# 3.3.4: Everyday Life - Sodium Silicide Fueled Bicycles

Previously, we explored the Stoichiometry of hydrogen powered bicycles that "run on water". They typically have a rechargeable battery pack and electric hub motor. The company that makes the electrical fuel cell won a Presidential Green Chemistry Award[1].


Electric hub motors on front or back wheels

Now we'll see how the water cannister and fuel canister need to be matched for maximum range.

In the laboratory as well as the environment, inexpensive reagents like atmospheric $O_2$ or water are often supplied in excess. Some portion of such a reagent will be left unchanged after the reaction. Conversely, at least one reagent is usually completely consumed. When it is gone, the other excess reactants have nothing to react with and they cannot be converted to products. The substance which is used up first is the **limiting reagent**.

A new electricity source combines a hydrogen fuel cell with a ***"sodium silicide"*** fuel cartridge, winner of a "Green Chemistry Challenge Award"[2]. The sodium silicyde reacts with water to make the hydrogen fuel [3][4][5]:

$$2\ NaSi(s) + 5H_2O(l) \rightarrow Na_2Si_2O_5(s) + 5H_2(g)\ (1)$$

The composition of sodium silicide may depend on the method of synthesis. Silicides can be made by the reaction of active metals (like Mg) with sand, or by heating sodium with silicon. Dye et al [6] prepare sodium silicide by the reaction of sodium metal with silica gel, obtaining black powders of (hypothetically) $Na_4Si_4$ nanoparticles.

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## Example 1

Sodium silicide/water bikes produce about 200W to run a bicycle for about 30 miles with a NaSi cartridge weighing about 1.5 lb [7]. If a bicyclist wants to travel about 30 miles and brings 1 quart of water and one 1.5 lb cartridge, which is the limiting reagent? What mass of solid product will be formed?

**Solution**

The balanced equation

$$2\ NaSi(s) + 5H_2O(l) \rightarrow Na_2Si_2O_5(s) + 5H_2(g)\ (1)$$

tells us that according to the atomic theory, 2 mol NaSi is required for each 5 moles of $5H_2O$. That is, the stoichiometric ratio $S(NaSi/H_2O)$ = 2 mol NaSi/ 5 mol $H_2O$. Let us calculate the amount in moles of each we actually have, assuming the density of water is 1.00 g/mL:

$$m_{H_2O} = 1\text{ quart} \times \frac{1\text{ L}}{1.05668821\text{ quart}} \times \frac{1000\text{ g}}{1\text{ L}} = 1057\text{ g}$$

$m_{NaSi} \;=\; < math > 1.5\text{ lb} \times \frac{453.59\text{ g}}{\text{quart}} \;=\; 680\text{ g}$

$n_{NaSi} = 680\text{ g} \times \frac{1\text{ mol NaSi}}{51.075\text{ g}} = 13.3\text{ mol NaSi}$

$n_{H_2O} = 1057\text{ g} \times \frac{1\text{ mol }H_2O}{18.015\text{ g}} = 58.57\text{ mol }H_2O$

If all the $H_2O$ were to react, the stoichiometric ratio allows us to calculate the amount of NaSi that would be required:

$n_{NaSi} \;=\; n_{H_2O} \;\times\; \frac{2\text{ mol NaSi}}{5\text{ mol }H_2O} \;=\; 23.5\text{ mol NaSi}$

This is more than the amount of NaSi present,so NaSi is the ***limiting reactant*** and $H_2O$ is present in excess.

If all the NaSi reacts, the stoichiometric ratio allows us to calculate the amount of $H_2O$ that would be required:

$n_{H_2O} \;=\; n_{NaSi} \;\times\; \frac{5\text{ mol }H_2O}{2\text{ mol NaSi}}$

$= 13.3\text{ mol NaSi} \;\times\; \frac{5\text{ mol }H_2O}{2\text{ mol NaSi}} \;=\; 33.3\text{ mol }H_2O$

We require less than the amount of $H_2O$ present, so it is the ***excess reactant***.

When the reaction ends, 13.3 mol of NaSi will have reacted with 33.3 mol $H_2O$ and there will be

(58.57 mol - 33.3 mol) = 25.4 mol $H_2O$ left over. NaSi is therefore the limiting reagent.

b. Since the water doesn't all react, we need to calculate the amount of solid product produced from the amount of NaSi consumed, by using the stoichiometric ratio:

$n_{Na_2Si_2O_5} \;=\; n_{NaSi} \;\times\; \frac{1\text{ mol }Na_2Si_2O_5}{2\text{ mol NaSi}} \;=\; 6.65\text{ mol }Na_2Si_2O_5$

The mass of water is then calculated by using the molar mass:

$6.65\text{ mol }Na_2Si_2O_5 \;\times\; \frac{182.148\text{ g}}{1\text{ mol }Na_2Si_2O_5} \;=\; 1211\text{ g }Na_2Si_2O_5$

c. About a pound (458 g) of water will react, and 1057-458 = 599 g of water will remain. That's enough for another 1.5 lb canister of NaSi.

These calculations can be organized as a table, with entries below the respective reactants and products in the chemical equation. We can calculate (hypothetically) how much of each reactant would be required if the other were completely consumed to demonstrate which is in excess, and which is limiting. We use the amount of limiting reagent to calculate the amount of product formed.

| | 2 NaSi | + 5 $H_2O$ | → 1 $Na_2Si_2O_5$ | + 5 $H_2$ |
|---|---|---|---|---|
| m (g) | 680 | 1057 | | |
| M (g/mol) | 51.075 | 18.015 | 182.148 | 2.016 |
| n (present,mol) | 13.3 | 58.57 | | |
| ~~if all $H_2O$ reacts~~ | ~~-58.67~~ | ~~-23.50~~ | ~~+11.73~~ | |
| if all NaSi reacts | -13.3 | -33.3 | +6.65 | +33.3 |
| Actual Reaction Amounts | -13.3 | -33.3 | +6.65 | +33.3 |
| Actual Reaction Masses | -680 | -600 | +1211 | +67.2 |

In the end, 1057 - 599 = 458 g of $H_2O$ will remain, along with 1211 g of sodium silicate. The 67.2 g of hydrogen produced gives a total of 1736 g. The mass of the reactants was also 1057 + 680 = 1737 g, equal within the error of measurement.

## General Strategy for Limiting Reactant Problems

From this example you can begin to see what needs to be done to determine which of two reagents, X or Y, is limiting. We must compare the stoichiometric ratio S(X/Y) with the actual ratio of amounts of X and Y which were initially mixed together.

The general rule, for any reagents X and Y, is

$$\text{If } \frac{n_{\mathrm{X}}(\text{initial})}{n_{\mathrm{Y}}(\text{initial})} \text{ is less than S}\left(\frac{\mathrm{X}}{\mathrm{Y}}\right)\text{, then X is limiting.} \tag{3.3.4.1}$$

$$\tag{3.3.4.2}$$

$$\text{If } \frac{n_{\mathrm{X}}(\text{initial})}{n_{\mathrm{Y}}(\text{initial})} \text{ is greater than S}\left(\frac{\mathrm{X}}{\mathrm{Y}}\right)\text{, then Y is limiting.} \tag{3.3.4.3}$$

(Of course, when the amounts of X and Y are in exactly the stoichiometric ratio, both reagents will be completely consumed at the same time, and neither is in excess.). This general rule for determining the limiting reagent is applied in the next example.

## Example 2

Suppose the sodium silicide made by a different method is $Na_2Si$ [8][9], and it produces ordinary "water glass", or sodium silicate ($Na_2SiO_3$(s)[10]) rather than $Na_2Si_2O_5$(s)[11]. In that case, if the bicyclist wants to travel about 30 miles and brings 1 quart of water and one 1.5 lb cartridge, which is the limiting reagent?

**Solution**

The balanced equation is:

$Na_2Si$(s) + $3H_2O$(l) → $Na_2SiO_3$(s) + $3H_2$(g) (1)

Now the stoichiometric ratio S(NaSi/$H_2O$) = 1 mol $Na_2Si$/ 3 mol $H_2O$. Again, let's calculate the amount in moles of each we actually have, assuming the density of water is 1.00 g/mL:

$$\mathrm{m_{H_2O}} \;=\; 1\text{ quart} \times \frac{1\text{ L}}{1.05668821\text{ quart}} \times \frac{1000\text{ g}}{1\text{ L}} = 1057\text{ g}$$

$$\mathrm{m_{NaSi}} \;=\; <math> 1.5\text{ lb} \times \frac{453.59\text{ g}}{\text{quart}} = 680\text{ g}$$

$$\mathrm{n_{Na_2Si}} \;=\; 680\text{ g} \times \frac{1\text{ mol Na}_2\text{Si}}{74.065\text{ g}} = 9.18\text{ mol Na}_2\text{Si}$$

$$\mathrm{n_{H_2O}} = 1057\text{ g} \times \frac{1\text{ mol H}_2\text{O}}{18.015\text{ g}} = 58.57\text{ mol H}_2\text{O}$$

If all the $H_2O$ were to react, the stoichiometric ratio allows us to calculate the amount of NaSi that would be required:

$$\mathrm{n_{Na_2Si}} \;=\; \mathrm{n_{H_2O}} \;\times\; \frac{1\text{ mol Na}_2\text{Si}}{3\text{ mol H}_2\text{O}} \;=\; 19.52\text{ mol Na}_2\text{Si}$$

This is more than the amount of $Na_2Si$ present,so $Na_2Si$ is the ***limiting reactant*** and $H_2O$ is present in excess.

If all the $Na_2Si$ reacts, the stoichiometric ratio allows us to calculate the amount of $H_2O$ that would be required:

$$\mathrm{n_{H_2O}} \;=\; \mathrm{n_{Na_2Si}} \;\times\; \frac{3\text{ mol H}_2\text{O}}{1\text{ mol Na}_2\text{Si}}$$

$$= 13.3\text{ mol Na}_2\text{Si} \;\times\; \frac{3\text{ mol H}_2\text{O}}{1\text{ mol Na}_2\text{Si}} \;=\; 27.54\text{ mol H}_2\text{O}$$

We require less than the amount of $H_2O$ present, so it is the ***excess reactant***.

When the reaction ends, 9.18 mol of $Na_2Si$ will have reacted with 27.54 mol $H_2O$ and there will be:

(58.57 mol - 27.54 mol) = 31.03 mol $H_2O$ left over. $Na_2Si$ is therefore the limiting reagent.

These calculations can again be organized as a table, with entries below the respective reactants and products in the chemical equation. We can calculate (hypothetically) how much of each reactant would be required if the other were completely consumed to demonstrate which is in excess, and which is limiting. We use the amount of limiting reagent to calculate the amount of product formed.

| | 1 $Na_2Si$ | + 3 $H_2O$ | → 1 $Na_2SiO_3$ | + 3 $H_2$ |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| m (g) | 680 | 1057 | | |
| M (g/mol) | 74.065 | 18.015 | 122.06 | 2.016 |
| n (present,mol) | 9.18 | 58.57 | | |
| ~~if all $H_2O$ reacts~~ | ~~-58.67~~ | ~~-19.52~~ | ~~+58.67~~ | ~~+19.52~~ |
| if all NaSi reacts | -9.18 | -27.54 | +27.54 | +9.18 |
| Actual Reaction Amounts | -9.18 | -27.54 | +27.54 | +9.18 |
| Actual Reaction Masses | -680 | -496 | +1121 | +55.5 |

In the end, 1057 - 496 = 561 g of $H_2O$ will remain, along with 1121 g of sodium silicate. The 55.5 g of hydrogen produced gives a total of 1176 g. The mass of the reactants was also 496 + 680 = 1176 g, equal within the error of measurement.

This process seems less efficient than the one in Example 1, because only 55.5 g of hydrogen is produced, compared to 67.2 g in Ex. 1. Also, 496 g of water and 680 g of silicide are consumed (totalling 1176 g), while in Ex. 1, 599 g water and 680 g of silicide (1280 g total) were consumed, so we get 0.047 g hydrogen/g reactants in Ex. 2, while we get 0.053 g hydrogen/g reactants in Ex. 1.

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