MATH AND SCIENCE @ WORK

AP* CHEMISTRY Educator Edition

FUEL CELL GENERATION

Note: This problem is related to the chemistry problem *Cryogenic Storage* in the Math and Science @ Work series.

Instructional Objectives

Students will

- find mass and molar ratios of reactants through stoichiometry; and
- use half reactions to determine standard cell potential.

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 40-55 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: 25-30 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
Stoichiometry
Electrochemistry

Degree of Difficulty
Moderate

Teacher Prep Time
5 -10 minutes

Class Time Required
40-55 minutes

Technology
Calculator, computer with projector and movie player (optional)

AP Course Topics

Reactions:
- Reaction Types
- Stoichiometry
- Thermodynamics

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.

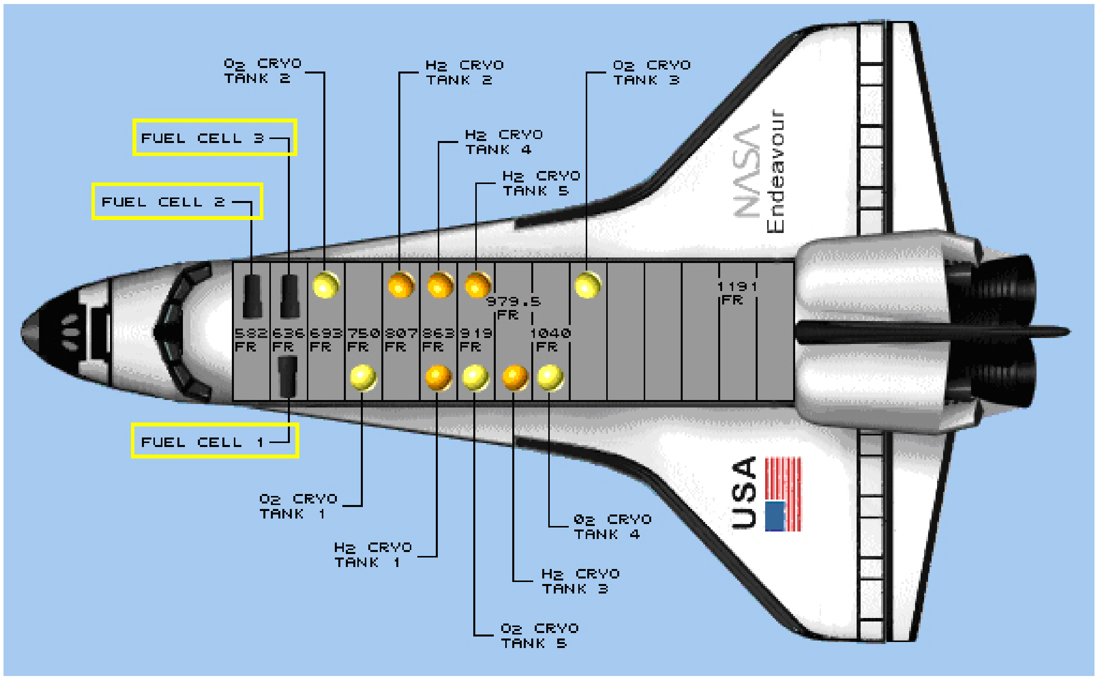

Figure 1: Typical space shuttle cryogenic tank layout

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

Reactions

- Reaction types
  - Oxidation-reduction reactions
    - Oxidation number
    - The role of the electron in oxidation-reduction
    - Electrochemistry: standard half-cell potentials
- Stoichiometry
  - Mass and volume relations with emphasis on the mole concept, including empirical formulas and limiting reactants
- Thermodynamics
  - First law: heat of formation

NSES Science Standards

Unifying Concepts and Processes
- Evidence, models, and explanation
- Change, constancy, and measurement

Physical Science
- Chemical reactions

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 fuel cells operate when a series of heaters within the cryogenic storage tanks are actuated to provide pressure above the minimum tank pressure. The pressurized reactants flow through a manifold and into a dual-gas regulator that maintains a specific flow of gas to the fuel cells. During normal operations on the space shuttle, 0.544 kg of hydrogen is used per hour and 4.58 kg of oxygen is used per hour. Some of the oxygen is used in the space shuttle cabin for breathing. The standard heat of formation of water is -242 kJ per mole.

Equation: $2H_2 + O_2 \rightarrow 2H_2O$

A. Use the above information to determine, quantitatively, which reactant is the limiting reagent.

$$0.544\ \text{kg}\ H_2 \cdot \frac{1000\ \text{g}\ H_2}{1\text{kg}\ H_2} \cdot \frac{1\text{mol}\ H_2}{2\ \text{g}\ H_2} = 272\ \text{mol}\ H_2$$

$$4.58\ \text{kg}\ O_2 \cdot \frac{1000\ \text{g}\ O_2}{1\text{kg}\ O_2} \cdot \frac{1\text{mol}\ O_2}{32\ \text{g}\ O_2} = 143\ \text{mol}\ O_2$$

$$272\ \text{mol}\ H_2 \cdot \frac{1\text{mol}\ O_2}{2\ \text{mol}\ H_2} = 136\ \text{mol}\ O_2$$

Hydrogen is the limiting reagent.

B. Assuming a 12 day mission, what is the total amount of energy in joules generated by the fuel cells?

Stoichiometry is used to find the number of moles of H_2O.

$$12\ \text{days} \cdot \frac{24\ \text{hours}}{1\ \text{day}} \cdot \frac{0.544\ \text{kg}\ H_2}{1\ \text{hour}} \cdot \frac{1000\ \text{g}}{1\ \text{kg}} \cdot \frac{1\ \text{mol}\ H_2}{2\ \text{g}\ H_2} \cdot \frac{2\ \text{mol}\ H_2O}{2\ \text{mol}\ H_2} = 78300\ \text{mol}\ H_2O$$

$$78300 \text{ mol } H_2O \cdot \frac{-242 \text{ kJ}}{1 \text{ mol } H_2O} = -18900000 \text{ kJ} \text{ or } -1.89 \times 10^{10} \text{ joules}$$

C. What is the total mass of water produced on the space shuttle which must be used by the astronauts, stored, or dumped into space?

$$78300 \text{ mol } H_2O \cdot \frac{18 \text{ g } H_2O}{1 \text{ mol}} = 1410000 \text{ g} \text{ or } 1.41 \times 10^{6} \text{ g } H_2O \text{ used, stored, or dumped.}$$

D. Energy is generated on the space shuttle in three fuel cells that use a chemical reaction between hydrogen and oxygen in a potassium hydroxide electrolyte.

Half-Reactions	**Standard Reduction Potential, *E*°**
$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	+0.40 V
$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	-0.83 V

I. Write the half reactions for the anode and the cathode.

Anode: $2(2H_2O + 2e^- \rightarrow H_2 + 2OH^-)$

Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

(Flip and change sign of the anode equation) + 0.83

II. Write the net equation for the galvanic cell.

$$2H_2 + O_2 \rightarrow 2H_2O$$

E. Calculate the standard cell potential ($E°_{cell}$).

$$E°_{cell} = 0.40 \text{ V} + 0.83 \text{ V}$$
$$E°_{cell} = +1.23 \text{ V}$$

F. Determine the standard free energy change, ΔG^o_{rxn} at 298 K.

Equation: $\Delta G°_{rxn} = -nFE°$

$$\Delta G°_{rxn} = -(4 \text{ mol } e^-)(96{,}485 \ \tfrac{\text{J}}{\text{V-mol e}^-})(+1.23 \text{ V}) = -475{,}000 \text{ J} \text{ or } -475 \text{ kJ}$$

Scoring Guide

Suggested 10 points total to be given.

Question		Distribution of points
A	*2 points*	1 point for determining correct mols of oxygen and hydrogen 1 point for determining hydrogen is the limiting reagent
B	*2 points*	1 point for correct stoichiometry to determine mols of H_2O 1 point for determining total energy consumed
C	*1 point*	1 point for determining total mass of water used, stored, or dumped
D	*3 points*	1 point for the correct half-reaction equation for the anode 1 point for the correct half-reaction equation for the cathode 1 point for the correct net reaction
E	*1 point*	1 point for correct standard cell potential
F	*1 point*	1 point for calculating free energy

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.

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