Mass Relationships in a Chemical Reaction: Incorporating Additional Graphing Exercises into the Introductory Chemistry Laboratory

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It is a customary practice in chemical education to allow introductory laboratory students to determine graphical relationships between substances undergoing chemical change. Typical plots that illustrate the relationship between reactants and products often involve the variables of mass or moles *(1, 2)*. This article is intended for instructors who would like to increase student involvement with graph construction specifically in the context of introductory laboratory activities that involve mass relationships between reacting substances and products. I am specifically thinking about the incorporation of graph construction in experiments where introductory students perform a synthesis for the first time such as the traditional syntheses of a metallic sulfide or a metallic oxide from their elements or a popular precipitation reaction such as the reaction between iron and copper sulfate *(3)*. I am advocating additional graphing not only because of the benefit of providing learners with additional opportunities to use higher-order cognitive processes but because certain mass plots represent fundamental chemical knowledge that students must know such as the law of the conservation of mass, the law of constant composition, limiting and excess reactants, as well as empirical formula.

To incorporate graphing exercises involving mass relationships into lab activities, three simple actions are necessary:

(i) The quantities of reactants that have undergone transformation and the quantities of products that have been made as a result of the chemical reaction must be directly measured or deduced

(ii) The mass of reactants in the experiment must be varied

(iii) To save time, students should work in groups and pool data

In regard to these conditions, I have collected and described a variety of mass plots that have been developed and used in our general chemistry program. After each different graph, I have included a set of questions along with their answers that educators might find useful to prompt students' understanding of the graphical relationship between specific variables. While each plot is not completely novel, taken together the collection is a contribution to the graphing literature in chemical education. The mass plots that will be presented are based on the synthesis of zinc iodide from its elements and are taken from our instructor's manual *(4)*. Since these plots are not necessarily dependent upon these chemical substances, educators might consider adapting the plots to the reactions they presently use to illustrate some of the above chemical concepts.

Table 1. Masses of Zinc and Iodine per Synthesis

Assigned Synthesis Number	Initial Mass of Zinc/g	Initial Mass of Iodine/g	Volume of Water/mL
1	2.0	3.0	10
2	1.0	2.0	5
3	2.0	1.0	5
4	3.0	2.0	5

The Synthesis of Zinc Iodide

To show how I varied the mass of reactants to promote graph construction, I have simply required students to form groups of four, do as many trials as they can of their assigned synthesis and then pool their data. Table 1 is given out at the beginning of the laboratory activity. The procedure for the reaction has been described in a previous issue of this *Journal (5)*. The chemical equation for this reaction is:

$$Zn(s) + I_2(s) + H_2O(l) \rightarrow ZnI_2(s) + H_2O(g)$$

The manner in which this reaction is used in the lab calls for iodine to be the limiting reactant; any quantities of iodine larger than the ones listed here will demand more water to be used, which will prolong the isolation of the product.

Hazards

When properly handled, zinc and solid iodine are nontoxic or only pose slight hazards. Iodine gas is toxic, but is not produced in this activity. Zinc, iodine, and zinc iodide can be disposed of by changing the solids to ions and then diluting them in a drain attached to a sewer system at a rate that is in compliance with local authorities. Recycling of the excess zinc after the synthesis also can be done if desired.

Graph 1: Mass of Reacting Iodine versus Mass of Reacting Zinc

This graph (Figure 1) allows students to realize that a relationship exists between the quantities of reactants that undergo chemical change. Based on the linear plot there is a proportional relationship between the reacting species; no matter how much of the two reactants react, their ratio is always fixed. This gives rise to the law of constant composition or definite proportions.

Question: Comment on the graphical relationship between the reacting mass of zinc and the mass of reacting iodine.

Answer: There is a linear relationship between the mass of iodine reacted and the mass of zinc that reacted. Zinc and iodine react in a certain fixed manner. This is apparent because not all reactants react entirely: zinc is excess and was observed to be left behind in the test tube, and iodine is limiting since it was no longer visible in its original form.

Question: What is the specific chemical law that defines the relationship in graph 1 (look in your textbook if necessary)?

Answer: The name of the relationship is called the law of constant composition or definite proportions.

Question: Using the graph you have made, predict how much zinc would react with 2.75 g of iodine. After doing this, can you comment on the utility of making a graph?

Answer: About 0.7 g of zinc should react with 2.75 g of iodine. The graph is valuable because new experiments do not have to be run.

Question: Comment on the relationship between the slope of the line in this graph and the molar mass ratio of iodine (I_2) to zinc (Zn) found from the periodic table.

Answer: From the periodic table, the molar mass of I_2 is 253.8 g/mol and the molar mass of Zn is 65.38 g/mol. The ratio of iodine to zinc is 3.882. The molar mass ratio and the slope of the line in the graph are very close to each other. This similarity supports the law of constant composition.

Question: Why is iodine the limiting reactant in all of the experiments? Explain in terms of the slope.

Answer: The mass ratio or slope that was found suggests that 3.8 g of iodine will react with 1 g of zinc. This ratio holds for the quantities of zinc and iodine in this experiment. If the mass of one reactant initially weighed out is less than dictated by the ratio, that substance will be used up or limiting. The quantity of iodine that was given never exceeded the ratio; therefore, it is limiting in all the experiments.

Question: When will iodine be the excess reactant instead of the limiting? Give an example in terms of the slope.

Answer: Iodine will be in excess when the mass of iodine initially weighed out is more than dictated by the mass ratio. For example, if 3.9 g of iodine and 1 g of zinc were used we would have 0.1 g of iodine left over.

Question: Why is zinc the excess reactant in all these experiments? Explain in terms of the slope.

Answer: Zinc is left over after a reaction for the same reason iodine is all used up. More of zinc is given than dictated by the mass ratio of 3.8.

Question: When will zinc be the limiting reactant instead of the excess? Give an example in terms of the slope.

Answer: Zinc will be all used when it does not exceed the mass ratio. For example if 3.8 g of iodine and 0.9 g of zinc were given, all the zinc would react and about 0.4 g of iodine would be left over or in excess.

Graph 2: Mass Ratio of Reacting Iodine to Reacting Zinc versus Mass of Zinc Weighed Out

This is another way of addressing the meaning of a fixed mass ratio as described in the law of constant composition. If a ratio is fixed it should not be influenced or be dependent upon other variables such as how much of the reactants are initially weighed out. For example, when the mass ratio of iodine to zinc is plotted against the mass of zinc initially weighed out a straight line is produced with a slope close to zero (Figure 2). A zero slope is also found when students plot the mass ratio against the initial mass of iodine, the limiting reactant. Taken together, the mass ratio is constant and is independent of the initial quantities of the reactants. It is interesting to note that with quality data and plots, many students have difficulty interpreting this graph correctly.

Question: Comment on the shape and slope of the second graph. What is the relationship between the variables that you plotted?

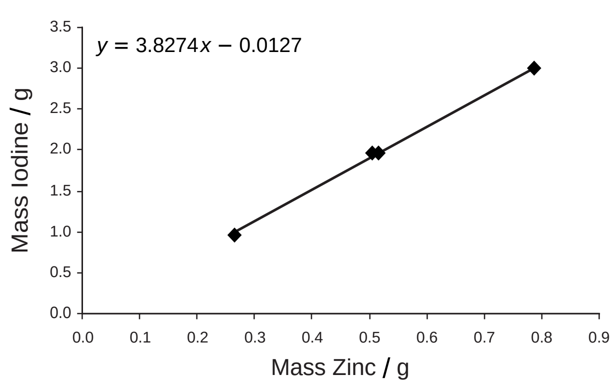

Figure 1. Mass of reacting iodine versus the mass of reacting zinc.

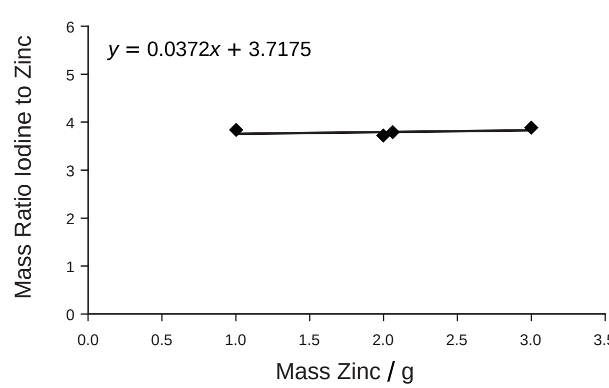

Figure 2. Mass ratio of reacting iodine to reacting zinc versus the mass of zinc weighed out.

Answer: The plot is linear and the slope is 0.04, which is close to zero. This indicates that the mass ratio does not change with respect to the changing quantity of zinc initially used in the experiments. The mass ratio is constant and is not affected by the initial quantities of the reactants.

Graph 3: Mass of Reacting Iodine versus Mass of Zinc Iodide Produced

Graph 3 (Figure 3) introduces the product as a variable. It shows that the more iodine that reacts, the more product will be produced. This graph is also useful because it represents how much iodine is in zinc iodide in terms of percent composition.

Question: Comment on the shape of graph 3.

Answer: A positive linear relationship is evident. The quantity of product is in direct proportion to how much iodine reacts.

Question: Convert the slope of the plot in graph 3 to a percent. What does this tell you?

Answer: Changing the slope of graph 3 to percent will produce 79.1%. This means that zinc iodide is made up of 79.1% iodine (I not I_2). This value is close to the value of 79.5% calculated from the periodic table.

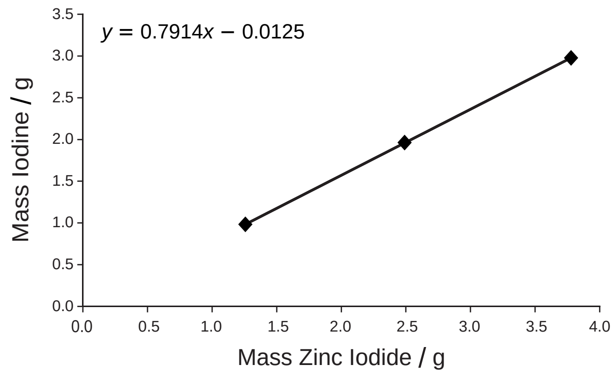

Figure 3. Mass of reacting iodine versus mass of zinc iodide produced.

Graph 4: Mass of Reacting Zinc versus Mass of Zinc Iodide Produced

This graph (Figure 4) is similar to the preceding one, but it involves zinc instead of iodine. The comparison of the two graphs allows one to draw the students' attention to the differences in slopes, which translates to the different percent of the elements in the product. If an empirical formula is not known, this could lead to its determination as well as a balanced chemical equation. Students can confirm the values of the coefficients in their balanced chemical equation by producing mole plots. For example, the moles of reacting zinc can be plotted against the moles of zinc iodide produced. A slope close to 1 would support the 1:1 mole ratio between this reactant and the product zinc iodide.

Question: Comment on the shape of graph 4.

Answer: A positive linear relationship is evident with this graph. The quantity of product is in direct proportion to how much zinc reacts.

Question: Convert the slope to a percent. What does this tell you?

Answer: Changing the slope of graph 4 to percent will produce a value of 20.7%. This means that zinc iodide is made up of 20.7% zinc. This value is close to the value of 20.5% calculated from the periodic table.

Question: Use the percents found in graphs 3 and 4 to calculate the empirical formula and write a balanced chemical equation between zinc metal, iodine, and zinc iodide.

Answer: The empirical formula is ZnI_2, and the balanced chemical equation is: $Zn(s) + I_2(s) \rightarrow ZnI_2(s)$.

Graph 5: Masses of Reacting Zinc and Iodine versus Mass of Zinc Iodide Produced

This graph (Figure 5) combines graphs 3 and 4. When one examines the quantities of zinc and iodine reacted, it is evident that a proportional quantity of product is produced. Furthermore, the mass values between reactants and products are nearly the same (the slope is nearly 1) indicating that mass of the reactants are conserved through chemical change.

Question: What does the plot in graph 5 tell you in terms of conservation?

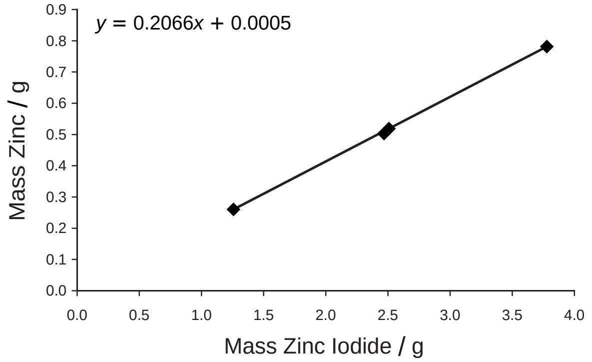

Figure 4. Mass of reacting zinc versus the mass of zinc iodide produced.

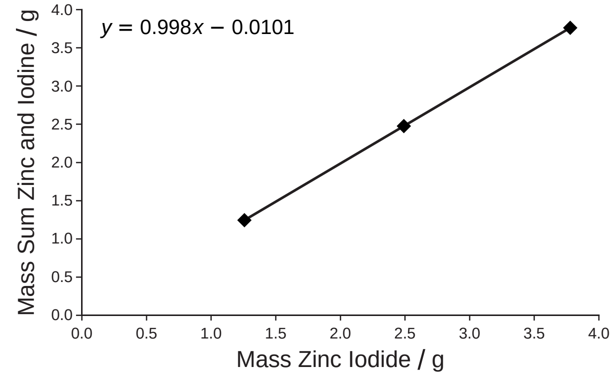

Figure 5. Masses of reacting zinc and iodine versus the mass of zinc iodide produced.

Answer: The sum of the masses of reacting zinc and iodine is nearly equal to the mass of zinc iodide. Also the slope of graph 5 is 0.998 or nearly 1. Both indicate that mass is conserved within experimental error. If one expresses the slope in terms of a percent, 99.8%, the reaction can be said to go to completion.

Question: Now review your plots. Which plots have two data points that overlap or nearly overlap each other? Explain this occurrence in graph 1, for example.

Answer: Graphs 1 through 5 have two data points that are close together. In graph 1, the two points correspond to initial weighing of 1.0 g of zinc and 2.0 g of iodine, and 2.0 g of zinc and 2.0 g of iodine. The two data points indicate that for both initial weighings only about 0.51 g of zinc reacted and 2.0 g of iodine reacted. These similar values for both data points indicate that iodine limits the reaction with zinc. Only a specified quantity of zinc will react with iodine with the rest being in excess.

Another plot relevant to this discussion would show how one reactant can go from being an excess reactant to a limiting reactant *(6)*. This type of plot cannot be made with the zinc iodide reaction since students must be given quantities that will always allow zinc to be the excess reactant. If instead iodine was the excess reactant, it would be more difficult to isolate and quantify the product within the time consideration of an academic lab.

Conclusion

The five mass plots presented above are visual summaries of data that when analyzed represent fundamental conceptual knowledge that introductory students are required to know. When students construct the graphs and answer the accompanying questions sets, they are being asked to become more involved in the interpretation of results. This requires students to draw upon as well as to develop higher levels of cognitive activity to understand the relationships between plots and chemical concepts. Varying the quantities of reactants in a synthesis and allowing students to pool data could provide educators with the means to increasing the time students are involved in higher-order learning.

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