

Ignition of Thermite Using the Potassium Chlorate “Rocket” Reaction: A Systematic Demonstration of Reaction Chemistry

Brett A. McGuire,^{*,†,‡} P. Brandon Carroll,^{‡,§} Adam N. Boynton,^{‡,§} Jeffrey M. Mendez,[‡] and Geoffrey A. Blake^{‡,||}

[†]National Radio Astronomy Observatory, Charlottesville, Virginia 22903, United States

[‡]Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125

^{||}Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, United States

ABSTRACT: Presented here is a set of demonstrations that are used as visual tools for engaging students in a discussion of reaction chemistry and thermodynamics. Students are first shown a series of simple exothermic reactions: (1) the reaction of H_2SO_4 with sugar, (2) the decomposition of KClO_3 , and (3) the reaction of H_2SO_4 with KClO_3 . These three basic reactions are then combined as a pyrotechnic chlorate demonstration in which H_2SO_4 is used to ignite a KClO_3 + sugar mixture. It is finally shown that this latter reaction is very effective for igniting the highly exothermic thermite redox reaction.



KEYWORDS: First Year Undergraduate/General, High School/Introductory Chemistry, Demonstrations, Physical Chemistry, Hands-On Learning/Manipulatives, Reactions, Kinetics, Thermodynamics, Oxidation/Reduction

INTRODUCTION

The use of the thermite reaction as an exciting demonstration for young science students is documented in this Journal as early as 1930. In his article, J. E. Nelson describes the melting of a steel nail with thermite, tying the chemistry concept of displacement reactions to the real-world application of industrial welding.¹ Since then, the refinement of the thermite reaction demonstration has been documented several times. In particular, the ignition of the reaction, which possesses a large activation energy, has been a key topic of discussion.

In 1937, O. C. Klein documented the use of potassium permanganate (KMnO_4) as an ignition system.² This system remained unchanged in the public view until 1952, when C. P. Brockett demonstrated that the addition of a BaO_2 –aluminum powder mixture greatly improves the success rate of the ignition.³ A secondary method for ignition was proposed by Fortman and Schreier in 1993 involving a reactive mixture of potassium chlorate (KClO_3) with sugar and ignited with a standard fuse.⁴ G. W. Eastland had previously used thermite to ignite such a KClO_3 mixture for effect.⁵ Indeed, the KClO_3 reaction itself has been used to great effect in its own right as a tool for demonstrating reaction dynamics.⁶

We have found that the KClO_3 + sugar mixture, chemically ignited with sulfuric acid (H_2SO_4), provides sufficient energy to ignite a mixture of thermite. This also presents a valuable opportunity to perform several demonstrations leading up to the thermite reaction which build upon simple chemical principles students have been studying. Prior to the final

demonstration, students are shown how the individual constituent reactions of (1) H_2SO_4 with sugar, (2) H_2SO_4 with KClO_3 producing HClO_3 , followed by the combustion of sugar, and (3) H_2SO_4 with a KClO_3 –sugar mixture can be combined to produce the exciting “chlorate rocket” pyrotechnic display. This reaction is then used to ignite the thermite in a demonstration of redox chemistry and reaction barriers.

Here we outline the procedures for each reaction, as well as the chemical principles to be demonstrated at each step.

DEMONSTRATIONS

For best effect, demonstrations should be performed in order, with discussion of the chemistry before and after each demonstration.

H_2SO_4 + Sugar

The procedure is well-described in the literature.⁷ 70 g of common granulated sugar ($\text{C}_{12}\text{H}_{22}\text{O}_{11}$) are placed in a tall, 300 mL beaker. 70 mL of concentrated (18 M) H_2SO_4 is added. After several seconds, the reaction proceeds, producing a column of elemental carbon.

Decomposition of KClO_3

A small quantity of KClO_3 is placed in a mortar and exposed to the flame from a small torch. Decomposition occurs, but the reaction is otherwise unremarkable. The interested student could collect the evolved O_2 and test for it.

$\text{H}_2\text{SO}_4 + \text{KClO}_3$

A small quantity of KClO_3 is placed in a mortar. To this, a few drops of concentrated (18 M) H_2SO_4 are added. Sugar is then sprinkled into the resulting liquid, producing sparks and sizzles with each crystal, which quickly subside. A tightly twisted paper towel may also be dipped in the liquid, which will rapidly combust.

$\text{H}_2\text{SO}_4 + \text{KClO}_3 + \text{Sugar}$

KClO_3 and sugar are mixed in a mortar in a 100:15 molar ratio mixture. To this, a few drops of concentrated (18 M) H_2SO_4 are added, initially producing the sparks and sizzles seen previously. After a few seconds, intense, continuous combustion will occur.

Thermite

A thermite mixture is prepared by mixing aluminum powder and iron oxide (Fe_2O_3) in a 1:3 mixture by mass. Enough volume to fill 3/4 of a small garden planter pot provides for an exciting demonstration. Pots with small drainage holes in the bottom are preferred as they easily direct the flow of molten iron. A layer of aluminum foil can be used to contain the thermite sample before ignition (see Figure 1).



Figure 1. Thermite mixture in aluminum foil containment prepared inside a flower pot. A small divot in the center is formed for containing the ignition powder mixture.

A second pot layered with the first protects against the inner pot shattering during the reaction. Both pots should be suspended on a ring stand over a much larger pot filled with sand to collect and cool the molten iron flow (see Figure 2).

A divot is made in the thermite mixture, and the $\text{KClO}_3 + \text{sugar}$ mixture, prepared as before, is added. Shaping the mixture into a cone or steep mound produces the best results (see Figure 3). To this, several drops of concentrated (18 M) H_2SO_4 are added. The combustion reaction is observed as before, followed quickly by the far more energetic thermite reaction, which produces a flow of molten iron from the bottom of the pots which is caught in the sand below (see Figure 4). After a few moments, students can observe the red-hot molten iron. Once the glow recedes, the iron can be carefully retrieved with a pair of tongs and cooled in a water bath. A video of the demonstration is available online.⁸

HAZARDS

For all demonstrations, proper personal protective equipment is necessary including safety glasses, gloves, laboratory coats, long pants, and close-toed shoes. The first four demonstrations



Figure 2. Finished reaction showing the preferred arrangement of a double-layered flower pot suspended above a larger pot filled with sand to catch the molten iron flow.



Figure 3. Roman candle ignition mixture added to thermite divot. A second divot is made to accept the H_2SO_4 .

should be performed in a well-ventilated area: an outdoor setting is preferable, as many of these reactions generate large quantities of smoke (some sulfurous), which can be agitating to observers with respiratory conditions. Observers should be situated well back from the reactions, at least 15 or 20 feet from the estimated extent of the reaction. We strongly recommend a trial run before any demonstration to determine an appropriate location and observation distance given the quantities of thermite desired. A web camera could also be used to provide a detailed close-up of the demonstration for students to view. Hazards associated with specific demonstrations are listed below.



Figure 4. Thermite reaction. The display shown here was prepared with roughly 10 times the amount of thermite as shown in Figures 1 and 3

H_2SO_4 + Sugar

Concentrated H_2SO_4 is extremely caustic, and saturates the carbon column produced in the dehydration of sugar reaction. This reaction also produces very hot steam and SO_2 vapor.

H_2SO_4 + KClO_3 + Sugar

The reaction proceeds quickly upon the addition of the H_2SO_4 and emits sparks which may jump a considerable distance from the crucible. A quick retreat to a safe distance after the addition of the acid is recommended.

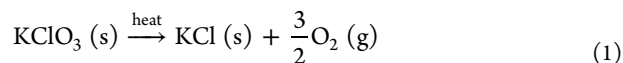
Thermite

When using a fine-grain aluminum powder, extreme care should be taken, especially against inhalation. In addition to full standard personal protective equipment, respiratory masks are strongly recommended when mixing the thermite as the aluminum powder is difficult to contain. An empty parking lot, large, wet lawn, or other suitably nonflammable, outdoor location is recommended for this demonstration. For a demonstration of the scale shown here (a small flower pot), students should stand well-clear (at least 15–20 feet) of the reaction vessel—farther if a larger quantity of thermite is used. If windy conditions prevail, students should stand upwind from the reaction, to avoid inhalation of any of the resulting fumes. The reaction is extremely violent, with sparks of molten iron being thrown a considerable distance from the flower pot. A clear blast shield, large enough to reach a foot or more over the top of the flower pot and placed to shield the audience, can be used for larger demonstrations or in more confined locations. After the acid is added to the mixture, the demonstrator should retreat to a safe distance to observe. If ignition fails, we recommend waiting a few minutes before attempting a second ignition. Once the reaction has subsided and sparks have ceased, the reaction vessel should be safe for the demonstrator to approach with caution.

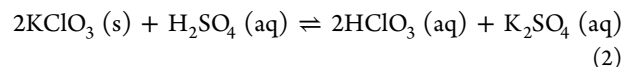
DISCUSSION

The thermite reaction possesses a high reaction energy barrier—a simple combustion reaction with atmospheric O_2 will not produce enough heat. In order to provide the required energy, a combustion reaction requires a larger supply of O_2 . That O_2 can be generated through the decomposition of KClO_3 .

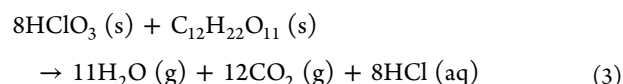
Decomposing KClO_3 will produce significant oxygen (see eq 1), but the reaction terminates quite quickly as soon as the heat source is removed.



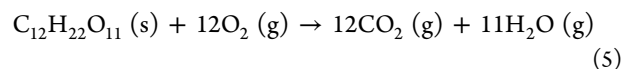
As an alternative, H_2SO_4 can be used to facilitate the decomposition reaction indirectly. The reaction of KClO_3 with H_2SO_4 creates chloric acid (HClO_3) and potassium sulfate (K_2SO_4) via an exchange reaction (eq 2).



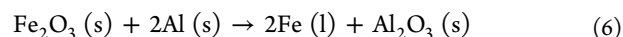
While a relatively effective method, this reaction terminates as soon as the limiting reagent, in this case H_2SO_4 , runs out. Adding the sugar to the mixture solves this problem by creating a sustaining reaction mixture. The HClO_3 initially reacts violently with the sucrose (eq 3), providing ample heat to decompose the remaining, unreacted KClO_3 (eq 4).



The resulting oxygen excess, combined with the heat of the decomposition, ignites the sucrose combustion, which continues until the sucrose or the KClO_3 is depleted (eq 5). The addition of metal salts produces a colored flame, which provides for a further discussion of atomic transitions.



The reactive mixture is then used to produce sufficient energy to overcome the activation energy for the thermite redox reaction (eq 6), thus achieving the goal (and the spectacular finish).



Finally, this demonstration can also serve as an opening to discuss kinetic versus thermodynamic control of a reaction with students. While the thermite reaction is massively exothermic, its high activation energy means that the components can be safely mixed and stored until sufficient energy is input into the system via an ignition source, as demonstrated here. Although beyond the scope of this paper, the interested instructor could engage students by calculating the thermodynamics of the individual reactions in this sequence.

CONCLUSION

By introducing a series of basic reactions one by one and subsequently demonstrating how they can be applied together in the ignition of the thermite reaction, students are shown how simple concepts such as combustion, dehydration, exchange, and decomposition can be used in the context of overcoming large reaction activation energies.

AUTHOR INFORMATION

Corresponding Author

*E-mail: bmcguire@caltech.edu.

Author Contributions

§P.B.C. and A.N.B. contributed equally to this work;

Notes

The authors declare no competing financial interest.

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