JOURNAL OF CHEMICAL EDUCATION
Activity
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Exploring the Gas Chemistry of Old Submarine Technologies Using Plastic Bottles as Reaction Vessels and Models

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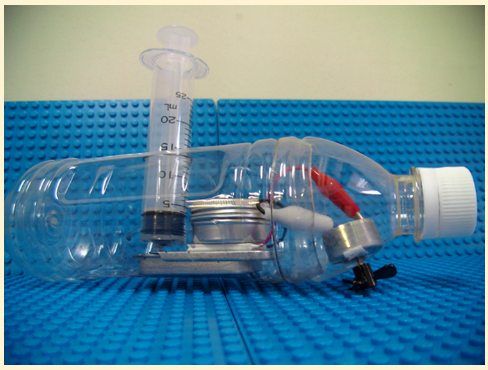
S Supporting Information

ABSTRACT: We describe an activity that is suitable for high school students and makes use of plastic bottles. This activity allows students to familiarize themselves with gas chemistry by introducing technologies that were applied in old submarine systems. Plastic bottles, which are representative of submarines, are used as reaction vessels. Three simple experiments regarding gas chemistry are carried out in the plastic bottles: (1) a carbon dioxide absorption reaction using soda lime, which mimics an air-cleaning canister; (2) a chlorine and hydrogen evolution reaction by the electrolysis of brine, which highlights the accidental generation of gases by lead batteries on board submarines; and (3) a catalytic hydrogen peroxide decomposition that exists in submarine propulsion system. To introduce an antisonar countermeasure system outside the submarine, a fourth experiment on hydrogen generation by the reaction of calcium hydride and water is also conducted.



KEYWORDS: *Hands-On Learning/Manipulatives, High School/Introductory Chemistry, First-Year Undergraduate/General, Gases, Inorganic Chemistry*

Classroom activities can connect seemingly separate concepts in chemistry to different disciplines, thereby capturing students' attention and increasing their interest in chemistry.[1−3] Such activities are important in education since they can relate chemistry in the classroom to the real world.[4−6] We have developed an activity that links gas chemistry to technologies applied in conventional old (non-nuclear) submarine systems. This activity aims to introduce gas chemistry to high school students, and includes the chemical experiments listed in Table 1.[7,8]

Plastic bottles, which represent submarines, are used as reaction vessels (Figure 1). Advantages of using plastic bottles as teaching aids include their availability, their ability to be modified and used for various applications, and their durability. Although none of the chemical reactions in this activity are new (Scheme 1),[9−13] they appear original by being considered with the submarine technology.

ACTIVITIES USING PLASTIC BOTTLES

After receiving an explanation regarding submarine systems and related chemical concepts, students should carry out experiments using plastic bottle submarines while referring to a student handout. This activity consists of four simple experiments and requires approximately 1 h when working with a group of three to four students. The total cost per student group is approximately US$25, and the materials and chemicals are available from homeware stores or science suppliers. Most materials can be reused. Photographs and corresponding schematic illustrations of the plastic bottle submarines are shown in Figures 1 and 2, respectively. Detailed submarine construction information is provided in the Supporting Information.

Activity 1: Carbon Dioxide Absorption

Soda lime (a mixture of calcium hydroxide and sodium hydroxide) is an important carbon dioxide absorbent used in anesthetic facemasks and in absorption columns for elemental analysis.

Materials and Reagents. Plastic bottle submarine for Activity 1, soda lime, color change adhesive (3M S/N 55C).

Procedure. A student was asked to breathe into and fill the hull of the plastic bottle submarine for Activity 1 through the hole, and a cut plastic syringe that contains soda lime was inserted in the hole. When the plastic syringe plunger was pushed down, soda lime dropped into the plastic dish in the hull and was exposed to carbon dioxide from the student's breath. Approximately 5 min later, the lid of the plastic case that contains the color change adhesive was opened by rolling up the rear part. The adhesive color remained unchanged because most carbon dioxide in the hull was absorbed by soda lime. Another plastic bottle submarine for Activity 1 without soda lime was constructed as a control. In this case, the adhesive

Received: September 7, 2015
Revised: April 2, 2016

DOI: 10.1021/acs.jchemed.5b00732
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Table 1. Relationship between Submarine System and Chemical Experiments

Activity	Submarine and its related systems	Chemical principle	Experiment	Connection with contents of high school chemistry
1	Air-cleaning canister	Gas absorption by solid material	Carbon dioxide absorption by soda lime	Gasses S-Block Elements
2	Accidental generation of chlorine and hydrogen on board	Gas generation by electrolysis	Chlorine and hydrogen evolution by electrolysis of brine	Electrochemistry Determining pH
3	Propulsion system: Walter turbine	Gas generation by catalytic decomposition	Oxygen generation by catalytic decomposition of hydrogen peroxide	Reaction Rate (Catalysis) Oxidation Numbers i.e., $H_2\underline{O}_2$ − 1; $H_2\underline{O}$ − 2; $\underline{O}_2$ 0
4	Antisonar countermeasure system	Gas generation by decomposition of solid material	Hydrogen generation from reaction of calcium hydride and water	Acid−Base Reactions i.e., Water will react as an acid when a very strong base is present.

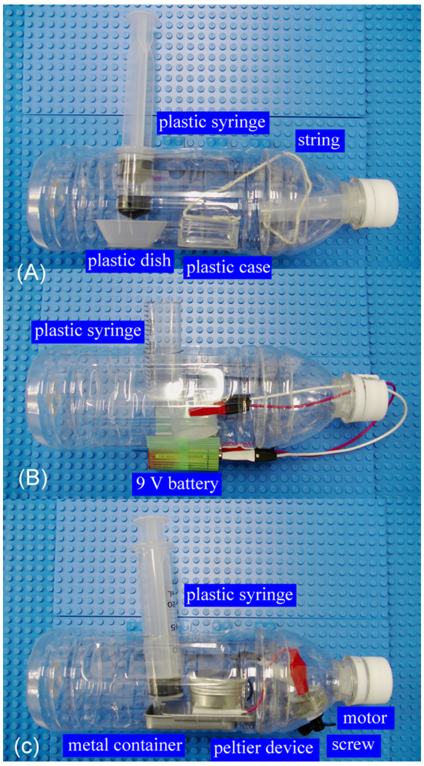

Figure 1. Assembled plastic bottle submarines for Activities 1−3: (A) Activity 1, (B) Activity 2, and (C) Activity 3.

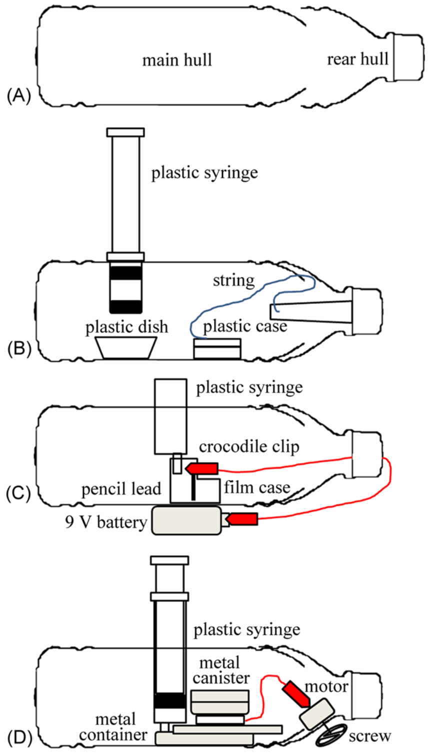

Figure 2. Schematic of plastic bottle submarines: (A) main hull and rear hull, (B) Activity 1, (C) Activity 2, and (D) Activity 3.

Scheme 1. Experiments in This Activity[a]

(1)
$$CO_2 + NaOH \longrightarrow NaHCO_3$$
$$NaHCO_3 + Ca(OH)_2 \longrightarrow CaCO_3 + H_2O + NaOH$$

(2)
$$2Cl^- \longrightarrow Cl_2 + 2e^-$$
$$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$$

(3)
$$2H_2O_2 \xrightarrow{MnO_2} 2H_2O + O_2$$

(4)
$$CaH_2 + 2H_2O \longrightarrow Ca(OH)_2 + 2H_2$$

[a]The numbers in parentheses correspond to those used in Table 1.

changed gradually to white because of the presence of carbon dioxide.

Safety Challenges. Instructors should direct students not to depress the plunger strongly to avoid breaking the plastic bottle submarine and being injured.

Context. When submerged for long periods, an apparatus that contained a canister of metal hydroxide with hose and mouthpiece was fitted over crewmembers' mouths to reduce the concentration of carbon dioxide that was breathed in. Among the metal hydroxides, soda lime was used frequently because of its low deliquescence. Sodium hydroxide acts as a catalyst in the absorption of soda lime by carbon dioxide (Scheme 1, reaction 1).

Activity 2: Chlorine Evolution

One of the possible methods for preparing chlorine gas is the electrolysis of saturated brine.

Materials and Reagents. Plastic bottle submarine for Activity 2, 9 V battery, electrical cable, saturated brine, chlorine test paper, pH test paper.

Procedure. Saturated brine was poured into a cut film case on the plastic bottle submarine for Activity 2 through a cut plastic syringe, and electricity was conducted via pencils using the 9 V battery. Chlorine gas was produced at one pencil or (+)-electrode, and was detected using chlorine test paper in the

DOI: 10.1021/acs.jchemed.5b00732
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plastic bottle. Hydrogen was generated at the other pencil or (−)-electrode. After electrolysis, the electrolyte pH value was greater than 7, as detected using pH test paper. Because alligator clips can be corroded by chlorine gas, they should be washed with water immediately after use.

Safety Challenges. Instructors should direct students not to detach the rear hull from the main hull during the gas generation and not to allow an electric current to flow for a long time.

Context. Most conventional old submarines were driven by a diesel engine that ran on light fuel oil when the submarine was on the surface, or by an electric motor with lead−acid batteries when submerged. In general, lead−acid batteries, which were charged by the diesel engine, were heavy and were stored in the lower half of the hull. When a submarine flooded, seawater sometimes filled the battery sections and accidentally generated chlorine and hydrogen gas by electrolysis of seawater (Scheme 1, reaction 2). Chlorine is a highly toxic gas and caused crewmembers to experience severe skin and lung irritation. Hydrogen is a colorless, odorless, flammable, and highly explosive gas, which could cause explosions in battery components.

Activity 3: Catalytic Decomposition of Hydrogen Peroxide

The catalytic decomposition of hydrogen peroxide results in the formation of oxygen gas, water, and heat. The prime example of the catalyst is manganese(IV) oxide, which is insoluble in the solution; therefore, it can be reused.

Materials and Reagents. Plastic bottle submarine for Activity 3, manganese(IV) oxide, 10% aqueous hydrogen peroxide.

Procedure. Aqueous hydrogen peroxide (10%) was added dropwise to manganese(IV) oxide in a metal container to generate oxygen gas and heat. Temperature differences applied to opposite sides of the Peltier device generated sufficient current to start the electronic motor.

Safety Challenges. Instructors should direct students not to touch the sides of the plastic bottle submarine to avoid being scalded once the gas is generated.

Context. Several old submarines were driven by Walter engines when submerged. A Walter engine is a steam turbine that uses concentrated aqueous hydrogen peroxide (70−80% v/v) as a source of oxygen gas and steam to run the engine. One advantage of using the Walter engine is that the system emits oxygen, water, and heat, which can be reused in a submarine (Scheme 1, reaction 3). The instructor should emphasize that the Walter engine system cannot be recreated in this activity, since plastic bottles may suffer from thermal deformation. Therefore, for safety purposes, a Peltier device was chosen to explain the relationship between the gas generation reaction and the submarine propulsion system. There is no relationship between the Peltier device and the Walter engine system.

Activity 4: Hydrogen Generation

The reaction of calcium hydride and water results in the formation of hydrogen gas and calcium hydroxide; therefore, calcium hydride can be recognized as a solid source of hydrogen gas.

Materials and Reagents. Plastic bottle, metal tube (6 mm diameter, 40 mm height), distilled water, calcium hydride, wafer (medicine wrapper made from starch).

Procedure. A metal tube that contained approximately 20 mg of calcium hydride and wafers was added to distilled water in a plastic bottle. Bubbles rose from holes in the metal tube to the surface.

Safety Challenges. Instructors should direct students not to tighten the lid of the plastic bottle during the gas generation to avoid cracking the bottle by the increase in the internal pressure.

Context. An antisonar countermeasure used in German submarines during the 1940s was termed the Bold.[7] The Bold is a metal canister that was filled with calcium hydride and emitted large quantities of hydrogen gas when mixed with seawater (Scheme 1, reaction 4). The resulting cloud of gas bubbles and the submerged submarine appeared identical and it was difficult for even skilled sonar operators in a destroyer to distinguish them.

■ HAZARDS

The experiments in this activity are potentially hazardous. All experiments should be performed in a well-ventilated area. Students should wear safety glasses and rubber gloves. The chemicals used in the experiments are harmful if swallowed, and cause eye irritation. Chlorine gas is highly toxic, an irritant, and corrosive. Aqueous hydrogen peroxide (10%) is a corrosive oxidant, which can cause serious burns. It should be transferred using only clean glassware and should never be exposed to metal or other chemicals. Oxygen gas is a powerful oxidizer and supports combustion. Hydrogen gas is extremely flammable and forms an explosive mixture with air.

■ CONCLUSIONS

This activity uses plastic bottles to show students the underlying gas chemistry of old submarine technology. Four experiments regarding gas chemistry, which are typical in high school chemistry textbooks, are integrated into the activity. The activity provides students with an opportunity to relate textbook chemistry to the real world.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00732.

Video S1 (AVI)
Video S2 (AVI)
Video S3 (AVI)
Video S4 (AVI)
Video S5 (AVI)
Video S6 (AVI)
Instructions for construction of the plastic bottle apparatus, the procedure and images from the experiments, notes for instructors, a student handout, students' comprehension, reference books, and CAS registry numbers of chemicals (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by a Scientific Research Grant from The Nihon Bungu Foundation for Science & Technology.

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DOI: 10.1021/acs.jchemed.5b00732
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