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Activity

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Using a Hands-On Hydrogen Peroxide Decomposition Activity To Teach Catalysis Concepts to K–12 Students

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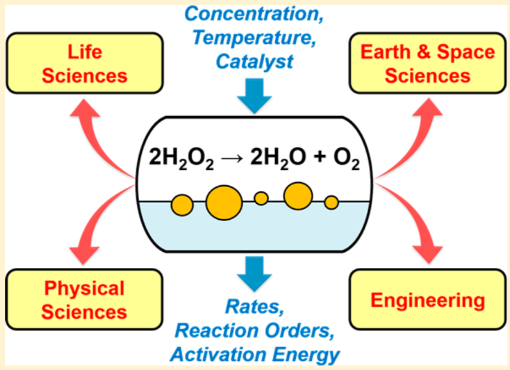
Supporting Information

ABSTRACT: A versatile and transportable laboratory apparatus was developed for middle and high school (6th–12th grade) students as part of a hands-on outreach activity to estimate catalytic rates of hydrogen peroxide decomposition from oxygen evolution rates measured by using a volumetric displacement method. The apparatus was constructed with inherent safety features and is compatible with different types of catalysts, catalyst and peroxide concentrations, and reaction temperatures to enable the design of various experiments. The hands-on outreach activity was created with the aim of building scientific proficiency and stimulating interest in STEM fields among students with limited chemistry background. This activity is designed to be completed in short times (45 min) by students in small groups (3–5 students), where each group measures reaction rates at various activity stations and then gathers as a larger group (~20 total) to discuss their observations and results and to assess their scientific understanding. Additionally, the activity is incorporated into a broader outreach program that uses hydrogen peroxide reactions as an underlying theme to introduce fundamental concepts in catalysis and kinetics to K–12 students. The program can be tailored to emphasize specific scientific topics including medicine, energy, or the environment.



KEYWORDS: *Elementary/Middle School Science, High School/Introductory Chemistry, Laboratory Instruction, Hands-On Learning/Manipulatives, Catalysis, Kinetics, Reactions*

■ INTRODUCTION

Hydrogen peroxide (H_2O_2) is a shelf-stable chemical reagent that is commonly stored for household use, but its rate of decomposition can be accelerated by orders of magnitude with various catalysts such as sodium iodide (NaI), platinum, and the enzyme catalase (Figure 1). The catalytic decomposition of H_2O_2 into water and oxygen ($2H_2O_2 \rightarrow 2H_2O + O_2$, $\Delta H_R° = -98.2$ kJ mol^{-1}) is a widely used reaction in chemistry demonstrations (the "elephant's toothpaste")[1,2] and laboratory experiments to demonstrate fundamental concepts in kinetics and catalysis, including catalyst and peroxide reaction orders,[3−8] reaction enthalpy,[4,9,10] and activation energy.[5−7,9,11] Laboratory experiments to measure H_2O_2 decomposition rates described previously have focused on targeting high school students or first-year undergraduates,[5−7,9−11] while the activity described herein is designed to align with best practices in informal science education[12] and to be accessible to middle school students with limited chemistry background.

Previous reports describe experiments to estimate reaction rates by using calorimeters for temperature changes,[4,9−11] or pressure transducers or level indicators to measure pressure[5,6,8] or volume[3,5,7,13] changes caused by the evolution of oxygen gases. The constant pressure apparatus described herein contains several built-in safety features, is easy to operate for middle school students, and uses a leveling bulb to measure volumetric changes from O_2 evolution upon H_2O_2 decomposition. It is a versatile unit that is designed to be compatible with different catalysts, different catalyst and reactant

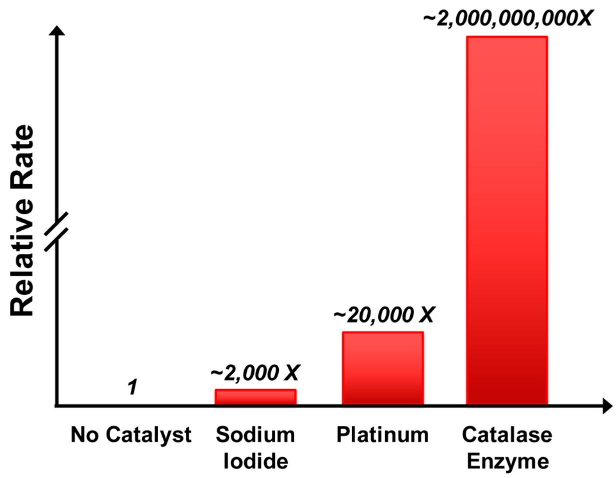


Figure 1. Relative H_2O_2 decomposition rates (arbitrary units) by different catalysts; adapted from Larsen et al.[14]

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concentrations, and different temperatures, allowing for the design of experiments to calculate reaction rates, apparent reaction orders, and apparent activation energies. The activity described herein, however, only considers the use of this apparatus to measure the H_2O_2 reaction order with a NaI catalyst.

■ EXPERIMENT

Description of Experimental Apparatus

The laboratory apparatus consists of a glass bottle that serves as the reactor, a buret with an integral stopcock for dispensing H_2O_2 solutions, and a leveling bulb (glass pipet + funnel) filled with colored water (e.g., red, yellow, green, blue, orange) that is used for measuring volumetric changes during the decomposition reaction (Figure 2). The cap on the glass bottle contains three ports: an inlet for the H_2O_2 solution, an outlet for the gas flow to the leveling bulb, and a dual-purpose port that is used to introduce catalyst solutions and to vent excess gases produced from the reaction. The apparatus is supported on a ring stand with clamps. Additional details can be found in Table S.1 and Figures S.1 and S.2.

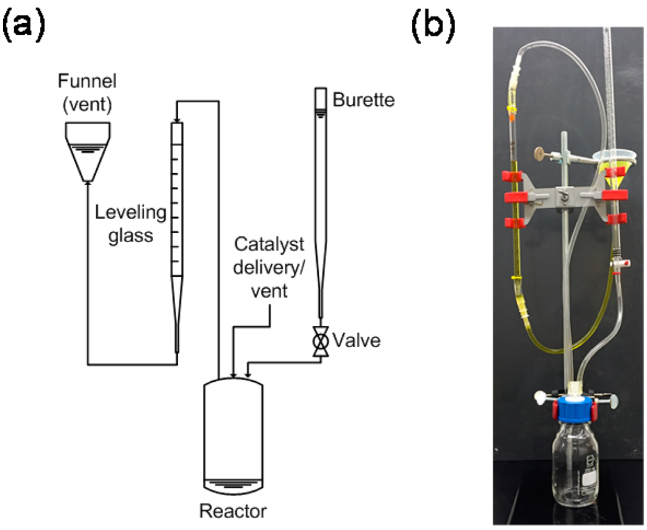

Figure 2. (a) Schematic and (b) photo of the H_2O_2 catalytic decomposition apparatus.

Hands-On Activity: Catalytic Rates of Hydrogen Peroxide Decomposition

The 45 min hands-on activity is integrated into a broader K−12 outreach program that features a presentation and demonstration of the "elephant's toothpaste" reaction as shown in Figure 3. Additional details of the outreach program are located in the Supporting Information. The activity is designed to accommodate groups of 20 students at a time, which are then split into five smaller teams comprising 3−5 students each (Figure 3). At the beginning of the activity, each team, along with an event volunteer, is assigned to one of the five color-coded activity stations where each color represents a different, unknown H_2O_2 concentration (Supporting Information section 3).

The experiment involves three distinct tasks and thus three students to complete: one to control the addition of H_2O_2 to the reactor, one to record the time elapsed and volume change during the reaction, and one to record the data and then calculate the H_2O_2 decomposition rate. An event volunteer fills the buret with the H_2O_2 solution, dispenses approximately 2 mL of a 2 M NaI catalyst solution into the reactor through the vent port via a pipet, and then leaves the vent port uncapped until the reaction begins. The student responsible for controlling the H_2O_2 addition opens the stopcock to allow 15 mL of H_2O_2 to flow into the reactor. Once the students observe bubbles effervescing from the reaction mixture, they insert the cap into the reactor vent port and monitor the displacement of water in the leveling bulb by the evolving oxygen gas. The student responsible for timing the reaction takes note of the initial volume on the leveling bulb, starts the timer, and records the time required for the gas to displace

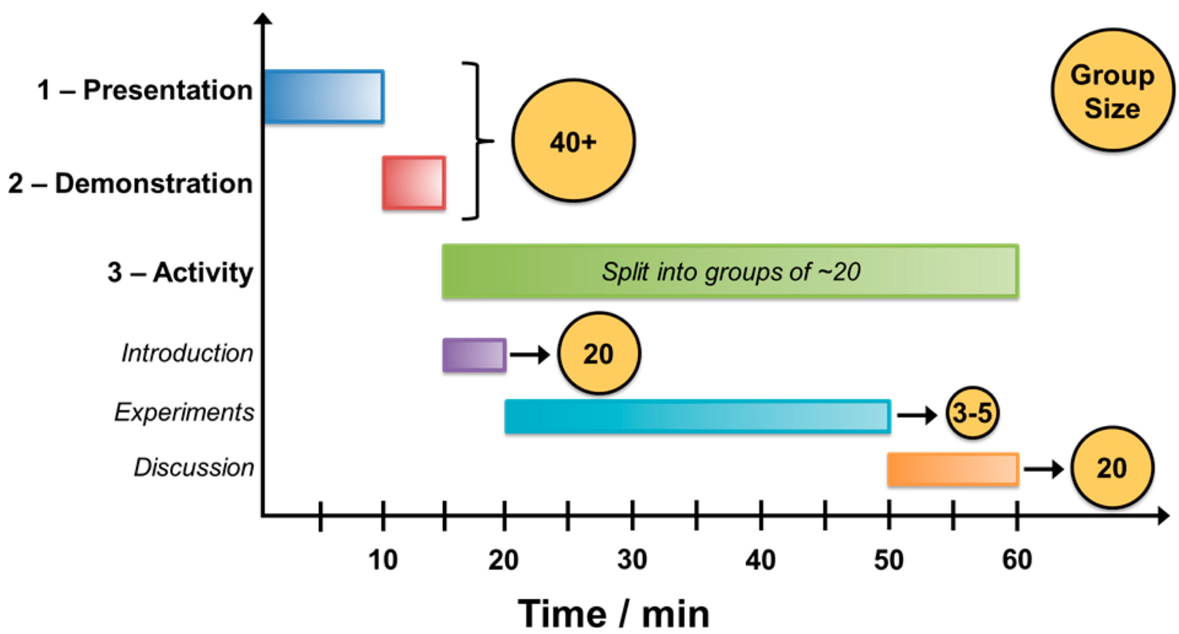

Figure 3. Timeline of events for the outreach program centered on H_2O_2 decomposition. Additional details about the outreach program can be found in Supporting Information section 6.

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approximately 10 mL of water. The remaining student team member records the volume change and elapsed time on the activity worksheet (Supporting Information section 4) and then calculates the rate of oxygen evolution from the reactor.

Afterward, the team records their results on a large whiteboard at the front of the room, and then rotates to a new station to repeat the experiment. Once at the new station, the students switch roles to gain experience with different tasks involved in the experiment. Usually, each group can measure reaction rates at three of the five total stations in 30 min. In the last 10 min of the activity, all of the students reconvene as the large group, and the results are discussed in order to assess their understanding of the experiment.

■ HAZARDS AND HAZARD MITIGATION

H_2O_2 is an oxidizing agent, even at low (3 wt %) concentrations,[15] that can rapidly decompose to release oxygen. It should be kept away from flammables and other reducing agents. The H_2O_2 concentrations used in this activity range from 1 to 6 wt %. Since H_2O_2 can irritate the skin and eyes, participants are required to wear safety glasses and gloves during the activity.

In order to mitigate these hazards, the apparatus was designed with several safety features. H_2O_2 is dispensed directly into the reactor via a buret equipped with a stopcock valve in order to avoid exposing students to the chemical. Additionally, the leveling bulb used to measure oxygen evolution rates during reaction is open to the atmosphere in order to prevent reactor overpressure. Lastly, the reactor is equipped with a dual-purpose port used to introduce the catalyst solution via pipet, and to vent the oxygen produced from the peroxide decomposition.

■ RESULTS

Hydrogen Peroxide Reaction Order

The results obtained from approximately 160 student participants (6th–9th graders) in outreach activities at Purdue University in 2015 show that the rates of H_2O_2 decomposition ranged from 0.10 ± 0.03 (mL O_2) $(g_{cat})^{-1}$ s^{-1} to 0.90 ± 0.30 (mL O_2) $(g_{cat})^{-1}$ s^{-1} at 25 °C for H_2O_2 mixtures between 1 and 6 wt %, respectively (Table S.2). Based on these results, students observed that the rate of H_2O_2 decomposition increases as the H_2O_2 concentration increases. Qualitatively, this observation reinforces the hypothesis proposed during the "elephant's toothpaste" demonstration that the visual display of foaming bubbles created by the fast rate of decomposition was due to the high (30 wt %) H_2O_2 concentration.

For students with a more advanced chemistry and mathematics background at the high school level, this activity can be expanded to include a quantitative analysis of the experimental data to determine the apparent H_2O_2 reaction order via linear regression of the ln(rate) against the ln(H_2O_2 concentration).[16] A full derivation of this relationship is included in Supporting Information section 5. The experimental data, which were collected by the 6th–9th grade participants from the five activity stations, were averaged and plotted by the instructors after the activity had concluded in order to estimate an apparent H_2O_2 reaction order of 1.3 ± 0.1 (Figure 4). This result agrees reasonably well with the reaction order of 1.1 ± 0.2 reported by Ragsdale et al.[7] for H_2O_2 decomposition by MnO_2, illustrating that the rate of H_2O_2 decomposition is proportional to the concentration of H_2O_2

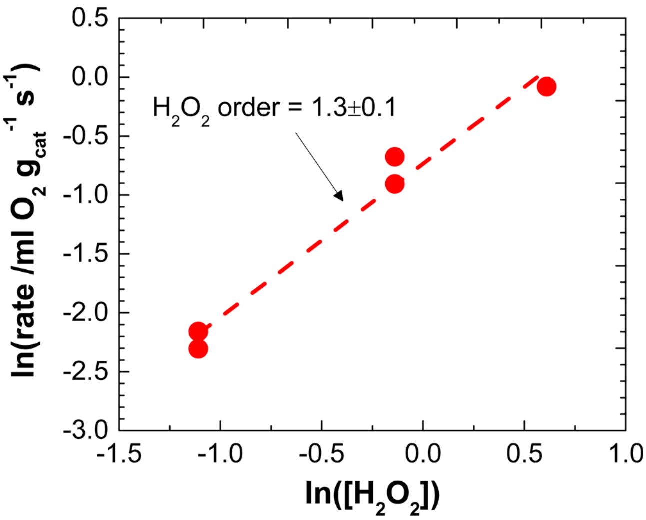

Figure 4. Apparent H_2O_2 reaction order obtained from oxygen evolution rates measured at 25 °C with 1−6 wt % H_2O_2 and a 2 M NaI catalyst.

and demonstrating that this activity can be used to measure quantitative reaction orders.

During the group discussion after the experiments, the students identified the activity stations that had the highest, lowest, and similar H_2O_2 concentrations based on the relative rates of H_2O_2 decomposition. By comparing results between the various teams for each activity station, the students were able to comment on the reproducibility of their results and observed how errors arise in experimental measurements. In order to assess their conceptual understanding, we prompted the students to connect their experimental observations to issues that relate to a specific scientific theme such as biology, medicine, energy, or the environment. For example, in the case of living organisms, the students formulated that fast H_2O_2 decomposition rates by the enzyme catalase are necessary due to the reactivity of H_2O_2 and its potential to damage cell tissue.[17] Additional notes for the instructor on how to guide the group discussion along with desired student responses can be found in Supporting Information section 6.

Developing Scientific Proficiency in K–12 Students

This hands-on activity was developed in order to promote scientific learning in an informal environment[12] among K−12 students by having them measure H_2O_2 decomposition rates, compare rates among different reactor units with different H_2O_2 concentrations, and discuss findings in a large group to assess their understanding of key concepts. During the activity, students participate in the practices of planning an experiment, carrying out an investigation, and analyzing and interpreting experimental data. By engaging in these activities, the students can identify with scientists and engineers who must properly plan and conduct experiments in order to interpret data and identify unknowns.

By using H_2O_2 decomposition as the central theme for these outreach events, we can incorporate guidelines based on next generation science standards (NGSS)[18] and make connections across the physical sciences (chemical reactions), life sciences (catalase enzyme), earth and space sciences (peroxide as a rocket engine propellant), and engineering and applications of science (reactor design and engineering). This activity aligns with the disciplinary core ideas (DCI) in the physical sciences

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of Matter and Its Interactions (PS1), by demonstrating how catalysts facilitate chemical reactions, and of Energy (PS3), by demonstrating how chemical energy is released upon H_2O_2 decomposition. The types of experiments performed in the versatile laboratory apparatus can be tailored to teach concepts in catalysis and kinetics to students of widely varying chemistry background and experience. For example, more advanced experiments can be performed with different types of catalysts (NaI, Pt, catalase), or at different temperatures with the same catalyst, to teach students about the concept of an activation barrier for a chemical reaction and how catalysts accelerate reaction rates by lowering this activation barrier.

We propose that this hands-on H_2O_2 decomposition activity and apparatus could be expanded into a laboratory experiment for a middle school or high school curriculum that aligns with the scientific and engineering practices defined by NGSS.[18] We have successfully used this activity as an informal science education tool that allowed students to plan and carry out investigations (NGSS practice 3), to analyze and interpret data (NGSS practice 4), and to obtain, evaluate, and communicate results (NGSS practice 8). Adaptation of this activity into a formal laboratory experiment would allow additional NGSS practices to be introduced and assessed in order to explore impacts on student learning, interests, and pursuits in STEM fields.

CONCLUSIONS

A laboratory apparatus and hands-on outreach activity were designed in order to stimulate scientific curiosity in K−12 students by introducing them to fundamental concepts in catalysis and reaction kinetics. This novel experimental apparatus is safe, transportable, and adaptable for a range of experiments with increasing levels of complexity for different grade levels. The catalytic decomposition of H_2O_2 is used as an underlying theme to connect the experimental observations made by students in the laboratory to related concepts in life sciences, earth and space sciences, physical sciences, and engineering.

In 2015, this hands-on H_2O_2 decomposition activity was performed by ∼200 6th−9th grade students across three different outreach events at Purdue University. These three separate outreach events demonstrated that the activity can be performed under time constraints with large groups of new students while producing results with reasonable scientific accuracy. Written feedback obtained from the student participants (Supporting Information section 7) indicated that they became excited and learned more about science and engineering by witnessing the demonstration and performing real hands-on laboratory experiments. Their suggestions for improvement focused on providing more opportunities for hands-on activities, more time in the laboratory, and, of course, more "elephant's toothpaste" in the demonstration.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00946.

> Itemized price list, student data, photos of apparatus, instructional materials and handouts, derivation of apparent reaction order for H_2O_2, instructor notes, student feedback, and program details (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Shakhashiri, B. Z. In *Chemical Demonstrations—A Handbook for Teachers of Chemistry*; University of Wisconsin Press: Madison, 1983; Vol. *1*, pp 180 − 185.

(2) Conklin, A. R., Jr.; Kessinger, A. Demonstration of the Catalytic Decomposition of Hydrogen Peroxide. *J. Chem. Educ.* **1996**, *73* (9), 838−840.

(3) Barlag, R.; Nyasulu, F. Wash Bottle Laboratory Exercises: Iodide-Catalyzed H_2O_2 Decomposition Reaction Kinetics Using the Initial Rate Approach. *J. Chem. Educ.* **2010**, *87* (1), 78−80.

(4) Nyasulu, F.; Barlag, R. Thermokinetics: Iodide-Catalyzed Decomposition Kinetics of Hydrogen Perioxide. An Initial-Rate Approach. *J. Chem. Educ.* **2009**, *86* (10), 1231−1233.

(5) Vetter, T. A.; Colombo, D. P., Jr. Kinetics of Platinum-Catalyzed Decomposition of Hydrogen Peroxide. *J. Chem. Educ.* **2003**, *80* (7), 788−789.

(6) Abramovitch, D. A.; Cunningham, L. K.; Litwer, M. R. Decomposition Kinetics of Hydrogen Peroxide: Novel Lab Experiments Employing Computer Technology. *J. Chem. Educ.* **2003**, *80* (7), 790−792.

(7) Ragsdale, R. O.; Vanderhooft, J. C. Small-Scale Kinetic Study of the Catalyzed Decomposition of Hydrogen Peroxide. *J. Chem. Educ.* **1998**, *75* (2), 215−216.

(8) Hansen, J. C. The Iodide-Catalyzed Decomposition of Hydrogen Peroxide: A Simple Computer-Interfaced Kinetics Experiment for General Chemistry. *J. Chem. Educ.* **1996**, *73* (8), 728−732.

(9) Tatsuoka, T.; Koga, N. Energy Diagram for the Catalytic Decomposition of Hydrogen Peroxide. *J. Chem. Educ.* **2013**, *90* (5), 633−636.

(10) Marzzacco, C. J. The Enthalpy of Decomposition of Hydrogen Peroxide. *J. Chem. Educ.* **1999**, *76* (11), 1517−1518.

(11) Sweeney, W.; Lee, J.; Abid, N.; DeMeo, S. Efficient Method for the Determination of the Activation Energy of the Iodide-Catalyzed Decomposition of Hydrogen Peroxide. *J. Chem. Educ.* **2014**, *91* (8), 1216−1219.

(12) National Research Council. *Learning Science in Informal Environments: People, Places, and Pursuits*; Board on Science Education, Division of Behavioral and Social Sciences and Education; The National Academies Press: Washington, DC, 2009.

(13) Bedenbaugh, J. H.; Bedenbaugh, A. O.; Heard, T. S. Oxygen from Hydrogen Peroxide. *J. Chem. Educ.* **1988**, *65* (5), 455−456.

(14) Larsen, D. Catalysis. *ChemWiki: The Dynamic Chemistry Hypertext* [Online]; University of California, Davis STEMWiki Hyperlibrary: Davis, CA. http://chemwiki.ucdavis.edu/Physical_

DOI: 10.1021/acs.jchemed.5b00946
J. Chem. Educ. XXXX, XXX, XXX−XXX

Chemistry/Kinetics/Complex_Reactions/Catalysis (accessed April 2016).
(15) Young, J. A. Hydrogen Peroxide Chemical Laboratory Information Profile. *J. Chem. Educ.* **2003**, *80* (10), 1132.
(16) Fogler, H. S. In *Elements of Chemical Reaction Engineering*, 4th ed.; Pearson Education, Inc.: Boston, 2006; p 833.
(17) Gaetani, G. F.; Ferraris, A. M.; Rolfo, M.; Mangerini, R.; Arena, S.; Kirkman, H. N. Predominant Role of Catalase in the Disposal of Hydrogen Peroxide within Human Erythrocytes. *Blood* **1996**, *87* (4), 1595−1599.
(18) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Committee on a Conceptual Framework for New K-12 Science Education Standards*; Board on Science Education, Division of Behavioral and Social Sciences and Education; The National Academies Press: Washington, DC, 2012.

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J. Chem. Educ. XXXX, XXX, XXX−XXX