

**Teacher’s Guide**

**Science Solves the Mystery of an Ancient, Deadly Ritual**

***October 2021***

**Table of Contents**

[Anticipation Guide](#_Anticipation_Guide) 2

Activate students’ prior knowledge and engage them before they read the article.

[Reading Comprehension Questions](#_Student_Reading_Comprehension_1) 3

These questions are designed to help students read the article (and graphics) carefully. They can help the teacher assess how well students understand the content and help direct the need for follow-up discussions and/or activities. You’ll find the questions ordered in increasing difficulty.

[Graphic Organizer 6](#_Graphic_Organizer)

Thishelps students locate and analyze information from the article. Students should use their own words and not copy entire sentences from the article. Encourage the use of bullet points.

[Answers 7](#_Answers_to_Reading)

Access the answers to reading comprehension questions and a rubric to assess the graphic organizer.

[Additional Resources 12](#_Additional_Resources)

Here you will find additional labs, simulations, lessons, and project ideas that you can use with your students alongside this article.

[Chemistry Concepts, Standards, and Teaching Strategies 13](#_Chemistry_Concepts,_Standards,)

# Anticipation Guide

Name: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**Directions: *Before reading the article*,** in the first column, write “A” or “D,” indicating your **A**greement or **D**isagreement with each statement. Complete the activity in the box.

As you read, compare your opinions with information from the article. In the space under each statement, cite information from the article that supports or refutes your original ideas.

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. In 2013, birds flying near a cave in an ancient sunken arena were instantly killed. |
|  |  | 1. The gas emitted from the cave in the arena was analyzed using infrared radiation (IR). |
|  |  | 1. The air we breathe contains about 1% of CO2. |
|  |  | 1. The CO2 levels above the arena’s sanctuary floor varied with both the time of day and the height above the ground. |
|  |  | 1. Humans need O2 for respiration. |
|  |  | 1. Energy produced during respiration is stored in cells by ATP (adenosine triphosphate). |
|  |  | 1. CO2 kills through poisoning the victim. |
|  |  | 1. 3He is commonly found in Earth’s crust. |
|  |  | 1. CO2 is lighter than air. |
|  |  | 1. Scientists’ findings support the report of the geographer and philosopher Strabo from the first century B.C.E. |

# Student Reading Comprehension Questions

Name: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**Directions**: Use the article to answer the questions below.

**Read ONLY the first four paragraphs, then answer question 1.**

1. After reading or listening to the introduction to the story, develop one specific hypothesis that could potentially explain why the animals died, while the priests did not, when entering the portal in the Plutonium. Your hypothesis must include scientific reasoning to explain why the hypothesis is plausible.

**Read the remainder of the intro and the first 3 paragraphs of “*What Makes This Cave So Deadly?*”, then answer question 2.**

1. Imagine that you are at the Plutonium with Hardy Pfanz and colleagues. You are standing in the arena, looking at the location of the portal that leads to the cave that is soon to be unearthed. Describe one test that you would do to decide whether your hypothesis has merit or if you should develop a new hypothesis. Describe what you would do and how the findings would help you know whether to continue testing your initial hypothesis. You do not need to know the names of equipment or tests. Just describe what you want to do and what you want to find out.

**Read the remainder of the article while answering the following questions:**

1. Pfanz’s hypothesis is not stated, but the article describes the initial test. In the same way that you wrote your own hypothesis in question 1, write a hypothesis that Pfanz could have been attempting to test with the IR analyzer.
2. IR light and visible light can both be used to analyze gases. Absorption of one kind of light affects how the bonds vibrate and absorption of the other affects the energy states of electrons. The scientists used IR radiation to analyze the cave gases.
   1. Which range of light has higher energy photons, visible or infrared?
   2. Based on your answer to (a), were the scientists studying bond vibrations or electron energy levels for the gases in the cave?
   3. Draw Lewis structures for each of the three major gases found in the cave.
      1. Which molecule likely has the shortest bond length? Explain.
3. The three most abundant gases in the cave are the same three gases that are the most abundant in our atmosphere.
   1. In what way does the composition of these gases in the cave differ from the composition of the atmosphere outside of the cave?
   2. Why is the cave atmosphere deadly, when the same three gases are not deadly in our atmosphere?
   3. What is it about the carbon dioxide that makes it deadly in this case?

**Student Reading Comprehension Questions, cont.**

1. Consider the respiration equation shown.
   1. Summarize the process of ATP being hydrolyzed to ADP by writing a chemical equation that includes only molecular formulas, rather than structural formulas. (You can use “ATP” and “ADP”, rather than the full chemical formulas for these. Your final equation should contain 5 different species.
   2. Carefully note the changes in bonding when ATP reacts to form ADP. Write the steps as though you were using a model kit to model the reaction. Identify which bonds must be broken and formed to accurately represent the overall process using as few steps (with your model kit) as possible.
   3. Are there more bonds broken or more bonds formed?
   4. Explain how the above situation can lead to a release of energy when ATP hydrolyzes to ADP.
2. Carbon dioxide levels in the atmosphere are relatively consistent within a given region. How is it possible that levels vary with height inside the relatively small region inside the cave?
   1. What is the property of carbon dioxide that allows for this layered concentration effect?
3. Choose any relevant chemistry concept to describe a mechanism that accounts for the carbon dioxide levels in the cave differing from night to day.
4. Pfanz and the team used isotope ratios to confirm the assumed source of the extra carbon dioxide in the cave.
   1. Write the full isotope notation for each of the two stable isotopes of helium.
   2. Most of the helium-3 found in the earth has been present since Earth’s formation, but helium-3 can also be produced by the beta decay of tritium (hydrogen-3). Write the nuclear equation that defines this radioactive process.
   3. Using the periodic table, identify the atomic mass of helium. Explain, using this value, which of the two isotopes must be more abundant throughout the earth.
   4. Following is a data table of simulated data that may have been taken while studying the gases in the cave.

|  |  |  |
| --- | --- | --- |
| **Atmospheric Concentration of Gas:** | **Outside of Cave** | **Inside of Cave** |
| **CO2** | 410 ppm | 8.90 x 105 ppm |
| **4He** | 5.12 ppm | 4.98 ppm |
| **3He** | 7.01 x 10-6 ppm | 1.36 x 10-4 ppm |

Make a claim about the reason for the extra carbon dioxide inside the cave. Explain how this data can be used as evidence to support your claim.

**Student Reading Comprehension Questions, cont.**

**Questions for Further Learning**

***Write your answers on another piece of paper if needed.***

1. Research the “fire triangle” or “fire tetrahedron” and use it to explain how a CO2 fire extinguisher works.
2. A CO2 fire extinguisher is filled to a pressure of 825 psi.
   1. What is the value of this pressure in atmospheres?
   2. Consult a phase diagram to determine what state of matter the CO2 in the fire extinguisher is in while at room temperature. Explain your answer.
   3. Though a CO2 fire extinguisher can put out a grease fire, it is not recommended for this use because it can do more harm than good. Imagine standing in a kitchen where a grease fire has just arisen. Propose an explanation for why you should not use a CO2 fire extinguisher in this situation. Use the term “atmospheric pressure” in your answer.

# Graphic Organizer

Name: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**Directions**: As you read, complete the graphic organizer below to describe the sources and properties of carbon dioxide in the ancient arena.

|  |  |  |
| --- | --- | --- |
|  | **Broad answer** | **Details** |
| **Significance of location of the Plutonium arena** |  |  |
| **How analysis of gases inside the cave was done** |  |  |
| **How CO2 can kill** |  |  |
| **How source of CO2 was confirmed** |  |  |

**Summary:** On the back of this sheet, write a short email to a friend describing how science confirmed the mystery of the arena in Hierapolis.

# Answers to Reading Comprehension Questions & Graphic Organizer Rubric

1. **After reading or listening to the introduction to the story, develop one specific hypothesis that could potentially explain why the animals died, while the priests did not, when entering the portal in the Plutonium. Your hypothesis must include scientific reasoning to explain why the hypothesis is plausible.**

*Students should proposed possible explanations, with some kind of reasoning. Example: The vapors are deadly to animals, but not to people, because there are other examples of things that affect one species, but not another.*

1. **Imagine that you are at the Plutonium with Hardy Pfanz and colleagues. You are standing in the arena, looking at the location of the portal that leads to the cave that is soon to be unearthed. Describe one test that you would do to decide whether your hypothesis has merit or if you should develop a new hypothesis. Describe what you would do and how the findings would help you know whether to continue testing your initial hypothesis. You do not need to know the names of equipment or tests. Just describe what you want to do and what you want to find out.**

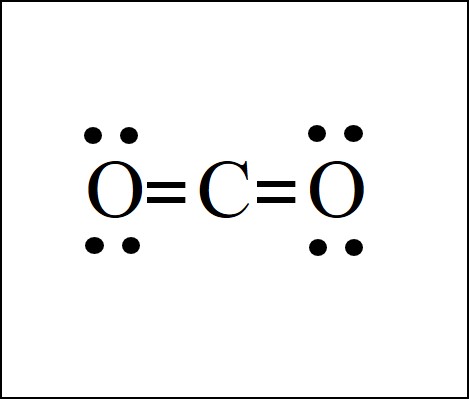
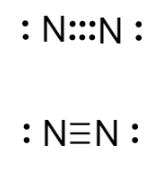
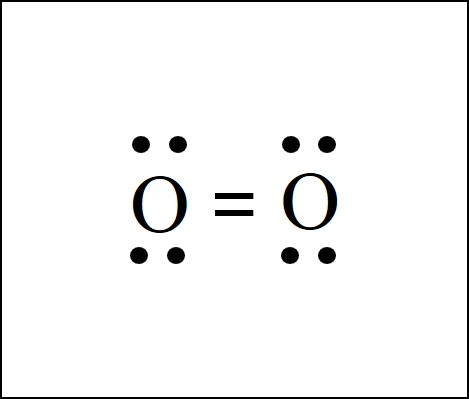
*Students should describe anything that is consistent with the hypothesis they made above. Example for the above hypothesis: Use a tube to go through the layer leading to the tunnel and collect a sample of the atmosphere in the cave. Then inject this sample into a controlled environment containing some kind of test animal to see if the animal lives or dies.*

1. **Pfanz’s hypothesis is not stated, but the article describes the initial test. In the same way that you wrote your own hypothesis in question 1, write a hypothesis that Pfanz could have been attempting to test with the IR analyzer.**

*Students should use information from the article to state this. Example: Carbon dioxide may be the gas that is killing the animals because other animals have been affected by carbon dioxide levels from volcano activity.*

1. **IR light and visible light can both be used to analyze gases. Absorption of one kind of light affects how the bonds vibrate and absorption of the other affects the energy states of electrons. The scientists used IR radiation to analyze the cave gases.**
   1. **Which range of light has higher energy photons, visible or infrared?** *Visible*
   2. **Based on your answer to (a), were the scientists studying bond vibrations or electron energy levels for the gases in the cave?** *Students need to consider that it would take more energy to change the energy level of an electron than it would to jiggle a bond, so the answer to (a) tells them that the IR radiation Phanz used is the lower of the two possibilities, thus concluding that the scientists used IR to study bond vibrations.*
   3. **Draw Lewis structures for each of the three major gases found in the cave.** 
      1. **Which molecule likely has the shortest bond length? Explain.**

*From the pie chart, the three gases are CO2, N2, and O2.*

*N2 would have the shortest bond length because it has the highest bond order (triple bond) and all of the involved elements are in the same period and thus similar enough in radius to make that distinction.*

1. **The three most abundant gases in the cave are the same three gases that are the most abundant in our atmosphere.** 
   1. **In what way does the composition of these gases in the cave differ from the composition of the atmosphere outside of the cave?**

*In the cave, the most significant difference is that the amount of carbon dioxide is significantly higher than the very small percentage found in our atmosphere.*

* 1. **Why is the cave atmosphere deadly, when the same three gases are not deadly in our atmosphere?**

*21% of our atmosphere is made of oxygen gas, while in the cave that number drops to 4%. This smaller amount does not allow our bodies to retrieve from the atmosphere the amount of oxygen we need to survive.*

* 1. **What is it about the carbon dioxide that makes it deadly in this case?**

*The higher amount of carbon dioxide basically replaces the needed oxygen for a body to survive. The high density of carbon dioxide means that its concentration on the ground is even higher than at higher levels where the air would be breathed in. This means that after losing consciousness, an animal (or person) would collapse to the ground and be further deprived of the oxygen.*

1. **Consider the respiration equation shown.** 
   1. **Summarize the process of ATP being hydrolyzed to ADP by writing a chemical equation that includes only molecular formulas, rather than structural formulas. (You can use “ATP” and “ADP”, rather than the full chemical formulas for these. Your final equation should contain 5 different species.**

*ATP + H2O 🡪 ADP + HPO42- + H+*

* 1. **Carefully note the changes in bonding when ATP reacts to form ADP. Write the steps as though you were using a model kit to model the reaction. Identify which bonds must be broken and formed to accurately represent the overall process using as few steps (with your model kit) as possible.**

*Students may interpret this in several ways. It does not need to be mechanistically accurate! Summary is: Break a P-O single bond in ATP to leave PO3 (don’t worry about charge), Break one H-O single bond in water, form a P-O bond between the OH from water and the P from the end phosphate that was broken off in the first step.*

* 1. **Are there more bonds broken or more bonds formed?**

*More bonds are broken than formed.*

* 1. **Explain how the above situation can lead to a release of energy when ATP hydrolyzes to ADP.**

*Most important is to understand that breaking bonds requires energy input and forming bonds releases energy. If more bonds are broken than formed, then for the process to release energy, the bond that is formed must be much stronger than the bonds that were broken.*

1. **Carbon dioxide levels in the atmosphere are relatively consistent within a given region. How is it possible that levels vary with height inside the relatively small region inside the cave?**

*Different temperatures and air movement can affect this, but the CO2 also is being released from the ground and the concentration there is higher than further up in height.*

* 1. **What is the property of carbon dioxide that allows for this layered concentration effect?**

*Carbon dioxide has a higher* ***density*** *than air, so in a still environment like the cave, the dense CO2 molecules can gather near the ground, pushing nitrogen and oxygen molecules up higher.*

1. **Choose any relevant chemistry concept to describe a mechanism that accounts for the carbon dioxide levels in the cave differing from night to day.**

*There are several options to explain this. The major one is that the higher temperatures in the daytime allow the CO2 molecules to spread apart more, thus decreasing the concentration in the air. Cooler temperatures have the opposite effect and, along with density, help explain high concentrations near ground level.*

1. **Pfanz and the team used isotope ratios to confirm the assumed source of the extra carbon dioxide in the cave.**
   1. **Write the full isotope notation for each of the two stable isotopes of helium.**
   2. **Most of the helium-3 found in the earth has been present since Earth’s formation, but helium-3 can also be produced by the beta decay of tritium (hydrogen-3). Write the nuclear equation that defines this radioactive process.**
   3. **Using the periodic table, identify the atomic mass of helium. Explain, using this value, which of the two isotopes must be more abundant throughout the earth.**

*The atomic mass of helium is 4.008 amu. Since this is a weighted average, there must be more helium-4 than helium-3 because the weighted average will be closer to the weight of the more abundant isotope.*

* 1. **Following is a data table of simulated data that may have been taken while studying the gases in the cave.**

|  |  |  |
| --- | --- | --- |
| **Atmospheric Concentration of Gas:** | **Outside of Cave** | **Inside of Cave** |
| **CO2** | 410 ppm | 8.90 x 105 ppm |
| **4He** | 5.12 ppm | 4.98 ppm |
| **3He** | 7.01 x 10-6 ppm | 1.36 x 10-4 ppm |

**Make a claim about the reason for the extra carbon dioxide inside the cave. Explain how this data can be used as evidence to support your claim.**

*Claim: The extra CO2 in the cave comes from deep in the earth and is released during the movement of tectonic plates.*

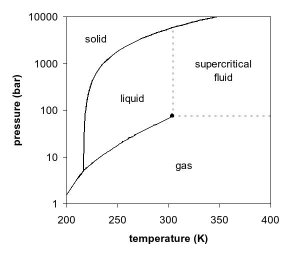
*Explanation: According to the data the ratio of 3He to 4He outside of the cave, which is assumed to be the natural ratio, is or 1.37 x 10-6 (this is unitless, as it is a ratio, expressed in decimal form). The ratio of 3He to 4He inside the cave is or 2.73 x 10-5. Since the ratio inside the cave is* ***higher*** *than the normal ratio, this indicates that extra helium-3 is somehow entering the cave. It is known that both helium isotopes can travel with CO2, and that helium-3 is found mostly in Earth’s mantle, while helium-4 is found mostly in Earth’s crust. The higher proportion of helium-3 is consistent with the hypothesis that the CO2 in the cave is originating in the mantle.*

1. **Research the “fire triangle” or “fire tetrahedron” and use it to explain how a CO2 fire extinguisher works.**

*The three points of the fire triangle are fuel (some kind of combustible material), oxygen (enough to sustain the combustion reaction), and a source of heat (enough to raise the temperature of the material to its ignition point, which is specific to each substance). All three must be present for a fire to occur. Carbon dioxide works by displacing the oxygen near the fire in hopes of decreasing it enough that it can no longer sustain combustion, thus removing one point of the triangle. (It will also come out of the hose at a very low temperature, which will assist in decreasing another point of the triangle, heat.)*

1. **A CO2 fire extinguisher is filled to a pressure of 825 psi.** 
   1. **What is the value of this pressure in atmospheres?**
   2. **Consult a phase diagram to determine what state of matter the CO2 in the fire extinguisher is in while at room temperature. Explain your answer.**

*The triple point is -57oC (216K) and 5.1 atm; The critical point is 31oC (304K) and 73 atm.*

**

*If the pressure in the fire extinguisher is 56.1 atm (~57 bar on shown graph), it is between the triple point pressure and the critical point pressure.*

*If the temperature is “room temperature”, it is approximately 293 K and this is between the triple point temperature and the critical point temperature.*

*This means it falls somewhere in the liquid or gas state on the chart. It is very close to being directly on the line between liquid and gas. You may not be able to find a phase diagram that is precise enough to make this distinction, but it would definitely be in gas form once the extinguisher is used and the pressure decreases even just a little.*

**Image Source: Wikimedia Commons**

* 1. **Though a CO2 fire extinguisher can put out a grease fire, it is not recommended for this use because it can do more harm than good. Imagine standing in a kitchen where a grease fire has just arisen. Propose an explanation for why you should not use a CO2 fire extinguisher in this situation. Use the term “atmospheric pressure” in your answer.**

*The very high pressure in a CO2 fire extinguisher (56.1 times the normal atmospheric pressure) means that the extinguishing material will shoot out of the hose extremely fast and with a lot of force. This force would hit the grease that is on fire and likely scatter it. Since grease is sticky, this scattered grease will stick wherever it lands, thus spreading the one fire into many small fires that can land on flammable things like curtains and paper towels.*

**Graphic Organizer Rubric**

If you use the Graphic Organizer to evaluate student performance, you may want to develop a grading rubric such as the one below.

|  |  |  |
| --- | --- | --- |
| **Score** | **Description** | **Evidence** |
| 4 | Excellent | Complete; details provided; demonstrates deep understanding. |
| 3 | Good | Complete; few details provided; demonstrates some understanding. |
| 2 | Fair | Incomplete; few details provided; some misconceptions evident. |
| 1 | Poor | Very incomplete; no details provided; many misconceptions evident. |
| 0 | Not acceptable | So incomplete that no judgment can be made about student understanding |

# Additional Resources

**Labs and demos**

* PhET Simulated Lab Molecules and Light <https://phet.colorado.edu/sims/html/molecules-and-light/latest/molecules-and-light_en.html>

**Simulations**

* Density (how changing variables affects density) <https://teachchemistry.org/classroom-resources/the-density-simulation>
* What is Temperature? <https://teachchemistry.org/classroom-resources/what-is-temperature>

**Lessons and lesson plans**

* ACS Landmark Lesson Plans: Radiocarbon Dating and Willard Libby <https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/lesson-plans/radiocarbon-dating-willard-libby-lesson.html>
* ACS Landmark Lesson Plans: Mars Exploration with Infrared Spectrometers <https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/lesson-plans/mars-exploration-infrared-spectrometers-lesson.html>
* AACT Lesson: Finding CO2 Mass in your Breath <https://teachchemistry.org/classroom-resources/finding-co2-mass-in-your-breath>

# Chemistry Concepts, Standards, and Teaching Strategies

**Connections to Chemistry Concepts**

The following chemistry concepts are highlighted in this article:

* Physical properties
* Identifying an unknown
* Gases
* Radioactive isotopes

**Correlations to Next Generation Science Standards**

This article can be used to achieve the following performance expectations of NGSS:

|  |
| --- |
| **HS-LS1-7.**  Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed, resulting in a net transfer of energy.  **HS-ESS2-3.** Develop a model based on evidence of Earth’s interior to describe the cycling of matter by thermal convection. |

**Disciplinary Core Ideas:**

* LS1.C: Organization for matter and Energy Flow in Organisms
* ESS2.3: Plate Tectonics and Large-Scale System Interactions

**Crosscutting Concepts:**

* Cause and effect
* Energy and matter
* Stability and change

**Science and Engineering Practices:**

* Analyzing and interpreting data
* Engaging in argument from evidence

**Nature of Science:**

* Scientific knowledge is based on empirical evidence.

See how *ChemMatters* correlates to the[**Common Core State Standards** online](https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/teachers-guide.html).

**Teaching Strategies**

Consider the following tips and strategies for incorporating this article into your classroom:

* **Alternative to Anticipation Guide:** Before reading, ask students what they know about carbon dioxide, and where it is found on or near Earth. Their initial ideas can be collected electronically via Jamboard, Padlet, or similar technology.
  + As they read, students can find information to confirm or refute their original ideas.
  + After they read, ask students what they learned about carbon dioxide.
* After students have read and discussed the article, consider showing the ACS Reactions Video “UNTOLD: The Invisible Tsunami that Killed 1500 People in One Night” (11:28) at <https://youtu.be/rNKDx3kR3tk>.The video describes how carbon dioxide gas suddenly released from Lake Nyos in Cameroon killed 1500 people in 1986.