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A systematic, in-depth study of the stoichiometry of the reaction of steel wool with air

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Introduction

High school chemistry students are usually taught how to calculate stoichiometric ratios by massing a chemical compound before and after combustion. For example, Mg is massed before combustion as the silver colored metal and after combustion as the white colored oxide. Similarly, AgO is massed before decomposition as the black colored oxide and after decomposition as the silver colored metal. In these experiments, it is critical that 1) all of the substance react with the air and consequently, no unreacted substance be present after the experiment, 2) an adequate supply of air (oxygen) be present throughout the combustion process, so that oxygen is never the limiting reactant, 2) The products of the reaction not be allowed to aerosolize and escape into the atmosphere (as for MgO) and 3) a sensitive enough balance be used that is capable of precisely measuring the difference between the masses of the substances before and after combustion. Such experiments frequently yield erroneous results because one or more of the above factors cannot be adequately controlled, given the time (a typical experiment may last 45 minutes), equipment and/or student variability limitations of a high school chemistry laboratory. For example, when performing experiments using Mg ribbon, the crucible needs to be partly uncovered to ensure an adequate supply of oxygen; however, this procedure also allows some aerosolized MgO to escape. High school students are usually not fastidious and frequently do not adhere to the exacting procedural rigor that the experiment demands, in spite of explicit directions. For example, not cleaning the MgO residue off the Mg ribbon before using it, contacting the inside surface of the crucible cover (with the MgO residue) with other surfaces before massing the combusted material, not massing to constant weight, massing the hot crucible and its contents and not waiting for the balance to register a stable weight, not waiting for the specified amount of time for complete combustion to occur, contacting the combusted substance before massing with a spatula to ‘check’ for complete combustion, either partly covering the crucible with the lid before ignition or waiting too long to partly cover the crucible with the lid after ignition, using a reducing flame rather than an oxidizing one and not cleaning, drying and massing the crucible again after the experiment is completed. The equipment itself, in particular, the crucibles, have typically been used multiple

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times leaving unspecified chemical residues that may interfere with the experiment. In addition, the time and resource constraints – as an example; too usually permit students to perform the experiment again to assure reproducibility. Consequently, there is no assurance

Materials

Steel wool (Grade 00, Very Fine, diameter = 0.04 mm) was manufactured by Red Devil Inc., Pryor, OK. Steel wool (Grade 0000, Super Fine, diameter = 0.025 cm) was manufactured by Rhodes American Inc., Bellingham, WA. Both grades were obtained from a local Wal-Mart store. Hydrochloric Acid Solution, 6 M, Lot No. 194167 and Iron Oxide, Black, mixed iron (II, III) oxide , ferrosoferric oxide, Fe_3O_4, lot No. 192752 were obtained from Flinn Scientific Inc. Batvia, IL. Cotton wool was from US Cotton LLC, Rio Rancho, NM. An OHAUS balance, Ohaus Inc., Parsippany, NJ (Model Number PA153, d=0.001g) was used to weigh the materials. Evaporating dishes of diameter 8.5 cm were used as containers for the steel wool before and after combustion. Polypropylene measuring cylinders, 25 mL (d=0.5 mL) fitted with one-hole rubber stoppers were used to measure evolved gas. A Trinocular biological microscope, Model No. M837T, OMAX Inc., USA was used to observe the structure of steel wool before and after combustion. Strike on matches and a portable butane gas burner from Flinn Scientific, Batavia, IL, were used to combust the Steel Wool.

Methods

The empty evaporating dish was weighed. An amount of steel wool of the appropriate grade, with a mass of > 0.09 g and < 0.22 g was placed in the dish. The steel wool

few precision balances available for multiple experiments usually performed within a time frame of 90 minutes – do not

whether the result obtained is due to chance alone, an outlier or accurate.

strands were separated before massing so that the maximum surface area was exposed to combustion. The mass of the evaporating dish with the steel wool was recorded. The evaporating dish was removed from the balance and the steel wool was set alight using a match. Approximately 5 matchsticks were required until no further sign of combustion could be observed. The color of the steel wool sample before and after combustion was measured with a smartphone (1) kept at a distance of 10 cm from the sample under ambient lighting.

The weight of the evaporating dish with the combusted steel wool was recorded. The evaporating dish was cleaned with a paper towel and its empty weight recorded again. The weight of the non-combusted Fe was found by subtracting the mass of the evaporating dish from that of the evaporating dish with Steel wool. The mass of oxygen was found by subtracting the mass of the evaporating dish with steel wool before combustion from the mass of the evaporating dish with steel wool after combustion. The obtained values were converted to moles by dividing by their respective atomic molar masses; 55.85 $g.mol^{-1}$ for Fe and 16 $g.mol^{-1}$ for O.

The density of steel wool was assumed to be equal to the density of Fe at 8 $g.\ cm^{-3}$. Using the relationship, volume x density = mass, the length of steel wool in cm required to equal the mass of steel wool for a particular trial was iteratively calculated using an Excel spreadsheet. Note that this length is not the length of one fiber, rather it is the sum of the lengths of the many

fibers that make up the sample for a particular mass. A representative calculation is shown in the first row of Table 1. A length of 4715 cm of grade 0000 steel wool with a diameter of 0.025 mm weighs 0.185 g (Table 3, trial #1). Table 3, trial #1 also results in an oxygen mass of 0.043 g, equivalent to 2.687×10^{-3} moles of O atoms. For a 1:1 mole ratio of Fe:O, this equals $[(2.687 \times 10^{-3}) \times 55.87] = 0.15017$ g of Fe. Assuming that the steel wool preferably combusts across its length, rather than along its cross-section, an iterative input of a diameter of 0.0225 mm yields a mass of 0.15017 g of Fe, as shown in the second row of Table 1. Using this method, it was possible to determine what percent of the mass and the diameter of both the grades of steel wool needed to be combusted to result in a 1:1 molar ratio of Fe:O. The calculations also allowed the determination of the percent diameter combusted as well as the percent by weight of Fe combusted (as shown in Table 1).

Table 1: A representative calculation of the mass of Fe required to obtain an Fe:O molar ratio of 1:1, grade 0000, trial # 1. (For a complete set of calculations, please refer to the attached Excel spreadsheet in the supplementary file).

Diameter (mm)	Diameter (cm)	radius (cm)	length[a] (cm)	volume ($cm^3 \times 10^2$)	Mass (g) $\times 10^1$	Percent diameter combusted	Percent weight of Fe combusted[b]
0.0250	0.0025	0.0013	4715	2.3133	1.8506		
0.0225	0.0023	0.0011	4715	1.8771	1.5017	90.08	81.14

a. The length was input in the spreadsheet so that the resulting mass was equal to that observed in the experiment. The mass was calculated as $[\pi r^2 l \times d]$, where r=radius of the steel wool fiber, l=length of the fiber and d=density of iron (8 $g.cm^{-3}$)

b. The percent ratio of the volume for row 2 divided by the volume of row 1 (since density of Fe is constant)

For determining the mass of Fe that remained un-combusted, the combusted steel wool was cut with scissors while held above the weighing paper kept on the balance. A mass of the cut steel wool that was calculated to generate < 12 mL of H_2 was weighed and transferred to a 25 mL plastic volumetric cylinder. The cylinder was filled to the brim with 6 M HCl and a one hole stopper immediately inserted to expunge all the air in the cylinder. The hole in the stopper was previously plugged with cotton wool. The cotton wool prevented the escape of small un-combusted particles from the cylinder into the beaker. It also prevented the rapid diffusion of the HCl inside the cylinder into the water in the beaker, thereby assuring that an excess of the HCl reactant was present in contact with the combusted steel wool for the entirety of the reaction time. The cylinder was inverted and immersed into a 1 L beaker filled with water (Figure 1). Gas generation was allowed to proceed until complete; usually overnight. The cylinder height was adjusted until the water in the beaker was level with the 6 M HCl in the cylinder and the volume of the gas

generated from the reaction was read from the markings on the graduated cylinder. A similar procedure, was followed for the steel wool that was not subjected to combustion, as well as for black Iron Oxide (Fe_3O_4).

The steel wool was assumed to be in the form of solid cylinders. This was roughly corroborated using photographs taken with a Samsung smart phone when held to the eyepiece at 4X magnification.

Results and discussion

Figures 1 and 2 below (both at 4X magnification) show photographs of the steel wool before and after combustion respectively. The color of the uncombusted steel wool was grey (hexadecimal # 58625C, Hue/Saturation/Value: 150,10,39). This changed to tangaroa (hexadecimal # 1C3334, HSV: 183, 46, 21) after combustion as measured by the Color grab® application.

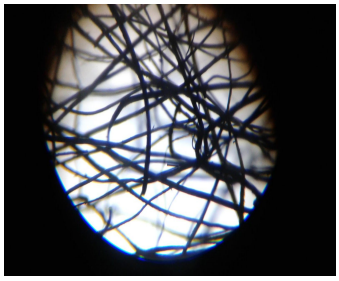

Figure 1: Steel Wool before combustion

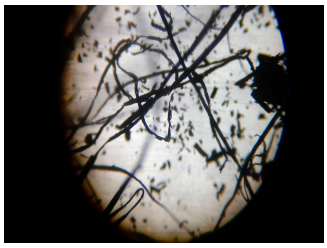

Figure 2: Steel Wool after combustion

A loss of intact fiber structure along with fragmentation is seen in the figures for the sample subjected to combustion. Figure 3 below shows the macroscopic appearance of steel wool before (top) and after (bottom) combustion.

Preliminary experiments that involved combustion of steel wool using matches resulted in a molar ratio of Fe:O of > 1 (see Tables 3 and 4 for uncorrected Fe:O mole ratio). This result is not consistent with the conventional model that +2 is the lowest oxidation state of Fe, and, in fact, argues against the accepted theories of periodicity and electron configurations. Steel wool contains > 99% Fe (2). A less than 1% compositional Fe deficit cannot produce a >20% deviation from accepted stoichiometry in the results (see Tables 3 and 4). A possible explanation to the discrepancy is that not all the Fe in the steel wool is being combusted, possibly forming a 'protective layer' of oxide on the surface that then retards or stops the Fe that is near the axial center from combusting. Whether or not all the Fe in the steel wool combusts can be determined by contacting the non-combusted and the combusted steel wool with a strong acid and measuring the volume of H_2 gas generated (equations 1 through 4). Since combusted Fe, as the oxide, is not capable of producing H_2 when reacted with HCl (equations 2, 3 and 4), if any H_2 is produced by the combusted Fe, it must originate from non-combusted Fe that has not been converted to the oxide during combustion.

Since the experiments were performed at constant temperature and pressure, the difference between the volumes of gas evolved using steel wool before and after combustion represented the mass of steel wool that was not converted to its oxide after combustion. From equation 1, since 1 mole of Fe results in the production of 1 mole of H_2, it can be calculated using the ideal gas law that 0.021 g of Fe should produce 8.4 mL of H_2 at STP.

Equation 1 $Fe + 2\ HCl \rightarrow FeCl_2 + H_2$

Equation 2 $FeO + 2\ HCl \rightarrow FeCl_2 + H_2O$

Equation 3 $Fe_2O_3 + 6\ HCl \rightarrow 2\ FeCl_3 + 3\ H_2O$

Equation 4 $Fe_3O_4 + 8\ HCl \rightarrow FeCl_2 + 2\ FeCl_3 + 4\ H_2O$

Table 2: Determination of steel wool not combusted with matches

	Before combustion	After combustion	Average percent by weight of steel wool combusted (Range%)
Grade of Steel Wool	Volume (mL) of H_2 collected[a] at 22 °C (± 0.25) mL ± RSD	Volume (mL) of H_2 collected[a] at 22 °C (± 0.25) mL ± RSD	
00	8.14 ± 3.14%	1.21 ± 45.5%	85.1% (71.9% to 93.4%)
0000	8.69 ± 0.61%	1.19 ± 25.1%	86.3% (82.7% to 90.3%)

a. n=4 for grade 0000 and n=12 for grade 00, the volume of gas collected in mL is normalized for 0.021 g mass of steel wool

The values for the percent steel wool (grade 0000) combusted are reasonably in agreement with that calculated using a molar ratio of Fe:O of 1:1 (81.78% for one individual value, from Table 3) and that measured as the difference in the volume of H_2 generated between the combusted and the non-combusted material (85.8% from Table 2). The percent relative standard deviation (RSD) for the H_2 generation experiment was >25% for grade 0000 and > 45.5% for grade 00. Different procedures, that included measuring out the combusted steel wool without further processing, using either the finer or coarser fraction of the combusted steel wool after shaking or grinding in a mortar and pestle, did not yield reproducible results. The most reproducible results were obtained when the combusted steel wool was cut with scissors directly over the weighing paper. This procedure presumably ensured that a homogeneous composition of combusted steel wool (consisting of fragmented granular material along with longer steel wool fibers was sampled. Using this combusted steel wool sample yielded the reproducibility shown in Table 2. At such large standard deviations, it is not possible to make inferences regarding the validity of using an uncombusted percentage of Fe corresponding to a 1:1 mole stoichiometry. The most that can be reasonably inferred from the results of the gas experiments is that the compounds formed during combustion are *not* Fe_3O_4 or Fe_2O_3 because the calculated ranges and average percent Fe uncombusted for these compounds; viz. 55.6% to 68.9% with an average of 61.4% for Fe_3O_4 and 48.9% to 60.3% with an average of 54.0% for Fe_2O_3 fall below and outside the range calculated and observed for the compound FeO. Some percentage of Fe in the steel wool does remain uncombusted using matches and the value of percent uncombusted Fe assumption using a 1:1 stoichiometry lie within the range of values obtained using the gas generation experiments.
Using either samples of steel wool that had been combusted with matches and subsequently with butane or Fe_3O_4 (as the negative control) did not result in the generation of any H_2 gas.

Table 3: Combustion using matches, of grade 0000 steel wool, diameter 0.025 mm

Trial #	Mass of empty evaporating dish (g)	Mass of dish and Steel Wool (g)	Mass of dish and combusted steel wool (g)	mass Steel wool (g)	mass Oxygen (g)	moles Fe (x 10^3)	moles O (x 10^3)	Fe:O mole ratio	Fe:O mole ratio using 81.78% by mass Fe combusted
1	48.485	48.67	48.713	0.185	0.043	3.312	2.687	1.23	1.01
2	48.485	48.678	48.719	0.193	0.041	3.456	2.563	1.35	1.10
3	48.485	48.668	48.712	0.183	0.044	3.277	2.750	1.19	0.97
4	44.943	45.066	45.096	0.123	0.030	2.202	1.875	1.17	0.96
5	44.942	45.049	45.074	0.107	0.025	1.916	1.562	1.23	1.00
6	44.944	45.065	45.091	0.121	0.026	2.167	1.625	1.33	1.09
7	44.944	45.039	45.064	0.095	0.025	1.701	1.562	1.09	0.89

Unsurprisingly, correcting for the non-combusted Fe in the steel wool significantly increased the accuracy of the results by two orders of magnitude. Using an Fe:O molar ratio of 1.00 as the true value, the percent errors for the uncorrected versus the corrected mass Fe combusted were 22.7% and 0.4% respectively (n=7). The average Fe:O mole ratios for the uncorrected and corrected Fe combusted were 1.23 and 1.00. The percent relative standard deviation for both, the uncorrected and corrected Fe:O ratios was 7.32%.

Table 4: Combustion using matches, of grade 00 steel wool, diameter 0.4 mm

Trial #	Mass of empty evaporating dish (g)	Mass of dish and Steel Wool (g)	Mass of dish and combusted steel wool (g)	mass Steel wool (g)	mass Oxygen (g)	moles Fe (x 10^3)	moles O (x 10^3)	Fe:O mole ratio	Fe:O mole ratio using 74.3% by mass Fe combusted
1	48.792	49.007	49.052	0.215	0.045	3.850	2.813	1.37	1.02
2	48.787	48.978	49.020	0.191	0.042	3.420	2.625	1.30	0.97
3	48.792	48.882	48.900	0.090	0.018	1.611	1.125	1.43	1.06
4	48.793	48.990	49.035	0.197	0.045	3.527	2.812	1.25	0.93
5	48.794	48.916	48.942	0.122	0.026	2.184	1.625	1.34	1.00
6	48.792	48.912	48.937	0.120	0.025	2.149	1.562	1.38	1.02
7	48.790	48.941	48.975	0.151	0.034	2.704	2.125	1.27	0.95
8	48.791	48.942	48.972	0.151	0.030	2.704	1.875	1.44	1.07

Again, the results obtained after correcting for the non-combusted Fe in the steel wool significantly increased the accuracy of the results. The percent errors for the uncorrected versus the corrected mass Fe combusted were 34.9% and 0.3% respectively (n=8). The average Fe:O mole ratios for the uncorrected and corrected Fe combusted were 1.35 and 1.02. The percent relative standard deviation for both, the uncorrected and corrected Fe:O ratios was 5.15%. These experiments were performed on a different day, yielding percent errors of 30.25% and 3.25% for the uncorrected and corrected Fe combusted respectively for a stoichiometry of Fe:O of 1:1 (see supplementary file for Excel worksheet).

If corrosion of the steel wool fiber occurred along its length, with the zone of corrosion migrating radially toward the center of the fiber strand, then – for a given method of combustion - one would expect a constant *thickness* of oxide material regardless of the diameter of the steel wool fiber used. This appears to be not the case however. Using the values of 81.78% and 74.3% by mass Fe combusted for grades 0000 and 00 respectively, the oxide layer thickness for steel wool grades 0000 and 00 is calculated to be 0.0113 mm and 0.0172 mm respectively, which are significantly dissimilar. We do not, at present, have an answer to this conundrum.

As Table 5 shows, the percent deviation from a 1:1 stoichiometric ratio of Fe:O increased as the mass of the initial Fe increased. This may be due to the the larger ratio of mass to heat energy input, even when subjected to heat from butane subsequent to combustion with matches. It is also evident that, over the range of Fe masses combusted, the percent error is the

smallest for the experiments with matches corrected for the mass of uncombusted Fe. This error is half that for the experiments where the match-combusted Fe was subsequently combusted with butane. These experiments also provided the rationale for keeping the mass of the Fe < 0.22 g when performing the match combustion experiments.

Figure 4 below shows the result of combusting the steel wool with matches (uncorrected matches), followed by combustion with butane (uncorrected butane). The figure also includes data from the matches combustion corrected for the uncombusted steel wool.

Table 5: Combustion of grade 0000 steel wool

Mass of Fe (g)	Fe:O molar ratio		
	After combustion with matches, uncorrected for mass of non combusted Fe	After combustion with matches, followed by combustion with butane, uncorrected for mass of non-combusted Fe	After combustion with matches, corrected for mass of non combusted Fe (18.2%)
0.125	1.194	1.023	0.976
0.184	1.171	0.976	0.958
0.255	1.238	1.074	1.013
0.263	1.256	1.142	1.027
0.293	1.554	1.312	1.270
Average molar ratio	1.213	1.105	1.049
Percent error	21.3	10.5	4.9

Burning a match releases 110 J of heat (3) (equivalent to 1 British Thermal Unit (BTU)). The average time that a match was held in contact with the steel wool was 5 seconds. Therefore, assuming a 1% heat transfer and an average of 5 matches, the total heat transferred to the steel wool was 55 Joules. This provided the activation energy for the conversion of Fe to FeO. The ΔH of this reaction was calculated to be -538.1 KJ_{rxn} upon rearranging equations 5 and 6 and applying Hess's law of heat summation.

Equation 5 $2\ Fe + (3/2)\ O_2 \rightarrow Fe_2O_3$ $\Delta H = -822.2\ KJ_{rxn}$

Equation 6 $2\ FeO + (½)\ O_2 \rightarrow Fe_2O_3$ $\Delta H = -284.1\ KJ_{rxn}$

The mass of butane in the cannister was 181 grams and the enthalpy of combustion of butane was taken as 2877.5 KJ mol^{-1} (4). Per the manufacturer, a cannister of butane could continuously burn for 5 hours. Hence, at 0.01 mole of butane combusted per minute, 287.7 J of heat would be transferred to the steel wool in one minute; again, assuming a 1% heat transfer. This represents 5 times the heat content of the

matches. It appears from Table 5 this amount of heat is sufficient for the steel wool to combust completely; albeit with a greater percent error of 10.5%.

It is discouraging to note that – with the exception of one manuscript (5)- *none* of the content in the public domain that purports to educate on the stoichiometry of the combustion of steel wool discusses the possibility of the steel wool not combusting all the way through, regardless of the amount of heat transferred. In addition, the product of combustion is assumed to be Fe_2O_3 (6). The discrepancy that then arises in these results is attributed to non-stoichiometric combinations of Fe and O (which do, and have been shown to exist (7)). Such non-stoichiometric Berthollide compositions themselves may not represent violations of the atomic theory; rather they could be local variations in composition of mixtures of oxides containing both oxidation states of Fe, i.e. Fe^{+2} and Fe^{+3}. Just because there are exceptions to a theory does not mean that any experiment that does not confirm to the theory can be lumped as an exception without a thorough investigation.

Conclusion

As opposed to commonly incorporated stoichiometry experiments in the curriculum, the burning of steel wool with matches can be performed in a fraction of the time, more safely, with no need for butane torches or bunsen burners. The stoichiometry of the formed oxide was found to be FeO. Since the experiment itself typically takes < 5 minutes, it can be performed multiple times in one class period, ensuring accuracy and precision. When a standard correction factor (depending on the grade of steel wool combusted) is applied to the calculations to account for the the mass of Fe not combusted, the percent error for accuracy is decreased to < 0.4%. This represents two orders of magnitude greater accuracy than that for combustion experiments currently performed; where the percent error may be as high as 22%. More importantly, all the material taught before comes across as plausible with a < 0.4% error – as opposed to students who get disillusioned with chemistry - when they arrive at a result that is far removed from the fundamentals of stoichiometry, periodicity and electron configurations that they were taught to believe before.

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