MATH AND SCIENCE @ WORK

AP* CHEMISTRY Educator Edition

SPACE SHUTTLE PROPULSION SYSTEM

Instructional Objectives

Students will

- identify the geometric structure, hybridization, and bonding of molecules; and
- evaluate the characteristics of reactions to determine their behavior.

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 45-60 minutes.

- Introduction: 5-10 minutes
- Student Work Time: 20-25 minutes
- Post Discussion: 20-25 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.

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 re-entry of the space shuttle

Grade Level
11-12

Key Topic
Thermodynamics, Molecular Structure and Bonding

Degree of Difficulty
Moderate

Teacher Prep Time
30 minutes

Class Time Required
45-60 minutes

Technology
Calculator

AP Course Topics

Structure of Matter:
- Chemical Bonding

Reactions:
- Thermodynamics

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

and the crew. The flight controllers provide the knowledge and expertise needed to support normal operations and any unexpected events.

One of the flight controllers in the Space Shuttle MCC is the Propulsion (PROP) Officer. The PROP position requires knowledge of fluid mechanics and extensive training in propulsion systems. This flight controller monitors two propulsion systems, the Orbital Maneuvering System (OMS) and the Reaction Control System (RCS). Both systems use propellants to produce the thrust for the orbiter of the space shuttle.

Figure 1: Technicians at Kennedy Space Center don Self-Contained Atmospheric Protective Ensemble (SCAPE) suits. These special suits are used by employees involved in hazardous chemical operations including the task of loading the propellant for the space shuttle.

Propellant is a general term for either of the two part chemical constituents (fuel or oxidizer) that is required to support the combustion process and deliver thrust in a rocket engine. The orbiter's OMS and RCS fuel is monomethyl hydrazine (CH_3NHNH_2), and the oxidizer is dinitrogen tetroxide (N_2O_4). This particular propellant combination is extremely reactive and spontaneously ignites on contact (hypergolic) with each other. This chemical reaction ($4CH_3NHNH_2 + 5N_2O_4 \rightarrow 9N_2 + 4CO_2 + 12H_2O$) occurs within the engine's combustion chamber. The reaction products are then expanded and accelerated in the engine bell to provide thrust. Due to their hypergolic characteristics these two chemicals are easily started and restarted without an ignition source, which make them ideal for spacecraft maneuvering systems.

Over a two day period, workers at the Kennedy Space Center load the fuel and oxidizer into the space shuttle while it sits on the launch pad. They must use extreme safety precautions when loading these propellants into the Orbiter OMS and RCS. When the space shuttle lifts off it is carrying more than 1200 kg of monomethyl hydrazine and 2000 kg of dinitrogen tetroxide.

When monitoring the propellant associated with the OMS and RCS systems, the PROP Officer looks for any conditions that are giving values that are different than expected (off nominal). Leak detection software, and fault detection and annunciation software will alarm if there are any leaks or if any parameters are out of specified limits. The PROP officer uses predetermined procedures, flight rules, and other certified documentation to determine the cause of a problem and to know what actions to take. Communication with other flight controllers is also crucial when resolving any problems that arise.

AP Course Topics

Structure of Matter

- Chemical Bonding
  - Molecular models
    - Valence bond: hybridization of orbitals
    - Geometry of molecules and ions

Reactions

- Thermodynamics
  - First Law: heat of formation

NSES Science Standards

Unifying Concepts and Processes

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

Physical Science

- Structure and properties of matter
- Chemical reactions
- Conservation of energy and increase in disorder
- Interaction of energy and matter

Science in Personal and Social Perspectives

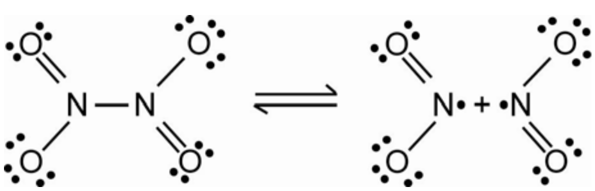
- Science and technology in local, national, and global challenges

History and Nature of Science

- Science as a human endeavor

Problem

The monomethyl hydrazine decomposes into a methyl group and nitrogen. Dinitrogen tetroxide decomposes to form an equilibrium mixture with nitrogen dioxide according to the reaction equation illustrated below.



A. Use the illustrated reaction equation to answer the following:

I. Identify the molecular geometry of N_2O_4.

II. Identify the hybridization of the N atoms in N_2O_4.

III. How many sigma bonds and pi bonds are in N_2O_4?

B. Predict the sign of $\Delta H°$ for the reaction. Justify your answer.

C. Predict the sign of $\Delta S°$ for the reaction. Justify your answer.

D. Sketch a graph that represents the relationship between $\Delta G°$ and temperature for the reaction given above and explain the graph in terms of the relationship $\Delta G° = \Delta H° - T\Delta S°$. Assume that $\Delta H°$ and $\Delta S°$ are independent of temperature.

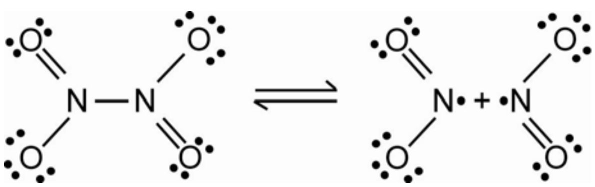
E. The reaction mixture of N_2O_4 and NO_2 is an equilibrium mixture. If heat is added to the mixture at constant pressure explain why the concentration of N_2O_4 decreases.

F. The value of K_{eq} at 25°C is 5.0×10^{-3}. If the temperature is raised to 150°C will the K_{eq} be greater than, less than, or equal to this value?

G. Discuss any potential environmental effects that N_2O_4 and NO_2 could pose if released from the space shuttle into the atmosphere. Justify your answer.

Solution Key (One Approach)

The monomethyl hydrazine decomposes into a methyl group and nitrogen. Dinitrogen tetroxide decomposes to form an equilibrium mixture with nitrogen dioxide according to the reaction equation illustrated below.



A. Use the illustrated reaction equation to answer the following:

I. Identify the molecular geometry of N_2O_4.

The molecular geometry is trigonal planar.

II. Identify the hybridization of the N atoms in N_2O_4.

The hybridization is sp^2 which is characteristic of trigonal planar geometry.

III. How many sigma bonds and pi bonds are in N_2O_4?

There is one sigma bond between N and N, two sigma bonds between N and O and there are two pi bonds between N and O.

B. Predict the sign of $\Delta H°$ for the reaction. Justify your answer.

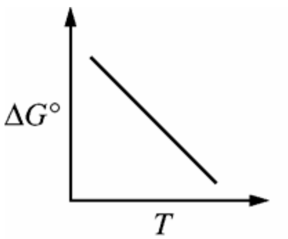
$\Delta H° = \sum$ enthalpies for bonds broken – $\sum$ enthalpies for bonds formed. Since only the N to N bond is broken and no new bonds are formed, the value must be positive.

Students could also justify a positive value of $\Delta H°$ by explaining that the bonds are broken when N_2O_4 form NO_2 molecules. When bonds are broken energy is absorbed and the reaction is endothermic.

C. Predict the sign of $\Delta S°$ for the reaction. Justify your answer.

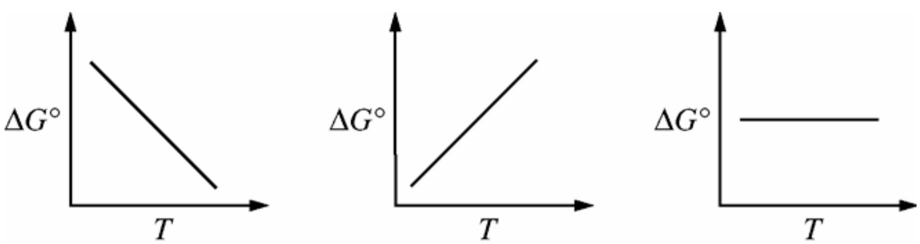
Each of the gaseous reactants results in two gaseous products. The products have more entropy than the reactants. As the reaction proceeds, the entropy increases, and the sign of $\Delta S°$ is positive.

D. Sketch a graph that represents the relationship between $\Delta G°$ and temperature for the reaction given above and explain the graph in terms of the relationship $\Delta G° = \Delta H° - T\Delta S°$. Assume that $\Delta H°$ and $\Delta S°$ are independent of temperature.



Since $\Delta S°$ is positive, and temperature increases, $T\Delta S°$ becomes a larger positive number. When temperatures are higher, you are subtracting larger positive numbers from $\Delta H°$ *to get* $\Delta G°$. The $\Delta G°$ decreases with an increase in temperature.

Note: if students are struggling with the graph, the teacher could adapt the problem by giving the students the following choices and asking them to choose the correct one explaining their answer in terms of the relationship $\Delta G° = \Delta H° - T\Delta S°$.



E. The reaction mixture of N_2O_4 and NO_2 is an equilibrium mixture. If heat is added to the mixture at constant pressure explain why the concentration of N_2O_4 decreases.

Since the reaction is endothermic, increasing the temperature drives the reaction to the right. This decreases the equilibrium concentration of N_2O_4 and increases the equilibrium concentration of NO_2.

F. The value of K_{eq} at 25°C is 5.0×10^{-3}. If the temperature is raised to 150°C, will the K_{eq} be greater than, less than, or equal to this value?

In an endothermic reaction the temperatures are increasing and the reaction is driven further to the right. The value of K_{eq} at 150°C will be greater than the value of K_{eq} at 25°C.

G. Discuss any potential adverse environmental effects that N_2O_4 and NO_2 could pose if released from the space shuttle into the atmosphere. Justify your answer.

NO_2 is a prominent component in smog, is toxic if inhaled, and exposure can lead to lung edema. N_2O_4 is highly toxic and corrosive. N_2O_4 and NO_2 are also both nonmetal oxides and when added to water they form an acidic solution which could contribute to acid rain.

Scoring Guide

Suggested 11 points total to be given.

Question		Distribution of points
A	*3 points*	1 point for correct geometric structure (part I) 1 point for correct hybridization (part II) 1 point for correct sigma and pi bonds (part III)
B	*1 point*	1 point for correct sign and a correct explanation
C	*1 point*	1 point for correct sign and a correct explanation
D	*2 points*	1 point for correct graph selection 1 point for correct explanation
E	*2 point*	1 correct graph with labels 1 point for correct explanation
F	*1 point*	1 point for correct answer
G	*1 point*	1 point for correct answer

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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