MATH AND SCIENCE @ WORK

AP* CHEMISTRY Educator Edition

CRYOGENIC STORAGE

Note: This problem is related to the chemistry problem *Fuel Cell Generation* in the Math and Science @ Work series.

Instructional Objectives

Students will

- find the volume of gases using the Ideal Gas Law; and
- create and interpret a phase diagram to explain a real world problem.

Degree of Difficulty

This problem requires students to integrate several aspects of the AP Chemistry curriculum to obtain the solution.

- For the average AP Chemistry student the problem may be moderately difficult.

Class Time Required

This problem requires 35-50 minutes.

- Introduction: 5-10 minutes

  To show students how a space shuttle fuel cell uses hydrogen and oxygen to produce energy and water you may want to play the animation provided for download with this problem (FuelCell.mov).
- Student Work Time: 20-25 minutes
- Post Discussion: 10-15 minutes

Background

This problem is part of a series of problems that apply Math and Science @ Work in NASA's Space Shuttle Mission Control Center.

Since its conception in 1981, NASA has used the space shuttle for human transport, the construction of the International Space Station (ISS), and to research the effects of space on the human body. One of the keys to the success of the Space Shuttle Program is the Space Shuttle Mission Control Center (MCC). The Space Shuttle MCC at NASA Johnson Space Center uses some of the most sophisticated technology and communication equipment in the world to monitor and control the space shuttle flights.

Grade Level
11-12

Key Topic
Gas Laws

Degree of Difficulty
Moderate

Teacher Prep Time
5-10 minutes

Class Time Required
35-50 minutes

Technology
Calculator, computer with projector and movie player

AP Course Topics
States of Matter:
- Gases
- Liquids and Solids

Reactions:
- Stoichiometry

NSES
Science Standards
- Unifying Concepts and Processes
- Physical Science
- Science in Personal and Social Perspectives
- History and Nature of Science

Within the Space Shuttle MCC, teams of highly qualified engineers, scientists, doctors, and technicians, known as flight controllers, monitor the systems and activities aboard the space shuttle. They work together as a powerful team, spending many hours performing critical simulations as they prepare to support preflight, ascent, flight, and reentry of the space shuttle and the crew. The flight controllers provide the knowledge and expertise needed to support normal operations and any unexpected events.

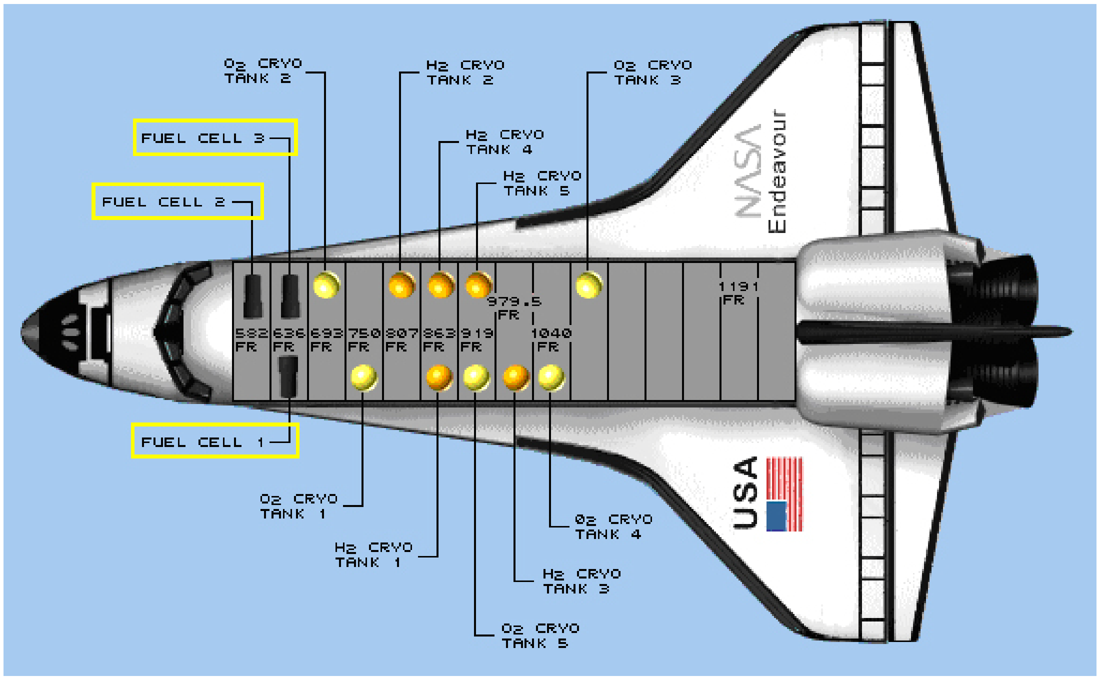


Figure 1: Typical space shuttle cryogenic tank layout

One of the flight controllers in the Space Shuttle MCC is the Electrical Generation and Illumination (EGIL) engineer. The space shuttle requires carefully metered power for operation during missions, and it is EGIL's responsibility to monitor the electrical systems, fuel cells, and associated cryogenics on the vehicle. Electricity is generated using three onboard hydrogen-oxygen fuel cells. A fuel cell is a device that combines externally stored reactants (a fuel and an oxidizer) to produce electricity and byproducts. Hydrogen (the fuel) and oxygen (the oxidizer) are stored in liquid cryogenic storage tanks located in the mid-body of the space shuttle. Custom built software is used in both preflight planning and real-time predictions for the management of these storage tanks which require constant monitoring.

AP Course Topics

States of Matter

- Gases
  - Laws of ideal gases
    - equations of state for an ideal gas
- Liquids and solids
  - Liquids and solids from the kinetic-molecular viewpoint
  - Phase diagrams of one-component systems
  - Changes of state, including critical points and triple points

Reactions

- Stoichiometry
  - Mass and volume relations with emphasis on the mole concept, including empirical formulas and limiting reactants

NSES Science Standards

Unifying Concepts and Processes

- Evidence, models, and explanation
- Change, constancy, and measurement

Physical Science

- Structure and properties of matter

Science in Personal and Social Perspectives

- Science and technology in local, national, and global challenges

History and Nature of Science

- Science as a human endeavor

Problem and Solution Key (One Approach)

The cryogenic storage tanks that contain the reactants (hydrogen and oxygen) are thermally insulated, double-walled spheres. The reactants are stored in a liquid state and at minimum pressures. Table 1 lists more detailed information on the cryogenic storage tanks. Use the information in Table 1 to answer the following questions.

Table 1: Cryogenic Tank Summary

Tank	**Liquid Hydrogen (H_2)**	**Liquid Oxygen (O_2)**
Number of Tanks	5	5
Total volume of all Tanks	3028.59 Liters	1591.4 Liters
Storage Temperature	-250° C	-183.3° C
Density	0.0678 kg/L	1.141 kg/L

A. Calculate the total number of moles of each of the following:

I. H_2

$$n = 3028.59\,\text{L}\,\text{H}_2 \cdot \frac{0.0678\,\text{kg}}{1\text{L}} \cdot \frac{1000\,\text{g}}{1\text{kg}} \cdot \frac{1\,\text{mol}\,\text{H}_2}{2\,\text{g}}$$

$$n = 103{,}000\,\text{mol}\,\text{H}_2$$

or

$$d = \frac{m}{v}$$
$$m = d \cdot v$$
$$m = \left(0.0678\ \tfrac{\text{kg}}{\text{L}}\right)\left(3028.59\ \text{L}\right)$$
$$m = 205\ \text{kg}\ \text{ or }\ 205{,}000\ \text{g}$$
$$n = 205{,}000\ \text{g H}_2 \cdot \frac{1\ \text{mol H}_2}{2\ \text{g}} = 103{,}000\ \text{mol H}_2$$

II. O_2

$$n = 1591.4\ \text{L O}_2 \cdot \frac{1.141\,\text{kg}}{1\text{L}} \cdot \frac{1000\ \text{g}}{1\text{kg}} \cdot \frac{1\text{mol O}_2}{32\ \text{g}}$$
$$n = 56{,}740\ \text{mol O}_2$$

or

$$d = \frac{m}{v}$$
$$m = d \cdot v$$
$$m = \left(1.141\ \tfrac{\text{kg}}{\text{L}}\right)\left(1591.4\ \text{L}\right)$$
$$m = 1816\ \text{kg}\ \text{ or }\ 1{,}816{,}000\ \text{g}$$
$$n = 1{,}816{,}000\ \text{g O}_2 \cdot \frac{1\ \text{mol H}_2}{32\ \text{g}} = 56{,}750\ \text{mol O}_2$$

B. Suppose that the oxygen and hydrogen were stored as gases on the space shuttle at Standard Temperature and Pressure (STP).

I. Find the combined tank volume that would be required to store the hydrogen?

Use the Ideal Gas Law: $PV = nRT$ to find the volume of hydrogen.

STP gives the temperature, T = 273 K and the pressure, P = 1 atm. The gas constant, R, is $0.0821\ \text{L} \cdot \text{atm} / \text{mol} \cdot \text{K}$ and n is the number of moles.

$$V = \frac{nRT}{P}$$
$$V = \frac{(103{,}000\ \text{mol H}_2)(0.0821\,\text{L} \cdot \tfrac{\text{atm}}{\text{mol}} \cdot \text{K})(273\ \text{K})}{1\ \text{atm}}$$
$$V = 2{,}310{,}000\ \text{L or } 2.31 \times 10^6\ \text{L of hydrogen}$$

or

$$V = 103{,}000 \text{ mol } H_2 \cdot \frac{22.4 \text{ L } H_2}{1 \text{ mol } H_2}$$
$$V = 2{,}310{,}000 \text{ L of hydrogen}$$

II. Find the combined tank volume that would be required to store the oxygen?

The volume of oxygen is found in a similar manner as hydrogen.

$$V = \frac{nRT}{P}$$
$$V = \frac{(56{,}740 \text{ mol } O_2)(0.0821 \text{ L} \cdot \frac{\text{atm}}{\text{mol}} \cdot \text{K})(273 \text{ K})}{1 \text{ atm}}$$
$$V = 1{,}270{,}000 \text{ L or } 1.27 \times 10^6 \text{ L of oxygen}$$

or

$$V = 56{,}740 \text{ mol } O_2 \cdot \frac{22.4 \text{ L } O_2}{1 \text{ mol } O_2}$$
$$V = 1{,}270{,}000 \text{ L of oxygen}$$

III. Explain the advantage for the space shuttle to store the reactants as liquids rather than gases.

Storing the reactants as liquids minimizes the volume required to store them. This allows for more room to store other necessary items on the space shuttle.

The two reactants are maintained in the cryogenic storage tanks at minimum pressures of 12.8 atm for hydrogen, and 49.8 atm for oxygen. The tanks provide a flow of reactant through manifolds to the fuel cells. A minimum pressure is required in the tanks to keep the hydrogen and oxygen supercritical (at a temperature and pressure above its critical point). This prevents local pockets of gas from forming which, under the correct circumstances, could damage tank hardware.

C. Use the data provided in Table 2 to complete the following.

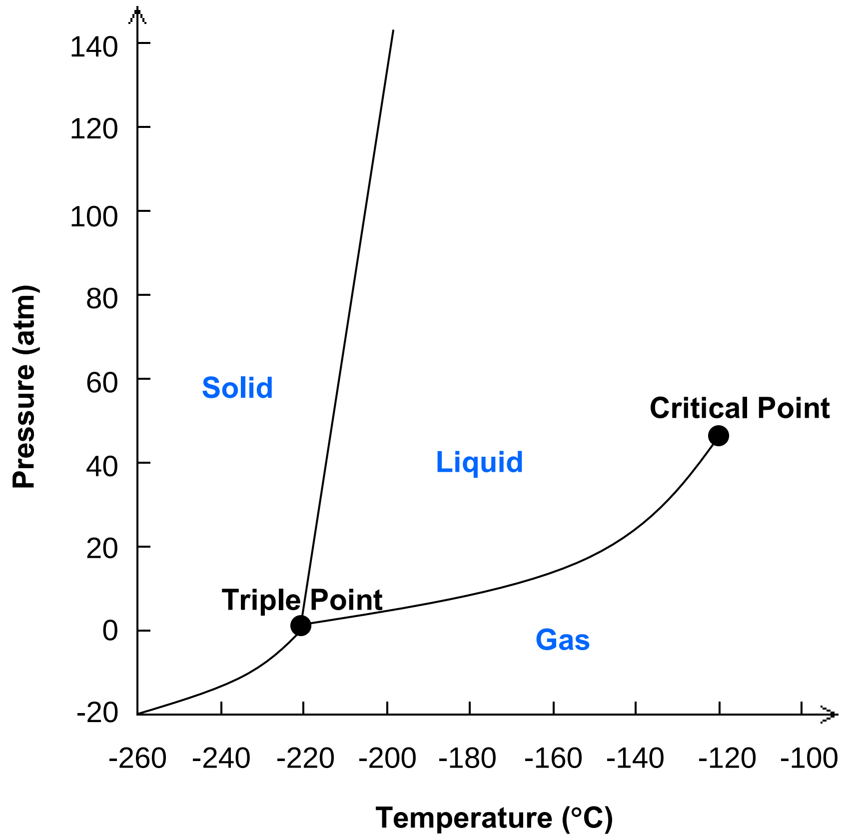
Table 2: Temperature and Pressures for H_2 and O_2

	Normal melting point	**Normal boiling point**	**Triple point**	**Critical point**
H_2	-259° C	-253° C	-259° C and 0.0695 atm	-240° C and 12.8 atm
O_2	-219° C	-183° C	-219°C and 1.14 torr	-119° C and 49.8 atm

I. Sketch a phase diagram for O_2.

Phase diagrams will vary but should be similar to the one shown here with the phase boundary line between solid and liquid having a positive slope.

Phase Diagram of Oxygen



II. Based on the phase diagram, explain which would be more dense, solid O_2 or liquid O_2?

Since the slope of the solid-liquid phase boundary is positive the solid would be more dense than the liquid.

III. Explain how storing the reactants at minimum tank pressures and below critical temperatures allow conversion from liquid to gas without forming a large volume of gas within the manifold or tanks.

Gas cannot be liquefied above the critical temperature. The critical pressure is the pressure required to produce liquefaction at the critical temperature. Both together are the critical point. Liquid and gas phases are indistinguishable at this point and occupy a uniform volume. This keeps the gas from building up and damaging the manifold.

Scoring Guide

Suggested 8 points total to be given.

Question		Distribution of points
A	*2 points*	1 point for determining mols of H_2 1 point for determining mols of O_2
B	*3 points*	1 point for finding volume of H_2 1 point for finding volume of O_2 1 point for identifying the room saved because of
C	*3 points*	1 point for a correct phase diagram 1 point for identifying a solid-liquid line with a positive slope resulting in the solid being more dense 1 point for identifying that at the critical point the liquid and gas phases are indistinguishable and occupy a uniform volume

Contributors

This problem was developed by the Human Research Program Education and Outreach (HRPEO) team with the help of NASA subject matter experts and high school AP Chemistry instructors.

NASA Experts

Chris Mundy and Mel Friant – EGIL Flight Controllers, NASA Johnson Space Center

Joseph R. Trevathan – Chief Design and Development Branch, Engineering Directorate, NASA Johnson Space Center

AP Chemistry Instructors

Teresa St John – Clear Springs High School, Clear Creek Independent School District, TX

Tonya York – Manvel High School, Alvin Independent School District, TX

Dick Castle – Pine Creek High School, Academy District 20, CO