



## Student Performance Q&A: 2015 AP<sup>®</sup> Chemistry Free-Response Questions

The following comments on the 2015 free-response questions for AP<sup>®</sup> Chemistry were written by the Chief Reader, Roger Kugel of the University of Cincinnati. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student performance in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

### Question 1

#### *What was the intent of this question?*

Question 1 assessed students' understanding of electrochemistry and its relationship to concepts from thermodynamics, equilibrium, and atomic structure. Students were asked a series of questions about a metal-air cell, a relatively modern type of portable energy source, which represents a real world application of chemistry.

#### *How well did students perform on this question?*

Question 1 did an excellent job of discriminating among students in terms of their understanding of the topic of electrochemistry and its relationships to thermodynamics, equilibrium, and atomic structure. The mean score was 3.79 out of 10 points. Most students were able to earn some points. Less than 1 percent of the students earned all 10 points.

#### *What were common student errors or omissions?*

In part (a)(i) students were asked to calculate the cell potential in a zinc-air cell. This involved taking the value for the half-reaction at the cathode ( $\text{O}_2$  is reduced to  $\text{OH}^-$ ,  $E^\circ = +0.34 \text{ V}$ ) directly from the table. In the reaction at the anode, Zn is oxidized to  $\text{Zn}^{2+}$  so the reaction in the table is reversed, and the sign of the potential value is changed to  $+1.31 \text{ V}$ . Thus, the total is  $E^\circ_{\text{red}} + E^\circ_{\text{ox}} = 0.34 + 1.31 = 1.65 \text{ V}$ . (Some students presented this as  $E^\circ_{\text{red for cathode}} - E^\circ_{\text{red for anode}} = 0.34 - (-1.31)$  to find the same answer.) Common mistakes included failing to change the sign of the oxidation half-reaction and calculating incorrectly  $(0.34) + (-1.31) = -0.97$ , and changing the wrong signs (so that the calculation becomes  $(-0.34) + (-1.31) = -1.65$ ). Some students added or subtracted all the possible values in the table to report  $(+0.34) + (-1.31) + (-1.60) + (-2.78) = -5.35$ . Some students noticed that the zinc half-reaction would have to be doubled to make the electron flow balance when the half-reactions are combined and incorrectly doubled its potential (thus,  $(+0.34) + (+2.62) = +2.96$ ).

In part (a)(ii) students were asked to place an arrow on the diagram to indicate the direction of migration of hydroxide anions through the electrolyte. Many students drew a left-pointing arrow in the light grey box labeled “electrolyte paste,” as directed. Others placed the arrow near the diagram and this was accepted as long as the orientation toward the anode was clear. Unacceptable answers included the following: some students drew an arrow following the external circuit, complete with bends; some students offered vertical arrows, pointed up or down or both; and some drew a double-headed arrow.

In part (b)(i) students were asked to predict the change in mass of the cell as it operated. “Increase” was intended as the correct answer while “decrease” or “remain the same” were incorrect. Some students selected two choices and did not earn the point.

Part (b)(ii) asked students to use a supplied reaction to justify the change in the mass of the zinc-air cell predicted in part (b)(i). Since the zinc anode reacted with oxygen that had entered the cell to form zinc (II) oxide, a heavier compound, the mass of the cell increased. A common mistake involved missing the idea that oxygen had entered the cell from outside and predicting that the mass remained the same, justifying this with the Law of Conservation of Mass.

In part (c)(i) students were asked to predict the effect on cell potential of moving the cell to a mountaintop where the air pressure is lower. The intended answer is “lower.” In part (c)(ii) students were asked to justify their answers and were able to do so by using the trial equilibrium ratio  $Q$ ; some even used the Nernst equation in a qualitative way to make the prediction. Common mistakes included using LeChatelier’s Principle to analyze a system not at equilibrium, using a stoichiometric argument even though atmospheric oxygen is not a limiting factor and using a kinetics argument.

Part (d) required students to determine which one of a pair of possible lighter-weight metals, sodium or calcium, would transfer more electrons, given identical 1.0-gram masses of each metal. Since calcium has a greater atomic mass, there would be fewer moles of calcium than of sodium when comparing identical masses. However, calcium gives two moles of electrons for each mole of metal while sodium would supply only one mole of electrons per mole of metal. Therefore, an identical mass of calcium would give a greater quantity of electrons than the same mass of sodium. Many students were able to calculate the number of moles of each metal. Fewer students noticed the difference in the number of electrons lost by an atom of each metal, thereby selecting sodium as the answer for a lightweight anode. This step represented the most common mistake. Another common mistake was to indicate that a calcium atom had more total electrons to use than a sodium atom. Some students used  $\text{CaO}$  and  $\text{Na}_2\text{O}$  in their calculations rather than the metals. Yet another common mistake involved using cell potentials to choose which metal provided more electrons. Students need to understand the difference between cell potential and current.

Part (e) required students to give an electron configuration for an atom of zinc. Most students were able to do this, and many even used a noble gas core to shorten the process. In one common error, some students omitted the noble gas core and wrote simply “ $4s^2 3d^{10}$ .” Another common error gave an excited state rather than the requested ground state:  $[\text{Ar}] 4s^2 3d^{10}$ . The students were then asked to predict from which sublevel electrons were lost as a zinc atom in the ground state is oxidized. Fewer students were able to predict that the highest energy valence electrons, those in  $4s$ , are the ones to be removed. Many thought that  $3d$  electrons would be removed first. Some students had difficulty predicting the electron configuration and some even merged electron configurations with orbital hybridization ideas to offer answers like “ $sp^3d^{10}$ .”

***Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?***

In general, it appeared that students need to hone their exam-taking skills. Reading the prompt carefully to find important information is a useful skill. Responding directly to the question with concise, to-the-point language is another. For any calculation, work should be shown, and all numbers should be labeled. Attention

should be paid to significant figures each time a calculation is made. Learning to follow directions is another important skill. For example, if one is directed to draw an arrow on the electrolyte section of a diagram, then one should put the arrow in that section and not in some other location on or near that part of the diagram.

Electrochemistry is a topic that is frequently covered late in the school year, and it may appear after thermodynamics is introduced. Students should be able to link concepts of electrochemistry with ideas from thermodynamics and equilibrium. It is important that students understand that an operating battery is NOT at equilibrium. While quantitative calculations using the Nernst equation are excluded from the curriculum, qualitative understanding of the relationship between  $Q$  and  $E$  are part of the curriculum.

Many students mastered electron configurations during Chemistry I and it might be important to review such a topic shortly before the AP Chemistry Exam administration.

## Question 2

### ***What was the intent of this question?***

Question 2 was designed to evaluate student understanding and ability to analyze data generated empirically during common laboratory procedures. Students were presented with a picture of laboratory equipment arranged for the collection of gas over water in a dehydration experiment.

The students were given the chemical equation for the reaction that occurs in the experiment. They were given data, and in part (a) they were asked to calculate the experimental yield in moles at a certain time in the experiment. Then, they were asked to calculate the theoretical yield in moles if the reaction proceeded to completion. In part (b) students were asked to use their calculations to determine the percent yield. In part (c) students used given thermodynamic data to verify a student's claim about the  $K_p$  of the reaction. In part (d) students were instructed to complete a Lewis electron-dot diagram for a molecule. Part (e) asked students to give the value of the bond angle in a certain part of the molecule based on their Lewis diagram from part (d). Finally, in part (f) students applied their conceptual understanding of intermolecular forces to explain experimental observations of the difference in the water solubility of two gases.

### ***How well did students perform on this question?***

Students primarily struggled with the basic understanding of the stoichiometric calculations required for this question as well as the conceptual understanding of molecular interactions. The mean score on Question 2 was 3.88 out of 10 points. Approximately 1 percent of the students earned all 10 points.

### ***What were common student errors or omissions?***

This question was worth 10 points: part (a)(i) was worth 2 points; part (a)(ii) was worth 1 point; part (b) was worth 1 point; part (c) was worth 2 points; parts (d) and (e) were worth 1 point each; part (f) was worth 2 points. One point in 10 was subtracted for incorrect use of significant figures ( $\pm 1$  digit) in the final answer for each part. This error deduction was only taken once in the paper. Note: In part (c)  $\Delta G^\circ$  has two significant figures; the other answers have three.

Part (a): Students demonstrated their understanding of gas law calculations as they related to empirical data obtained from a student experiment where a gas is collected over water.

In part (a)(i) 1 point was earned for calculating the pressure of dry ethene. A second point was earned for using this value in the gas law relationship to correctly solve for the moles of gas in the experimental yield. Students could also earn full credit (2 points) for correctly determining the moles of dry ethene by calculating the difference between the total moles of the ethene/water vapor mixture and subtracting the moles of water vapor.

Common student errors or omissions included:

- Omitting the correction for the vapor pressure of water;
- Incorrectly converting torr to atm or vice versa;
- Using the incorrect value for the gas constant,  $R$ ;
- Making errors in significant figures (e.g., incorrectly assuming that .003 contains three significant figures);
- Erroneously calculating the moles of product by simply dividing the mass of reactant by molar mass of product; and
- Converting volume of gas to moles by using the standard molar volume (22.4 L/mol) when the gas is not at 1.00 atm and 273 K.

In part (a)(ii) 1 point was earned for correctly determining the theoretical yield of ethene if the reaction were carried to completion.

Common student errors or omissions included:

- Reversing the placement and labeling of questions (a)(i) and (a)(ii), thus making it difficult to determine which calculation represented the experimental yield and which represented the theoretical yield; and
- Improperly calculating the moles of product by using a value for molar mass other than the one given in the problem.

Part (b): Students demonstrated their ability to calculate percent yield. One point was earned for correct calculation based on student values for part (a)(i) as actual and part (a)(ii) as theoretical yields.

Common student errors or omissions included:

- Confusing the calculation of percent yield and percent error;
- Reversing the calculated values for actual and theoretical yield; and
- Converting moles to mass and solving for a mass/moles or moles/mass relationship rather than a mol/mol relationship.

Part (c): One point was earned for the correct calculation of the thermodynamic value of  $\Delta G^\circ$ . The value for  $\Delta G^\circ$  has only two significant figures so student answers must be within one to three significant figures. The second point was earned for correctly supporting or refuting the student claim with a valid justification based on the student's calculated value for  $\Delta G^\circ$ . Correct calculation of the equilibrium constant may be used but was not required in the justification for the second point.

Common student errors or omissions included:

- Using  $\Delta G_{305}^\circ$  instead of the correct standard  $\Delta G_{298}^\circ$ ;
- Using inconsistent units for  $\Delta H^\circ$  and  $\Delta S^\circ$ ;
- Conflating 1 and 0 (For example,  $K < 1$  is not  $K < 0$ , and  $\Delta G^\circ < 1$  is not  $\Delta G^\circ < 0$ );
- Justifying based on values for  $\Delta H^\circ$  or  $\Delta S^\circ$  alone;
- Using irrelevant equations such as attempting to calculate  $\Delta G^\circ$  from  $-RT \ln K$ , or trying to use  $\Sigma G_f^\circ (\text{products}) - \Sigma G_f^\circ (\text{reactants})$ ;
- Using the incorrect value for the gas constant,  $R$ ;
- Answering "Yes" or "No" without justification; and
- Calculating  $K$  incorrectly, leading to an erroneous justification.

Part (d): One point was earned for correct placement of electrons on the given Lewis electron-dot diagram for ethanol in the box next to the boxed Lewis electron-dot diagram for ethene.

Common student errors or omissions included:

- Incorrectly inserting a double bond between the carbons in ethanol;
- Using  $\div$  for an electron without an explanation;
- Failing to add lone pairs of electrons to oxygen;
- Adding extra electrons to carbon to make up for omission of lone pairs and account for number of electrons calculated; and
- Creating stray marks on the structure that could be interpreted as extra electrons.

Part (e): One point was earned for stating the correct value for the angle in C–O–H. Values from  $100^\circ$  to  $115^\circ$  were accepted.

Common student errors or omissions included:

- Assigning a bond angle of  $90^\circ$ ,  $120^\circ$ , or  $180^\circ$  were the most common errors (Note: An angle consistent with an incorrect Lewis structure for ethanol was accepted.);
- Giving more than one bond angle; and
- Describing or drawing the shape of the bond angle (bent, tetrahedral, etc.). Students had to give a numerical value for the bond angle.

Part (f): This part was worth 2 points. The first point was an entry level point, earned for comparing the solubility of ethene in water with the solubility of ethanol in water in terms of the differences in their polarity. The second point was earned for articulating an understanding of the intermolecular forces responsible for the difference in the solubility of the two gases. For this point, students needed to clearly identify and name the types of intermolecular forces involved as well as clearly show an understanding of the attractions as intermolecular. Discussion needed to include the dipole/induced-dipole or London dispersion forces of attraction between molecules of ethene and water and the hydrogen bonding forces between molecules of ethanol and water. Excellent responses discussed the difference in the energy of these forces and/or the difference in the strength of these attractions. In addition, students could have said that the dipoles of ethene are not strong enough to break the hydrogen bonds between water molecules.

Common student errors or omissions included:

- Using intermolecular forces to discuss pure substance properties such as melting and boiling points, densities, or molar masses;
- Making arguments based on phase changes;
- Simply stating stronger or weaker attractions, rather than identifying specific intermolecular forces;
- Using “ionize” for “dissolve;”
- Explaining with words such as bonded, reacted, attacked, attached, trapped, or dissociated;
- Discussing weaker hydrogen bonds in ethane;
- Confusing intra- and intermolecular bonding/forces, shown by labeling the covalent O–H bond within the molecule as a hydrogen bond; and
- Describing a conjugate acid/base reaction of water grabbing  $H^+$  ion from the ethanol to form  $H_3O^+$  and  $CH_3CH_2O^-$ .

***Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?***

- Convince students to read the question carefully and be certain to answer what was asked.
- Provide students practice on significant figures by requiring that the final answer to all problems is recorded in the correct number of significant figures.
- Train students to correctly label each part of the question. For example, in this question part (a)(i) asks for the actual experimental yield and part (a)(ii) asks for the theoretical yield.

- Emphasize the importance of showing calculations. For example, credit was not earned for the water vapor pressure correction when work was not shown.
- Reinforce the vapor pressure of water correction by using it in a laboratory context.
- Emphasize the importance of units: Choose the value for  $R$  that corresponds to torr or atm in part (a)(i) and note that in part (c) that  $\Delta H^\circ$  is given in kJ and  $\Delta S^\circ$  in J. Practice canceling units to avoid this error.
- Not all percentages are percent error. For example, percent yield is not percent error.
- Practice estimation and recognizing the validity of answers. For example, a percent yield greater than 100 percent is not reasonable.
- Emphasize the importance of comparing units during calculating such as  $\Delta H^\circ$  given in kJ and  $\Delta S^\circ$  in J.
- When asked to justify, simply stating an answer or giving “yes” or “no” is insufficient.
- In the study of VSEPR include the numerical values for the angles.
- If the question only asks for the value of the bond angle, don’t waste time explaining.
- Intermolecular forces do not cause a “reaction” or “chemical bonding” when a solute dissolves in a solvent.
- Many students were unable to explain how intermolecular forces affect solubility.
- Train students to consider the dissolving process as the relative strength (energy) involved in three intermolecular attractions: attractions among solvent particles, attractions among solute particles, and attractions between solvent and solute particles.

### Question 3

#### ***What was the intent of this question?***

Question 3 addressed a range of chemical concepts associated with acid-base chemistry. Students were provided a laboratory scenario that involved the titration of a known volume of weak base ( $C_6H_7O_2^-$ , sorbate ion) with a strong acid (HCl) of known concentration. In part (a) students were asked to write the net-ionic equation for the reaction between potassium sorbate ( $KC_6H_7O_2$ ) and hydrochloric acid (HCl). In part (b) students were provided experimental data pertaining to the volume of HCl required to reach the equivalence point of the titration. Based on this data, the students were asked to calculate the concentration of the  $KC_6H_7O_2$  stock solution. In part (c) students were provided an equivalence point pH and a table consisting of various indicators and their respective  $pK_a$  values. Based on the pH at the equivalence point, students were asked to choose the appropriate indicator and to justify their selection. In part (d) students were asked to calculate the pH at the half-equivalence point. In part (e) students were asked to sketch a titration curve representative of the curve generated by the titration of the sorbate ion with HCl. In part (f) students were asked to identify the component of the conjugate pair ( $HC_6H_7O_2/C_6H_7O_2^-$ ) that is present in the larger quantity at a particular pH.

#### ***How well did students perform on this question?***

The mean score for Question 3 was 3.72 out of a possible 10 points. In general, the vast majority of all points were earned in parts (b) and (c), with parts (e)(ii), the change in slope to a relatively horizontal curve through the “X,” and (f) being the most difficult points to earn. Approximately 2 percent of the students earned all 10 points.

### ***What were common student errors or omissions?***

Part (a): [1 point]

- Students seemed to struggle transitioning from the total ionic equation to the net-ionic equation.
- Some students would write the sorbate ion reacting with HCl, but would subsequently include the chloride ion as a product.
- Some students would cancel out the sorbate and hydrogen ions, leaving potassium and chloride ions reacting to form KCl as their net-ionic equation.
- Students would omit one or both of the reactant charges ( $\text{C}_6\text{H}_7\text{O}_2^-$  and  $\text{H}^+$ ).
- Some students gave the molecular equation as their response.

Part (b): [2 points]

- The majority of students successfully calculated the concentration of  $[\text{KC}_6\text{H}_7\text{O}_2]$  in the stock solution.
- Some students used the traditional stoichiometric approach to solve this problem.
  - Calculating moles of HCl
  - Calculating moles of  $\text{C}_6\text{H}_7\text{O}_2^-$  based on a 1:1 mole ratio
  - Calculating  $[\text{C}_6\text{H}_7\text{O}_2^-]$  using the correct starting volume
- Many students approached the problem using  $M_aV_a = M_bV_b$  (acceptable only for monoprotic titrations) to reach the correct value for the  $[\text{C}_6\text{H}_7\text{O}_2^-]$ .
- Some students incorrectly tried to apply the equilibrium expression, using the provided  $K_a$  ( $\text{HC}_6\text{H}_7\text{O}_2$ ), to solve the problem, including elaborate ICE tables.
- Some students arrived at the incorrect volume for the  $[\text{KC}_6\text{H}_7\text{O}_2]$  stock solution.
  - Students would use the post-titration volume to calculate  $[\text{KC}_6\text{H}_7\text{O}_2]$ :  $0.02995 \text{ mL} + 0.04500 \text{ mL} = 0.07495 \text{ mL}$  (most common).
  - Students would also take the difference between the two provided volumes:  $0.04500 \text{ mL} - 0.02995 \text{ mL} = 0.015 \text{ mL}$  (less common).
- Converting from mL to L was problematic for some students.

Part (c): [2 points]

Many students earned both points for this part.

- The majority of students correctly identified thymol blue as the indicator to use for this particular titration, earning the first point.
  - Students who did not make a comparison between the  $\text{p}K_a$  of thymol blue to the equivalence point, the endpoint, the measured pH, etc. did not earn the justification point.
- Students did not choose the correct indicator due to:
  - Comparing the  $\text{p}K_a$  of methyl red ( $\text{p}K_a = 5.0$ ) with the  $\text{p}K_a$  of sorbic acid ( $\text{p}K_a = 4.77$ );
  - Doubling the measured pH ( $2.54 \times 2 = 5.08$ ), to compare against the  $\text{p}K_a$  of methyl red;
  - Confusing the pH at the half-equivalence point with the pH at the equivalence point;
  - Not comprehending that indicators are applied/utilized at the equivalence point; and
  - Ignoring the equivalence point in the stem and referencing “another” equivalence point. For example, “since the equivalence point of an acid/base titration is 7, I selected bromothymol blue.” This type of justification could earn the second point.
- Students substituted endpoint for equivalence point, and vice-versa, incorrectly. [No point deductions were made.]

Part (d): [1 point]

- Students were able to correctly set up and calculate the pH at the half-equivalence point.
- The most common errors students made involved either halving or doubling the equivalence point pH in order to determine the pH at the half-equivalence point.
  - $2.54 \div 2 = 1.27$
  - $2.54 \times 2 = 5.08$
- Some students misapplied the Henderson-Hasselbalch equation:  $\text{pH} = 4.77 + \log\left(\frac{[\text{A}^-]}{[\text{HA}]}\right)$  and plugged in non-equal concentrations.
- Some students reported a half-equivalence point pH of 9.23, which is the  $\text{p}K_b$  for  $\text{C}_6\text{H}_7\text{O}_2^-$ .

Part (e): [3 points]

- Of the three points assigned to part (e), the point associated with locating the half-equivalence “X” on the graph was most often successfully earned by the students. Many students had issues plotting the graph, perhaps due to a lack of experience in manual graphing.
- Locating the half-equivalence point on the graph required coordinating two pieces of data:
  - Students consistently used the half-equivalence pH value from their response in part (d).
  - Students had little trouble calculating the half-equivalence volume on the graph.
  - Primary error was associated with the careless plotting of the “X” onto the graph.
- The overall structure of the titration curve caused the students the greatest amount of difficulty. Students had a difficult time transitioning (changing to a less-steep, relatively horizontal slope) prior to the half-equivalence point and then transitioning again (changing to a steep, negative slope) prior to reaching the provided equivalence point.
- The majority of students did not have a general sense of what a weak base/strong acid titration curve should look like.
  - Students started the curve by coming horizontally off the pH axis rather than at a steep, negative slope from the initial pH point, often due to a high pH that was miscalculated in part (d).
  - Students resorted to drawing strong acid/strong base curves with the half-equivalence point serving as the equivalence point.
  - Students presented exponential curves through the half-equivalence point.
  - A number of students ignored the initial pH “dot” and started the curve at various points on the y-axis, including the origin.
- Students oftentimes used the “X” and equivalence points to initiate the change in the slope of the curve, rather than have the change in slope occur before and extend beyond, those two points.

Part (f): [1 point]

- Other than the required change in slope through the half-equivalence point, the point in part (f) was the most difficult for students to earn. To earn this point, a student was required to correctly identify the species with the highest concentration at a pH of 3.37 and to justify their reasoning.
  - Some students who earned this point employed the Henderson-Hasselbalch equation to justify their answer.
  - Others referenced the half-equivalence point to justify their answer.
  - It was an approximately even split between these two approaches.
- Approximately 60-70 percent of students correctly chose sorbic acid as possessing the higher concentration, but many failed to justify their choice. For example,
  - Students based their justification on the solution being acidic ( $\text{pH} < 7$ ). Stating that acidic solutions have a higher concentration of the acid species.
  - Students were unable to link and compare the given pH to that of the half-equivalence pH reported in part (d).
  - Some students stated that adding a conjugate base will increase the acidic species through reactions with hydrogen or hydronium ions (Le Châtelier’s Principle).



- Students who chose the base reasoned that a base added to the solution causes an increase in the pH.
  - Those students who chose the base could still earn this point if their pH at the half-equivalence point from part (d) was lower than 3.37. In this case, a pH greater than the half-equivalence pH would have a larger concentration of the conjugate base than that of the acid.
  - Other students who chose the base incorrectly reasoned that the pH of 3.37 was higher than the equivalence point pH, giving a more basic solution.

**Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?**

- Encourage students to pay close attention to the entire question so that they are aware of all of the information provided in the stem of the question (e.g., “the equivalence point of the titration is measured to be 2.54,” “A student titrates 45.00 mL,” “The initial pH and equivalence point are plotted,” “Mark the position of the half-equivalence point on the curve.”).
- Avoid teaching “single-case” shortcuts that omit underlying chemical concepts. The  $M_a V_a = M_b V_b$  approach to solving for an unknown concentration only works for monoprotic titrations and prevents students from seeing another application of stoichiometry.
- Spend additional time differentiating the concepts of equivalence, half-equivalence, and endpoints.
- Contrast the significance of the  $pK_a$  of an indicator as it relates to the equivalence point vs. the significance of the  $pK_a$  of a weak acid as it relates to the half-equivalence point.
- While the Henderson-Hasselbalch equation is not explicitly included in the AP<sup>®</sup> curriculum, it is a useful tool for analyzing acid-base chemistry, buffering action, pH curves, etc. Note the significance of the  $pK_a$  of a weak acid in terms of the  $[A^-]/[HA]$  ratio and how the ratio causes the pH of the acid to fluctuate above and below the  $pK_a$ . Distinguish between the pH of the solution and the dominant species of a conjugate acid-base pair.
- Point out the unique differences in shapes (beyond noting the position of the equivalence point) among the four typical titration curves: strong acid/strong base, strong base/strong acid, weak acid/strong base, and weak base/strong acid. Point out the characteristics of titration curves at the beginning and end of titrations and, when applicable, the buffering regions.
- Have students practice drawing titration curves, kinetic graphs, reaction profiles, etc., by hand so that they can get a general sense of the shapes of plots and know how to accurately convey data graphically.
- Although there is no longer a “reactions question,” spend time having students write chemical reactions from words, predicting products, and writing net-ionic equations. Reactions are still embedded in many of the questions.
- When the word “calculate” is in the stem of question, regardless of how “simple” that calculation may be, encourage your students to show all work.
- Encourage your students to use a pencil.

## Question 4

**What was the intent of this question?**

Question 4 assessed students’ understanding of the solubility of an ionic solid. Students were asked to communicate this using various representations, including symbolic and particulate. In part (a) students wrote a balanced equation for the dissolution of  $\text{Ca}(\text{OH})_2(\text{s})$  in pure water. Part (b) assessed the students’

ability to determine the molar solubility of  $\text{Ca}(\text{OH})_2$  when a common ion is present in solution. In part (c) students drew a particulate representation of water molecules surrounding a calcium ion in solution.

### ***How well did students perform on this question?***

The mean student score was 1.41 out of a possible 4 points. Approximately 6 percent of the students earned all 4 points. Parts (a) and (c) were the most accessible to students, with many not even attempting to answer part (b). A point was most often earned in part (c) though many responses did not earn credit due to improperly oriented water molecules. The second most common point earned was for part (a). Unfortunately, minor errors such as incorrect/missing ionic charge and incorrect stoichiometry prevented many responses from earning credit. Many students were not able to earn the two points for part (b), determining the molar solubility of  $\text{Ca}(\text{OH})_2$  in the  $\text{Ca}(\text{NO}_3)_2$  solution. Of the students who attempted this section, errors in setting up the calculation (forgetting to include the common ion and stoichiometry errors) most often prevented students from earning full credit. Students who correctly set up the calculation but committed a math error received 1 of 2 points.

### ***What were common student errors or omissions?***

Part (a): [1 point]

Students generally did well on this part of the question.

Common errors or omissions included:

- Incorrect/missing charges on the ions;
- Incorrect stoichiometry;
- Adding charges to solid  $\text{Ca}(\text{OH})_2$ ;
- Chemical reaction between  $\text{Ca}(\text{OH})_2$  and  $\text{Ca}(\text{NO}_3)_2$  or between  $\text{Ca}(\text{OH})_2$  and  $\text{H}_2\text{O}$ ; and
- Including  $\text{H}_2\text{O}$  on the reactant side of the equation but not accounting for it on the product side.

Part (b): [2 points]

This was the only mathematical problem in this question. In order to earn credit students had to show their work. The incorrect use of significant figures was not penalized.

Common errors or omissions included:

- Forgetting one or more of the following in the setup:
  - $0.10\text{ M} [\text{Ca}^{2+}]$  (common ion)
  - To double the  $[\text{OH}^-]$  (stoichiometry)
  - To square the  $[\text{OH}^-]$  ( $K_{sp}$  expression)
- Assuming the  $0.10\text{ M}$  is the concentration of  $\text{Ca}(\text{OH})_2$  and using it in the denominator of the  $K_{sp}$  expression;
- Assuming the  $0.10\text{ M}$  is the  $[\text{Ca}^{2+}]$  from  $\text{Ca}(\text{OH})_2$  (instead of that from  $\text{Ca}(\text{NO}_3)_2$ ), doubling the concentration for  $[\text{OH}^-]$  and calculating the  $K_{sp}$ ;
- Confusing molar solubility and  $K_{sp}$ ;
- Setting the  $[\text{Ca}(\text{OH})_2]$  equal to 1;
- Correctly solving for  $[\text{OH}^-]$  but failing to divide by 2 to determine the molar solubility of  $\text{Ca}(\text{OH})_2$ ; and
- Multiplying the  $0.10\text{ M Ca}(\text{NO}_3)_2$  by the  $K_{sp}$ .

Part (c): [1 point]

This was the most accessible point on the question.

Common errors or omissions included:

- Confusing the positive and negative dipole so the H<sub>2</sub>O molecules are improperly oriented around the Ca<sup>2+</sup>;
- Labeling H<sub>2</sub>O as O<sub>2</sub>H;
- Orienting the water molecules so they are all pointing in the same direction (2 correct and 2 incorrect);
- Including “hydrogen bonding” without regard for the orientation of H<sub>2</sub>O surrounding the Ca<sup>2+</sup>;
- Not drawing enough H<sub>2</sub>O molecules in the diagram; and
- Drawing other species, such as Ca<sup>2+</sup>.

***Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?***

- Students should read questions carefully and follow directions.
- Students should understand how to write  $K_{sp}$  expressions, and know how to exclude solids and liquids.
- Teachers should stress the difference between a chemical reaction and a dissolution equation and practice writing both.
- Teachers should stress that students use ICE charts to help keep track of [Ca<sup>2+</sup>].
- Teachers should ask students to explain the difference between the molar solubility of a solid in water and the  $K_{sp}$  value.
- Students should have a conceptual understanding of ionic solid solubility rather than just memorizing how to solve a  $K_{sp}$  problem.
- Teachers should ask students to complete equilibrium problems where the stoichiometric relationship is a non 1:1 ratio.
- Teachers should ask students to practice equilibrium problems that involve a common ion.
- Students should practice drawing particulate diagrams.

## **Question 5**

***What was the intent of this question?***

This question assessed the students' understanding of the spectrophotometric determination of reaction order for a pseudo-decomposition reaction, one of the common AP<sup>®</sup> Chemistry laboratory exercises included in the College Board lab manual. In part (a) students were challenged to determine the order of the oxidation reaction of blue food coloring from graphically presented data of absorbance versus time, ln (absorbance) versus time, and 1/absorbance versus time. Part (b) assessed the students' understanding of the experimental methodology by requiring them to select an appropriate modification to a poor experimental setup. Finally, part (c) tested the students' grasp of spectrophotometry and the relationship between absorbance, color, and wavelength.

***How well did students perform on this question?***

The mean score on Question 5 was 2.36 out of 4 possible points. Approximately 25 percent of the students earned all 4 points.

### ***What were common student errors or omissions?***

Part (a):

Students demonstrated their understanding of the graphical presentation of kinetic data.

- Students generally performed well on part (a). Because the question required only a determination of reaction order, with no supporting justification, reasons for incorrect or omitted responses cannot be surmised.

Part (b):

Two points were available in part (b) — 1 point for identifying which of the proposed experimental modifications would increase the time required for the reaction to reach an absorbance near zero, and a second point for a satisfactory explanation.

- The most common student error/misconception is that the time to near-zero absorbance was increased due to a decrease in the reaction rate. Students confused the vocabulary of kinetics and rates (faster, more quickly) with the vocabulary that would naturally refer to the duration of time intervals (longer, later).
- A second, less common, misconception was students treating the reaction as an equilibrium system and attempting to apply Le Châtelier's principle. In these cases, students generally presumed that the reaction was exothermic and indicated that a temperature increase would shift the system to the left, increasing the time required to reach near-zero absorbance.
- Finally, many students used incorrect or misleading vocabulary in responding to this part of the question.
  - Many responses did not successfully discriminate between the concepts of duration and rate. Vocabulary associated with the duration of a process (i.e., "longer," "more time") and the rate of a reaction ("slower," "not as fast") was freely intermingled.
  - Responses also did not demonstrate a distinction between the chemical reaction associated with the bleaching process and the absorbance of light by the colored solution. Responses frequently referred to the "absorption of the dye by the bleach."

Part (c):

This point seemed a good discriminator of students' familiarity and understanding of the absorbance of light and the relationship between absorbance, wavelength, and color.

- It is likely that students who failed to earn credit on this part had little to no familiarity with the underlying principles of spectrophotometry.
- Because new probeware has, in many schools, replaced the traditional spectrophotometer, the procedure for setting wavelength seemed unfamiliar to many students.
- A small but significant fraction of student responses seemed to treat the red and blue colored dyes as pH indicators, referring to the color fading in response to changes in the acidity of the solution (due to the basicity of the  $\text{OCl}^-$  ion).

### ***Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?***

This question assessed both the theory of the kinetics of the pseudo-first-order decomposition reaction as illustrated by the integrated rate laws and the laboratory practice of spectrophotometry. Teachers should continue to emphasize the relation between theory and practice — not only can the laboratory exercises serve as a focal point to present concepts and material, but open-ended (inquiry) approaches to the laboratory exercises can allow students to formulate questions, troubleshoot problems, and make appropriate adjustments. In the case of this question, "quick and dirty" trials designed to find a combination of reactants that would give acceptable results (high initial absorbance, reasonable time to reach near-zero) would give students experience with the concepts of amount, concentration, and volume as well as the principles of

kinetics. Collecting, graphing, and analyzing the spectrophotometric data would reinforce the students' grasp of kinetics.

## Question 6

### ***What was the intent of this question?***

Question 6 was designed to test the students' ability to identify evidence that supports a student hypothesis and explain their reasoning. This question also tested knowledge of salt hydrolysis and representation of this phenomenon. In part (a) students were given a data table of four compounds with corresponding melting points and asked to select two compounds that support a given hypothesis and explain their choice. In part (b) students were to identify a compound from the table that would produce a basic solution and then write the net ionic equation.

### ***How well did students perform on this question?***

The mean score was 2.05 out of 4 possible points. Students generally attempted both parts of the question. Approximately 11 percent of the students earned all 4 points. The most commonly earned points were earned in part (a) for selecting two compounds that support the student hypothesis and in part (b) for identifying a compound that would produce a basic solution. The most commonly missed points were the explanation in part (a) and the net ionic equation in part (b).

### ***What were common student errors or omissions?***

Part (a):

- Stating that both LiI and KI have small cations and large anions.
- Stating that  $\text{Na}^+$  is larger than  $\text{F}^-$ .
- Selecting more than one pair of compounds with one appropriate pair and one inappropriate pair.
- Comparing the two iodide compounds with the two fluoride compounds and not making a clear comparison of anion size in both sets.
- Comparing the size of the cation to the size of the anion in a single compound or between compounds.
- Interpreting "small" and "large" as molar mass instead of ionic radius.
- Using electronegativity instead of ion size to support hypothesis.
- Using IMF terminology to explain differences in melting points.
- Using the hypothesis as the basis for their selection (e.g., since the melting point of LiI is smallest it must have a small cation and a large anion while NaF must be opposite since it has the highest melting point).
- Using vague terminology such as ions are "different sizes."
- Using a Coulomb's law argument instead of ion size to support hypothesis.
- Interchanging the terms atomic radius and ionic radius.
- Writing every chemistry fact about all of the ions in the salts and never answering the question asked.
- Stating that LiI and KI are covalently bonded since the melting points were low.

Part (b):

- Selecting one of the iodide salts.
- Concluding that none of the salts would produce basic solutions.
- Concluding that all of the salts would produce basic solutions.
- Omitting ion charges.
- Incorrect ion charges.
- Writing complete molecular balanced equations.
- Writing complete total ionic equations.
- Showing only the dissociation of the salt.
- Writing a net ionic equation for the formation of NaOH (or LiOH) from ions.
- Writing a net ionic equation for the dissociation of water.
- Writing an equation for a salt not in the data table.
- Writing an explanation in words instead of the asked net ionic equation.
- Writing HF (a weak acid) as  $\text{H}^+$  and  $\text{F}^-$ .
- Writing water on top of the reaction arrow instead of including it as a reactant.

***Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?***

- Students should read the question carefully and answer the question asked.
- Students should be given opportunities to write their own hypotheses using data sets.
- Provide opportunities for students to write statements of explanation using correct scientific vocabulary and reasoning, using evidence to support the claims, giving concise answers, and writing legibly.
- Encourage the use of specific vocabulary in the chemistry classroom. Students should use terms appropriately. Confused or misused terms include:
  - Anion
  - Cation
  - Molecule
  - Atom
  - Anode
  - Cathode
  - Ion
  - Large
  - Small
- Provide opportunities for students to write complete, balanced equations and net ionic equations throughout the year.
- Engage students by using particulate images of salts dissolving in water and encourage them to make predictions regarding the pH of the salt solution.
- Provide opportunities for students to evaluate each other's hypotheses and lab analyses.

### **Note to Students:**

- Learn to distinguish between strong and weak acids and how to represent each type in aqueous solution.
- Write charges on all ions. Do not write charges on compounds.
- Follow the written instructions to write the answer on the lined pages and do not write within the question unless instructed to do so.
- Answer the question legibly, precisely, and concisely. Do not give the reader options.

- Read over your answer and make sure that you answer the question asked before moving to the next question.

## Question 7

### ***What was the intent of this question?***

Students were required to use calorimetry to compare two methods of producing aluminum, either through recycling it from scrap metal or by extracting it from aluminum oxide. Part (a) asked for the amount of heat needed to bring aluminum from its solid state at 298 K to its liquid state at 933 K. Part (b) required students to determine whether the amount of energy required to recycle aluminum is more or less than that required to extract the metal from aluminum oxide. The reaction for obtaining aluminum from the oxide, together with its standard enthalpy of reaction, is given in the question. Part (a) required students to use the molar heat capacity, together with the temperature change, to determine the heat required for aluminum to reach the melting point. Afterwards, the heat of fusion must be added to the result to obtain the overall heat required to convert the aluminum to a liquid. Part (b) required students to convert the enthalpy of reaction (in  $\text{kJ/mol}_{\text{rxn}}$ ) to the enthalpy change per mole of aluminum. Then, the result must be compared to the student's answer from part (a) to conclude that less energy is used in recycling the aluminum.

### ***How well did students perform on this question?***

The mean score was 1.21 out of a possible 4 points. A significant number of students addressed at least one part of the question but earned no points, and the majority of students attempted both parts of the question. Approximately 10 percent of the students earned all 4 points.

### ***What were common student errors or omissions?***

General considerations:

1. Units
  - A large number of students did not use units, either in their calculations or with their answers. Other students did not use units in their calculations, but would randomly (and often incorrectly) assign a unit to the result.
  - Many students improperly converted values from joules to kilojoules (e.g., equating 15,000 J to 15,000,000 kJ, or 15 kJ to 0.015 J, etc.).
  - Some students also attempted to compare two values having incompatible units.
2. Temperature vs. heat
  - A significant number of students would calculate a temperature change and incorrectly equate this with some amount of heat. This demonstrates a persistent misunderstanding between the two ideas.
3. Thermicity
  - Students would regularly confuse the terms “endothermic” and “exothermic”; both processes cited in the question are clearly endothermic processes.

Specifically in part (a):

1. Students frequently conflated molar heat capacity with specific heat capacity.
  - Many attempted to use the mass of Al, rather than moles, in calculating the heat required to raise the aluminum temperature. This stems from an algorithmic use of the equation  $q = mc\Delta T$  without considering what the variables actually mean.
  - Other students were able to convert the molar heat capacity to specific heat capacity, perform the calculation using the mass of Al, and then convert the result to J/mol. While the process is ultimately correct, it illustrates a rigidity of thought on the part of the student,

who appears convinced that the heat must be determined using a mass and a specific heat capacity rather than working in terms of moles.

- Additionally, various students would use either the initial temperature or the final temperature, rather than the temperature change, in performing the calorimetric calculation.
2. Students did not understand the term “heat of fusion”; this led to the term being used in several incorrect ways, including:
    - Simply omitting the heat of fusion, which is required to convert Al from solid to liquid at 933 K.
    - Subtracting, rather than adding, the heat of fusion to the heat associated with the metal’s temperature rise.
    - Adding, or multiplying, the heat of fusion to the molar heat capacity, then using the result in calculating  $q$ .
    - Using only the heat of fusion, without realizing that the solid metal must first be brought to the melting point.

Specifically in part (b):

1. Students frequently did not realize that the heat calculated in part (a) was for 1 mol Al, while the  $\Delta H^\circ$  given for the aluminum extraction was given in  $\text{kJ/mol}_{\text{rxn}}$ , i.e.,  $\text{kJ}/2 \text{ mol Al}$ , was the heat required to extract two moles of Al. This resulted in an incorrect comparison between the two values.
  - In some cases, students would attempt to correct the  $\Delta H^\circ$  value by multiplying, rather than dividing, by the 2 mol Al.
  - An algorithmic version of Hess’ Law,  $\Delta H^\circ_{\text{rxn}} = \sum n\Delta H^\circ_f (\text{products}) - \sum n\Delta H^\circ_f (\text{reactants})$ , was often used in attempts to reconcile the enthalpy value given in part (b) with the result in part (a). This relationship has no applicability to the question because enthalpies of formation are not germane to the discussion.
2. Students would make a comparison between the energy of recycling and the energy of extraction, using a statement such as, “recycling the Al takes less energy than extracting it,” but would not cite the specific energy (enthalpy) values to be compared. Without a clear reference to both of the appropriate data points, an unambiguous comparison cannot be made. This was a frequent reason for not earning a point.
3. Students would often confuse enthalpy with entropy, Gibbs energy, or (in limited cases) the equilibrium constant. They would also incorrectly cite reaction spontaneity or Le Châtelier’s Principle in their arguments.

**Based on your experience of student responses at the AP<sup>®</sup> Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?**

- Errors in unit conversions and/or dimensional analysis are persistent problems; these should be reviewed frequently.
- There is a common practice among many students to prematurely round intermediate answers when performing a calculation.
- There is a tendency, in class activities and in homework questions, to focus calorimetry only on the relationship  $q = mc\Delta T$ , where  $m$  is the mass and  $c$  is the specific heat capacity. Problems that use molar heat capacity should also be introduced and practiced.
- Likewise, students may only encounter questions regarding enthalpy in the context of Hess’ Law, particularly only problems that utilize standard enthalpies of formation and the typical formula  $\Delta H^\circ_{\text{rxn}} = \sum n\Delta H^\circ_f (\text{products}) - \sum n\Delta H^\circ_f (\text{reactants})$ . Exposure to additional enthalpy applications is necessary.



- Students should understand the difference between the addition of heat that causes a temperature change vs. the addition of heat that causes a phase change. The difference between these two is often misunderstood or forgotten. Some students benefitted from sketching a heating curve for Al when answering this question.
- Since the concepts of heat and temperature are frequently confused, teachers should focus on helping students recognize the important differences between the two ideas. Similarly, frequent opportunities to review endothermic vs. exothermic processes, and their differences, are necessary.
- When making a comparison, it is important to explicitly indicate the two items being compared, and to make sure the items being compared are, in fact, comparable. For instance, the items must have the same units, and involve the same amount of substance, e.g., 1 mol, as applicable. Comparisons should be supported by all relevant data; students should never assume that the value(s) used for a comparison are known.