #3</u>: *(16 points)*

Now that you've determined that it's safe to exit your spaceship, it's time to research Atomica. Can this planet support human life? If not, could anyone—or anything—be living here?

a. Your team investigates the planet by collecting a sample of a nearby water source in a solid aluminum container. The container starts to rapidly dissolve and bubble, signifying the water is highly acidic! Your team identifies the dissolved remains as $AlCl_3$ and the bubbles as H_2 gas. Propose the reaction that occurred with the container. ***(2 points)***

$$2Al(s) + 6HCl(aq) \rightarrow 2AlCl_3(aq) + 3H_2(g)$$

+1 point for correct reactants and products (note: the $AlCl_3$ and H_2 <u>must</u> appear on the products side for this point)
+1 point for a correctly balanced reaction (even if the species are wrong)
Note: states are not required for full credit

b. Use the table provided to aid you in answering the following questions. ***(2 points)***

$[H^+]$ **Concentration (mol/L)**	**pH at 25°C**	**pH at 80°C**
?	7.00	6.13
5.5×10^{-7}	6.26	5.26
1.0×10^{-6}	6.00	5.00
5.5×10^{-6}	5.26	4.26
1.0×10^{-5}	5.00	4.00
5.5×10^{-5}	4.26	3.26
1.0×10^{-4}	4.00	3.00
5.5×10^{-4}	3.26	2.26
1.0×10^{-3}	3.00	2.00
5.5×10^{-3}	2.26	1.26
1.0×10^{-2}	2.00	1.00

i. What should go in place for the question mark (**?**) in the table (top left corner)? ***(1 point)***

$[H^{+}] = -log(pH\ @\ 25^{\circ}C) = -log(7.00) = 1.0 \times 10^{-7}$ **(+1 point)**

ii. Using the data in the table, determine the neutral pH of water at 80˚C. ***(1 point)***

$pH = 6.13$ **(+1 point)**

c. A member of your team proposes that a certain amount of $NaOH$ can be added to the planet's water in order to remove the strong acid you identified in your reaction in part a. This would make the water safe to drink. ***(3 points)***

Write out the reaction that occurs when these two substances are mixed, and define what type of reaction it is (ex.: redox, precipitation, acid-base, etc.). *Note: if you were not able to answer part a, use HNO_3 as your strong acid.*

Reaction: ______________$HCl + NaOH \rightarrow H_2O + NaCl$_________________

(+2 points)

+1 point for a reaction involving NaOH and a strong acid
+1 point for that reaction producing water and some salt

Alternate: $HNO_3 + NaOH \rightarrow H_2O + NaNO_3$ **(receives full points)**

Reaction Type: ____Acid-Base (Neutralization)_____________________________
(+1 point)

Note: the student must say "Acid-Base," but they do not need to include "Neutralization"

Certain ions like Mg^{2+} are necessary to support any kind of life and are sourced either from water or vegetation.

d. From your team's observations, you conclude that magnesium carbonate and hydrochloric acid are present in high amounts on Planet Atomica. ***(9 points)***

   i. Write the balanced **molecular** and **net ionic** equations for the reaction between these compounds (assuming the reaction occurs in an aqueous environment and that magnesium carbonate is completely insoluble in water). ***(4 points)***

Molecular: ____

Net Ionic: ____

Molecular: $MgCO_3\,(s) + 2HCl\,(aq) \rightarrow MgCl_2(aq) + CO_2(g) + H_2O(l)$ **(+2 points)**

Net Ionic: $MgCO_3\,(s) + 2H^+(aq) \rightarrow Mg^{2+}(aq) + CO_2(g) + H_2O(l)$ **(+2 points)**

+2 points for <u>each</u> correct equation, not including states
(Note: some students may not leave $MgCO_3$ as a solid on the reactant side for either equation and will break it down into its component ions. This is conceptually incorrect since $MgCO_3$ is insoluble in water and should receive <u>no points</u>.)
(Note: some students may put H_2CO_3 (aq) on the products side of both equations. This should receive <u>full points</u>.)

ii. There are 89.63 kg of solid $MgCO_3$ present in a nearby lake of 1344.45 L of 2.0 M HCl. Calculate the theoretical yield (in moles) of magnesium ions formed from this reaction, assuming the magnesium carbonate is the limiting reactant. Then calculate the theoretical concentration of magnesium ions. ***(3 points)***

Theoretical Yield (moles): ____________1063.1 mol _____________________

Theoretical Concentration (M): _______0.791 M__________________________

$$\frac{89.63\ kg\ MgCO_3}{1} \times \frac{1000g}{1kg} \times \frac{1\ mol\ MgCO_3}{84.31g\ MgCO_3} \times \frac{1\ mol\ Mg^{2+}}{1\ mol\ MgCO_3} = 1063.1\ moles\ of\ Mg^{2+}$$ **(+2 points)**

$$\frac{1063.1\ mol\ Mg^{2+}}{1344.45\ L} = 0.791\ M$$ **(+1 point)**

+2 points for correctly calculating the theoretical yield of Mg^{2+} in moles
+1 point for correctly calculating the theoretical concentration of Mg^{2+} in M

iii. The percent yield for this reaction is 76%. What is the actual amount of magnesium ions present in moles? ***(2 points)***

$$\frac{actual\ yield}{theoretical\ yield} = 0.76$$ **(+1 point)**

$actual\ yield = 0.76 \times theoretical\ yield$

$actual\ yield = 0.76 \times 1063.1\ mol$

$807.956\ mol\ Mg^{2+}$ **(+1 point)**

+1 point for correct equation (correct ratio of actual to theoretical)
+1 point for correct final answer (note: students can still get this point if they correctly use an incorrect theoretical yield from part d(ii) - i.e. incorrect theoretical yield * 0.76)

Based on the highly acidic source of water, Planet Atomica could not support human life because it would harm our basic biological function. However, the presence of universally essential ions like Mg^{2+} suggests that *certain life forms* could thrive on the planet.

Problem #4: ***(17 points)***

You and your team of space explorers would like to observe the planet's alien race, the Elementari. During your investigation, you quickly find that the aliens are able to make themselves disappear and reappear by secreting an unknown solution that covers their skin and reacts with the air. This causes their blue skin to turn invisible, then back to blue again.

a. You run a sample of the secreted solution through your ship's solution analyzer. It turns out the sample is composed of water and an unknown acid base indicator. The solution reacts with the carbon dioxide in the atmosphere to form carbonic acid, then undergoes the reaction below with its indicator component, the forward direction of which is exothermic.

$$H_2CO_3 + Ind^- \rightleftharpoons HCO_3^- + HInd$$

Blue *Colorless (Invisible)*

Predict whether the Elementari will turn invisible for the following situations assuming that they are currently blue. Fill in the blanks with either **turn invisible** or **stay blue**. ***(3 points)***

i. The amount of carbon dioxide in the atmosphere increases. **(+1 point)**

____________turn invisible_____________

ii. Ammonia is added. **(+1 point)**

_______________stay blue_____________

iii. The temperature of the system is increased. **(+1 point)**

____________stay blue________________

b. You and your team want to see which acid-base indicator from Earth best matches the one in the secreted solution. You perform an experimental titration using 50.00 mL of the secreted solution and 0.100 M $NaOH$ and find that the solution changes color when 27.00 mL of $NaOH$ is added. ***(10 points)***

i. How many moles of H_2CO_3 are in the secreted solution? ***(2 points)***

Solution changes color at equivalence point where moles of $NaOH$ and H_2CO_3 are equal.

$27.00\ mL\ NaOH \times \frac{0.100\ mol\ NaOH}{1000\ mL} = 0.0027\ mol\ NaOH$ **(+1 point)**

Therefore 0.0027 moles of H_2CO_3 are in the secreted solution. **(+1 point)**

+1 point for converting the concentration of NaOH to moles
+1 point for correct final answer (setting the number of moles of NaOH equal to the number of moles of H_2CO_3 at the equivalence point)

ii. At the equivalence point, the reaction is governed by the weak base equilibrium:

$$HCO_3^- + H_2O \rightleftharpoons H_2CO_3 + OH^-$$

What is the concentration of HCO_3^- at the equivalence point of the titration? Use 0.0030 mol as the number of moles of H_2CO_3 in the secreted solution, regardless of your answer in part b(i). ***(2 points)***

At the equivalence point, all of the H_2CO_3 has been converted to HCO_3^- meaning that there should be 0.0030 moles of HCO_3^- in a total volume of 0.05 L + 0.027 L = 0.077 L. **(+1 point)**

$\frac{0.0030\ mol\ HCO_3^-}{0.077\ L} = 0.039\ M\ HCO_3^-$ **(+1 point)**

+1 point for calculating the new volume of the solution
+1 point for correct final answer (note: some students may disregard the direction to use 0.0030 moles and use their value from part b(i) instead - this point can be awarded if their math is correct and they use the value they reported in part b(i))

iii. An ideal indicator will change colors when the reaction has reached its equivalence point. What is the pH of the reaction from part b(ii) at the equivalence point? Use 0.040 M as the initial concentration of HCO_3^-, before equilibrium has been established. The K_{a1} for carbonic acid is 4.3×10^{-7}. ***(5 points)***

ICE Table:

	HCO_3^-	H_2O	$\rightleftharpoons$	H_2CO_3	OH^-
I	0.04 M	-		0	0
C	- x	-		+ x	+ x
E	0.04 - x	-		x	x

$K_b = \frac{10^{-14}}{4.3\times10^{-7}} = 2.33 \times 10^{-8}$ **(+1 point)**

$K_b = \frac{[H_2CO_3][OH^-]}{[HCO_3^-]} = \frac{x^2}{0.04 - x} = 2.33 \times 10^{-8}$ **(+2 points)**

Quadratic Formula:

$x^2 + (2.33 \times 10^{-8})x - 9.32 \times 10^{-10} = 0$ **(+1 point)**

$x = 3.05 \times 10^{-5} = [OH^-]$

$pOH = -log(3.05 \times 10^{-5}) = 4.52$

$pH = 14 - 4.52 = 9.48$ **(+1 point)**

+1 point for correctly solving for K_b using the given K_{a1} and the known K_w
+2 points for correct substitution into the K_b expression based on the E line of their ICE table (if they did one)
+1 point for indicating that they used the quadratic formula to solve for x (note: students may use MOSA, although this is not the method typically taught in AP Chemistry)
+1 point for correct final pH

iv. Using the provided table and your answer from part b(iii), which acid-base indicator from Earth best matches the indicator in the secreted solution? ***(1 point)***

Indicator	Approximate pH Range for Color Change
methyl orange	3.2–4.4
bromthymol blue	6.0–7.6
phenolphthalein	8.2–10
litmus	5.5–8.2
bromcresol green	3.8–5.4

Indicator: _______Phenolphthalein____________________________ **(+1 point)**

+1 point for correct indicator BASED ON their final pH reported in part b(iii)

Note: if no answer was obtained in part b(iii), this point cannot be awarded (i.e. the student cannot guess)

c. You decide to make a buffer solution to mimic the secreted solution using sodium bicarbonate, $NaHCO_3$, found on your ship. How many grams of sodium bicarbonate should you add to 650 mL of 0.05 M carbonic acid to form a buffer solution with a pH = 7.00? *Reminder: the* K_{a1} *for carbonic acid is* 4.3×10^{-7}. ***(4 points)***

Henderson-Hasselbach: $pH = pK_a - log_{10}(\frac{[HA]_0}{[A^-]_0})$ **(+1 point)**

$pK_a = -log(4.3 \times 10^{-7}) = 6.37$

$7.00 = 6.37 - log_{10}(\frac{0.05\ M\ H_2CO_3}{[A^-]_0})$ **(+1 point)**

$\frac{0.05\ M\ H_2CO_3}{[A^-]_0} = 10^{-0.63}$

$[A^-]_0 = 0.213\ M\ HCO_3^-$ **(+1 point)**

$650\ mL\ solution \times \frac{1\ L\ solution}{1000\ mL\ solution} \times \frac{0.213\ mol\ HCO_3^-}{1\ L\ solution} \times \frac{1\ mol\ NaHCO_3}{1\ mol\ HCO_3^-} \times \frac{84.007\ g\ NaHCO_3}{1\ mol\ NaHCO_3} = 11.63\ g\ NaHCO_3$

(+1 point)

+1 point for using the Henderson-Hasselbach equation

Note: some students may use the following variation: $pH = pK_a + log_{10}(\frac{[A^-]_0}{[HA]_0})$

Note: a combination of the two equations is incorrect (i.e. a "+" sign and the opposite ratio)

+1 point for correctly substituting in the pH, pK_a, and concentration carbonic acid (note: students can still get this point even if they use a wrong version of the H-H if they plug the values into the correct spots based on the equation they wrote)

+1 point for correctly isolating for $[A^-]_0$ (note: students must only obtain a value to get this point, it does not need to be correct)

+1 point for correct mass of sodium bicarbonate

<u>Problem #5</u>: *(19 points)*

The Elementari suddenly start attacking with laser guns! You and your team begin to retreat back to the ship.

a. The Elementari's laser beam shoots past you and strikes a nearby rock structure. The beam is comprised of a stream of electrons traveling at a speed of $4.24 \times 10^{6}\ \frac{m}{s}$. The lasers operate at a power of 5 W and eject 2.79×10^{18} electrons over a period of 5 seconds. Assume that for every one electron ejected, one photon is emitted. *Hint: The energy of the photons is equal to power divided by the photon rate.* ***(10 points)***

i. Determine the wavelength of the laser's radiation (in nm). ***(3 points)***

$Photon\ rate = \frac{2.79\times10^{18}\ photons}{5\ s} = 5.58 \times 10^{17}\ \frac{photons}{s}$ **(+1 point)**

$E_{ph} = \frac{5\ W}{5.58\times10^{17}\ \frac{photons}{s}} = 8.96 \times 10^{-18} J$ **(+1 point)**

$E_{ph} = \frac{hc}{\lambda}$

$\lambda = \frac{hc}{E_{ph}} = \frac{(6.626\times10^{-34}\ Js)(2.998\times10^{8}\ m/s)}{8.96\times10^{-18} J} = 2.22 \times 10^{-8} m = 22.17\ nm$ **(+1 point)**

+1 point for correctly calculating photon rate
+1 point for correct calculation of E_{ph} (i.e. power over photon rate - note: can still earn this point if the photon rate was calculated incorrectly)
+1 point for correct wavelength

ii. Determine the work function of the unknown element. ***(3 points)***

$KE = \frac{1}{2}(9.11 \times 10^{-31} kg)(4.24 \times 10^{6}\ \frac{m}{s})^{2} = 8.19 \times 10^{-18} J$ **(+1 point)**

$E_{ph} = \frac{5\ W}{5.58\times10^{17}\ \frac{photons}{s}} = 8.96 \times 10^{-18} J$

$KE = E_{ph} - \phi$

$8.19 \times 10^{-18} J = 8.96 \times 10^{-18} J - \phi$ **(+1 point)**

$\phi = 7.70 \times 10^{-19} J$ **(+1 point)**

+1 point for correctly calculating the kinetic energy of the electron
+1 point for correct substitution into the equation (this includes substituting their kinetic energy and bringing down their value of E_{ph} from part a(i), even if the value was incorrect)
+1 point for correct work function

iii. Based on your work in part a(ii), what is the unknown element? Circle your answer. ***(1 point)***

A. Silicon ($\phi = 7.77 \times 10^{-19} J$) **(+1 point for circling whichever matches a(ii) best)**

B. Silver ($\phi = 7.36 \times 10^{-19} J$)

C. Nitrogen ($\phi = 7.20 \times 10^{-19} J$)

D. Aluminum ($\phi = 6.73 \times 10^{-19} J$)

iv. Classify the unknown element as a metal, non-metal, or semimetal (metalloid), and describe **one** of that classification's important properties. ***(3 points)***

Silicon is a **semimetal (+1 point)** and thus has both metallic and non-metallic properties. Important among them is its ability to act as a **semiconductor** which makes it a useful component in electronics (such as solar panels). Other properties of silicon include its **metallic luster** and **brittleness**. **(+2 points for a correct property)**

<u>Alternate Key: student circled Silver</u>
Silver is a **metal** (transition metal) and some of its key properties include **shine/luster**, **high melting/boiling point, conductive**, **malleable**, **ductile** etc..

<u>Alternate Key: student circled Nitrogen</u>
Nitrogen is a **non-metal** and some of its key properties include **dull exterior**, **nonconductive**, **brittle**, **low melting point,** and **low boiling point**.

<u>Alternate Key: student circled Aluminum</u>
Aluminum is a metal (post-transition metal) and some of its key properties include **shiny**, **high melting/boiling point, conductive**, **malleable**, **ductile** etc.

+1 point for correct classification of WHICHEVER answer was circled
+2 points for correctly identifying one key characteristic of the classification stated

b. You and your team are finding shelter on the other side of a rock formation when you spot a field of superconducting solar panels. It seems the aliens have developed a superior energy source using a novel semiconductor that requires $8.15 \times 10^{-18} J$ to generate a current. What wavelength of light provided by the sun (in nm) would generate a current in the solar panel? ***(1 point)***

$$E_{ph} = \frac{hc}{\lambda} = 8.15 \times 10^{-18} J$$

$$\lambda = \frac{hc}{8.15\times10^{-18} J} = \frac{(6.262\times10^{-34} Js)(2.998\times10^{8} \frac{m}{s})}{8.15\times10^{-18} J} \times \frac{1\times10^{9}\,nm}{1\,m} = 24.4\,nm \text{ (+1 point)}$$

c. You collect a soil sample near the solar panels and identify the presence of four distinct elements: sulfur (S), sodium (Na), aluminum (Al), and silicon (Si). ***(8 points)***

i. Compare the properties of each element and match them to the correct element by circling your answer. *Note: you should have one element circled per row.* ***(4 points)***

- Element II has a higher **first** ionization energy than element III
- Element I has a **smaller** atomic radius than element IV
- Element III has the **second largest** electronegativity
- Element II has a **larger** electron affinity than element I

Element I:	S	Na	**Al**	Si
Element II:	**S**	Na	Al	Si
Element III:	S	Na	Al	**Si**
Element IV:	S	**Na**	Al	Si

+1 point for <u>each</u> correct answer

ii. Classify each of the four elements as a nonmetal, semimetal (metalloid), or metal. ***(4 points)***

Element	**Classification**
S	Nonmetal **(+1 point)**
Si	Semimetal/Metalloid **(+1 point)**
Al	Metal **(+1 point)**
Na	Metal **(+1 point)**

Problem #6: ***(12 points)***

You and your team make it safely back to your ship, but you notice that a laser has punctured the ship's fuel tank causing all of the fuel to pour onto the ground. Luckily, it turns out that the Elementari's diet includes hydrazine, the compound in your fuel! Thus, they interpret your spilled rocket fuel as a calorie-rich peace offering. In exchange, the aliens agree to build you a hydrogen fuel cell to help you get home.

For the remainder of this question, assume gases behave ideally on Planet Atomica.

a. A hydrogen fuel cell works by spontaneously combining hydrogen and oxygen gas into water vapor. This electrochemical reaction is described by the following equation:

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)$$

The relevant half-cell equations and standard reduction potentials are as follows:

$$2H^+(aq) + 2e^- \rightarrow H_2(g) \qquad \varepsilon° = 0\,V$$

$$\frac{1}{2}O_2(g) + 2H^+(aq) + 2e^- \rightarrow H_2O(l) \qquad \varepsilon° = +1.23\,V$$

Calculate the Standard Cell Potential, $\varepsilon°_{cell}$, of the hydrogen fuel cell reaction. ***(2 points)***

$$H_2(g) \rightarrow 2H^+(aq) + 2e^- \qquad \varepsilon° = 0\,V \quad \text{(Flipped)}$$

$$\frac{1}{2}O_2(g) + 2H^+(aq) + 2e^- \rightarrow H_2O(l) \qquad \varepsilon° = +1.23\,V \quad \text{(Same)}$$

+ ____ (Summed)

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) \qquad \varepsilon°_{cell} = 0\,V + 1.23\,V = +1.23\,V$$ **(+2 points)**

+1 point for a value of 1.23 V

+1 point for a positive Standard Cell Potential (even if the numerical value is wrong)

Note: "0 V" will not be accepted for this point (i.e. 0 will not be considered "positive")

b. The alien hydrogen fuel cell contains 4.0 atm of $H_2(g)$ and 1.0 atm of $O_2(g)$ and operates at a pH = 3.0 at 298 K. Calculate this cell's non-standard cell potential, using a Standard Cell Potential, $\varepsilon^{\circ}_{cell} = +2.35\,V$. ***(3 points)***

$\varepsilon_{cell} = \varepsilon^{\circ}_{cell} - \frac{RT}{nF} lnQ$ **(+1 point)**

$\varepsilon_{cell} = 2.35\,V - \frac{(8.314\frac{J}{mol \cdot K})(298\,K)}{(2\,mol\,e^{1-})(96485\frac{C}{mol\,e^{-}})} ln(\frac{1}{(1.0atm)^{1/2}(4.0\ atm)^{1}})$ **(+1 point) =** $+2.37\,V$ **(+1 point)**

+1 point for the use of the Nernst Equation
+1 point for correct expression for Q
+1 point for correctly final answer for ε_{cell}

c. Calculate the volume of gaseous H_2 produced (in L) by running a current of $45.16\,A$ through the cell for 12.00 hours at $1.43\,atm$ and $24°C$. Assume all gases involved are behaving ideally. *Hint: 1 A = 1 C/s. Note: this reaction is the electrolysis of water, as in the overall reaction given in part a, but run in reverse to decompose water into hydrogen and oxygen.* ***(3 points)***

$45.16\,A = 45.16\frac{C}{s}$

$45.16\,\frac{C}{s} \cdot \frac{60s}{1min} \cdot \frac{60min}{1hr} \cdot 12.00\,hr \cdot \frac{1mol\,e^{1-}}{96485\,C} \cdot \frac{1mol\,H_2}{2mol\,e^{-}} = 10.110\,mol\,H_2$ **(+1 point)**

$PV = nRT \Rightarrow V = \frac{nRT}{P}$ **(+1 point)**

$V = \frac{(10.110mol\,H_2)(0.08206\frac{L \cdot atm}{mol \cdot K})(24°C + 273.15K)}{(1.43atm)} = 172.39\,L\,H_2$ **(+1 point)**

+1 point for correctly solving for moles of H_2
+1 point for using the Ideal Gas Law equation
+1 point for correctly solving for liters of H_2

d. The aliens give you a tank of 2,000 kg of hydrogen gas, and 10,000 kg of oxygen gas. What is the maximum energy the fuel cell can generate (in Joules)? Assume that the combustion of one mole of H_2 generates 286 kJ of energy. ***(4 points)***

$2 \times 10^3\, kg\, H_2 = 2 \times 10^6 g\, H_2$

$mol\, H_2 = 2 \times 10^6 g\, H_2 \times \frac{1\, mol}{2.02\, g\, H_2} = 9.9 \times 10^5 mol\, H_2$

$10,000\, kg\, O_2 = 1 \times 10^7 g\, O_2$

$mol\, O_2 = 1 \times 10^7 g\, O_2 \times \frac{1\, mol}{31.999\, g\, O_2} = 3.13 \times 10^5\, mol\, O_2$ **(+1 point)**

$9.9 \times 10^5 mol\, H_2 = 9.9 \times 10^5 mol\, H_2O$

$3.13 \times 10^5\, mol\, O_2 = 6.26 \times 10^5\, mol\, H_2O \rightarrow$ O_2 is the limiting reactant **(+1 point)**

$Energy = (3.13 \times 10^5\, mol\, O_2) \times \frac{2\, mol\, H_2}{1\, mol\, O_2} \times \frac{286,000\, J}{1\, mol\, H_2} = 1.786 \times 10^{11}\, J$ **(+1 point)**

Maximum Energy = $1.786 \times 10^{11}\, J$ **(+1 point)**

+1 point for calculating moles of H_2 and O_2
+1 point for correct concept that oxygen is limiting reactant
+1 point for calculating an energy produced when all of the limiting reactant is combusted (note: can earn this point even if they said hydrogen was the LR)
+1 point for correct final maximum energy generated

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