

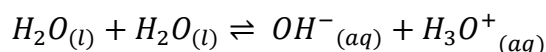
# ***Investigating the relationship between the pH of a solution and the rate of corrosion of iron in the solution***

## **Introduction:**

The process of corrosion of iron consists of the formation of hydrated oxide, that is,  $Fe(OH)_3$ ,  $FeO(OH)$ , and  $Fe_2O_3 \cdot H_2O$ . It is an electrochemical process which requires oxygen, water, and an electrolyte. Corrosion of iron is seen in our everyday life and is most commonly known as rust. Even as a child, when I was not aware of chemistry, I had noticed rust everywhere. One time, when I was playing a game of air hockey with my brother and held onto a metal pole, I realised it was rough, and that small brown flakes had fallen onto my hand. I also noticed the chains on my bicycle undergoing the same phenomenon. Later I learned that this was due to the presence of oxygen and moisture in the air. As I learned about the formation of rust, my interest in this topic was piqued. Researching further, I realised that corrosion is actually a major problem in today's society. This problem costs us more than all other natural disasters combined. In the USA alone it costs 437 billion dollars per year. Rust affects everything on this planet, and the battle against corrosion plays a vital part in the development of our future. Upon learning this, I was eager to investigate this process and find out how to minimize it. This led me to form the following research question: **How is the rate of corrosion of iron in a solution affected by the change in the pH of the solution?**

## **Background Knowledge:**

Pure water, which has no added electrolytes, is slightly electrically conductive. This indicates that there are ions present in the water, as it is known that water has no delocalized electrons. This occurs due to the autoionization of water<sup>1</sup>:



Where  $OH^{-}$  is a hydroxide ion and  $H_3O^{+}$  is a hydronium ion<sup>2</sup>. Hydronium ions are dissociated hydrogen ions present in the water which have bonded with water molecules. If the concentration of hydroxide ions,  $[OH^{-}]$ , and the concentration of hydronium ions,  $[H_3O^{+}]$ , are equal then the solution is considered neutral. As we can see through the formula, pure water will always have equal concentrations of hydroxide ions and hydronium ions and is thus a neutral solution of pH 7.

The equations below in this section taken from an online experiment<sup>3</sup>. Once we place the iron rod into the water, the pure, solid iron ionizes in water:

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<sup>1</sup> Clark, J. (2020, August 16). *Water Autoionization*. Chemistry LibreTexts.

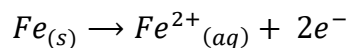
[https://chem.libretexts.org/Bookshelves/Physical\\_and\\_Theoretical\\_Chemistry\\_Textbook\\_Maps/Supplemental\\_Modules\\_\(Physical\\_and\\_Theoretical\\_Chemistry\)/Acids\\_and\\_Bases/Acids\\_and\\_Bases\\_in\\_Aqueous\\_Solutions/Water\\_Autoionization#:~:text=Water%2C%20even%20pure%20water%2C%20has,will%20form%20in%20pure%20water.&text=Thus%2C%20the%20proton%2Ddonating%20molecule,ion%2C%20H3O%2B.](https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Acids_and_Bases/Acids_and_Bases_in_Aqueous_Solutions/Water_Autoionization#:~:text=Water%2C%20even%20pure%20water%2C%20has,will%20form%20in%20pure%20water.&text=Thus%2C%20the%20proton%2Ddonating%20molecule,ion%2C%20H3O%2B.)

<sup>2</sup> LibreTexts. (2020, August 16). *The Hydronium Ion*. Chemistry LibreTexts.

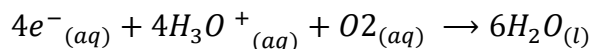
[https://chem.libretexts.org/Bookshelves/Physical\\_and\\_Theoretical\\_Chemistry\\_Textbook\\_Maps/Supplemental\\_Modules\\_\(Physical\\_and\\_Theoretical\\_Chemistry\)/Acids\\_and\\_Bases/Acids\\_and\\_Bases\\_in\\_Aqueous\\_Solutions/The\\_Hydronium\\_Ion](https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Acids_and_Bases/Acids_and_Bases_in_Aqueous_Solutions/The_Hydronium_Ion)

<sup>3</sup> Lee, M. (2007). *Rusting Rates of Iron Nails*. Growth & Development.

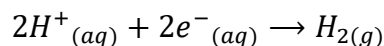
<http://www.csun.edu/~7Eml727939/coursework/695/rusting%20rates%20of%20iron%20nails/rusting%20rates%20of%20iron%20nails.htm>



The resultant electrons will react with dissolved oxygen and dissociated hydrogen ions present in the water, that is, the aforementioned hydronium ions, to form water.

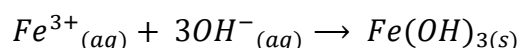
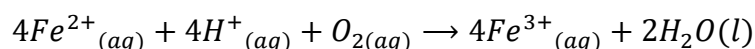
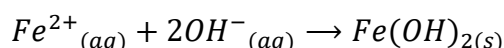


At extremely low pH values, the hydrogen ions react directly with the electrons:

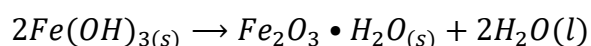


From the above equations we can see that if the pH of the solution is lower, the rate of corrosion would be faster, as there would be more hydronium ions due to acid dissociating and thus the electrochemical process would occur at a greater rate. From the above equation of autoionization, we can see that the water will be in equilibrium with the hydronium and hydroxide ions. Thus, the produced water will once again break down into hydronium and hydroxide ions until an equilibrium is reached.

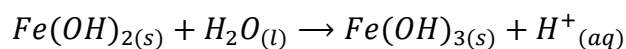
The iron cations then react with the hydroxide and hydronium ions to form several different compounds, which will eventually result in the formation of different kinds of rust. In the equations below, the hydronium ions are simplified to aqueous hydroxide ions ( $H^{+}_{(aq)}$ ), as we can cancel out the water molecule from both sides of the equation.



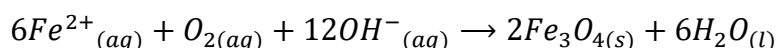
The  $Fe(OH)_{3(s)}$  rust is porous and will slowly disintegrate into a crystallized form, which is the most common form of rust.



The  $Fe(OH)_{2(s)}$  can also form rust:



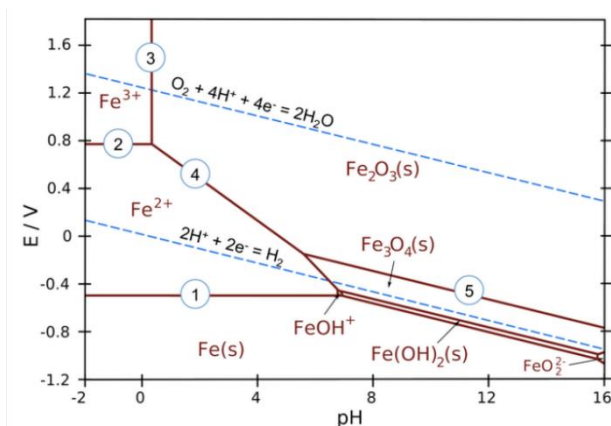
The amount of oxygen is also of importance. Only in the cases where there is limited oxygen present is  $Fe_3O_{4(s)}$  formed, which is a black solid commonly known as lodestone.



The lodestone forms a passivation layer around the iron and slows down the rate of corrosion. However, I will be conducting the experiment with enough dissolved oxygen present in the water, which will lead to a negligible amount of lodestone forming. Thus, I have not taken lodestone into consideration for the rest of my IA.

On the right is a simplified Pourbaix diagram<sup>4</sup> for iron in an aqueous solution at 298 K and at ionic concentrations of 1mM:

A Pourbaix diagram, which is also known as a potential/pH diagram, shows the most stable species in a solution by plotting the electrochemical stability of the species as a function of pH. It involves both acid-base reactions, which are pH dependant, and redox reactions, which are dependent on potential. Other factors include temperature, pressure, and the concentration of the species present, and thus, in the above Pourbaix diagram, these conditions are kept constant.



**Figure 1:** Pourbaix diagram for iron at 25°C

The lines mark the equilibrium between two species where both species will be present in similar amounts, and the areas mark the single predominate specie in the solution. The vertical lines are purely acid-base reactions, and they depend only on hydrogen ions. The horizontal lines are purely redox reactions, and they only involve electron transfer. The sloped lines are dependent on both electrons and hydrogen ions, and thus are both acid-base and redox reactions.

Water is only stable in the region between the blue lines. If water is above the top blue line, it will produce oxygen, and if it is below the bottom blue line, then hydrogen will be generated. If the water is well oxygenated, the potential would be closer to the top blue line. As iron always has lower potential than water, it will always ionize and corrode in water. As the pH increases, it enters the region of passivation where a passivation film is formed, consisting of insoluble oxides. It is not clear what the film is made up of, however, it is considered to consist of  $Fe_2O_3$ , which can also be hydrated, and  $FeO(OH)$ . At pH values below 4, the passivation film becomes soluble. At this point the hydrogen reacts directly with the electrons to produce hydrogen, as mentioned earlier, and thus hydrogen evolution begins. At pH values greater than 10, there is an increase in the formation of the passivation film made up of  $Fe_2O_3$  due to an increase in the reaction between oxygen and  $Fe(OH)_2$ .

In my experiment, I will be investigating the rate of corrosion of an iron nail in solutions with different values of pH. The container lid will be left open so that oxygen can enter the solution for the reaction to occur. We can measure the rate of corrosion by the increase in the mass of the nail per unit time, as the oxygen would react with the iron to form rust and increase the mass of the nail. However, some rust may fall off while removing the nail from the solution to measure its mass. Although the amount may be small, since the experiment is only 10 days long, this small loss may significantly impact my experiment. Hence, I decided to measure the mass of the whole container, as the only increase in mass would be by the rusting of the nail. To this effect, a measuring cylinder will be used as the container, to enable more accurate volume measurements. However, we still face a problem – evaporation, due to the open lid, which will change the volume of the solution.

<sup>4</sup> LibreTexts. (2020, December 4). 4.6: Pourbaix Diagrams. Chemistry LibreTexts. [https://chem.libretexts.org/Bookshelves/Inorganic\\_Chemistry/Book%3A\\_Introduction\\_to\\_Inorganic\\_Chemistry/04%3A\\_Redox\\_Stability\\_and\\_Redox\\_Reactions/4.06%3A\\_Pourbaix\\_Diagrams](https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Book%3A_Introduction_to_Inorganic_Chemistry/04%3A_Redox_Stability_and_Redox_Reactions/4.06%3A_Pourbaix_Diagrams)

This will then change the mass of the container, but through certain mathematical processes, we can find the mass of the container at different volumes, allowing us to effectively control the volume of the solution.

### **Hypothesis:**

As the pH decreases, the species that are thermodynamically favoured are iron ions, and thus they lie within a region of corrosion, leading to a greater rate of corrosion. At higher pH values, the rate of corrosion will be slower, as  $Fe_2O_3$  is the predominate specie and thus it is within a region of passivation. When the passivation film becomes soluble at low pH values, the rate of corrosion will increase drastically. At pH values greater than 10, the corrosion rate drops suddenly, due to a sudden increase in the formation of a passivation film.

### **Variables:**

Independent Variable: pH of the solution. Ranges of pH were created by using concentrated acid, diluted acid, distilled water, diluted base, and concentrated base.

Dependant Variable: Mass of the container (g).

### **Control Variables:**

#### 1) Temperature:

- a) Reason: The rate of corrosion is affected by a change in temperature. When temperature rises, the rate of reaction increases. This can also be seen as a factor in the Pourbaix diagram changes.
- b) Method: To keep the temperature constant at 25°C, the experiment was conducted in a room with the air-conditioner switched on.

#### 2) Pressure:

- a) Reason: Changes in pressure affect the rate of corrosion. Just like temperature, this can also be seen as a factor in the Pourbaix diagram changes.
- b) Method: The experiment was conducted in an enclosed room with fixed volume and temperature. Thus, pressure was also kept constant.

#### 3) Volume of Solution:

- a) Reason: Changes in the volume of the solution would also change the mass of the solution.
- b) Method: The volume of solution could not be controlled as the lid had to be kept open for sufficient oxygen to enter the measuring cylinder, thus leading to evaporation. Therefore, as mentioned earlier, mathematical processes will be used to find the mass of the solution at different volumes. This enables us to effectively control the volume and compare just the masses.

#### 4) Surface Area of Iron Nails:

- a) Reason: The surface area of the iron nails has to remain constant because if more iron is exposed to the solution then the rate of corrosion would be faster.
- b) Method: A packet of identical nails was bought and used for the experiment.

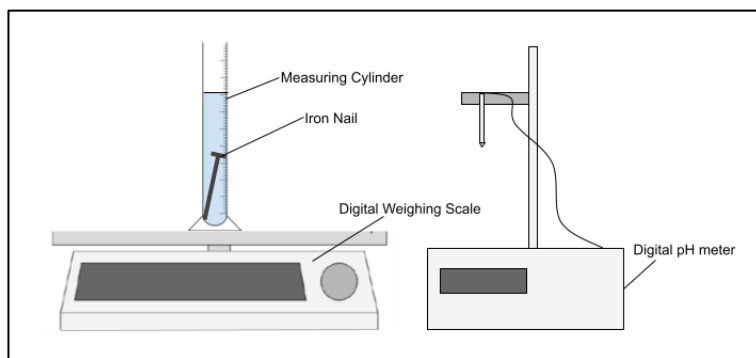
### **Apparatuses and Material:**

**Apparatuses:**

- Measuring cylinders ( $150\text{cm}^3$ )
- Digital Weighing Scale
- Electronic pH meter

**Methodology:****Procedure:**

- 1) Measure the mass of an empty measuring cylinder using the digital weighing scale.
- 2) Measure the mass of one iron nail.
- 3) Add the iron nail to the measuring cylinder.
- 4) Fill the measuring cylinder with distilled water until the  $100\text{cm}^3$  mark.
- 5) Use the pH meter to check the pH of the distilled water.
- 6) Repeat steps 1 to 6 three times.
- 7) Repeat Steps 1 to 7 with hydrochloric acid (concentrated), hydrochloric acid (diluted), sodium hydroxide (concentrated), and sodium hydroxide (diluted).
- 8) Check on the experiment on the third, sixth and tenth day to record the new mass and volume of each of the solutions.



**Figure 2: Experimental Setup**

**Safety Instructions:**

The use of concentrated acids and bases is extremely dangerous. Therefore, safety glasses and gloves should be worn at all times, and the solutions should be handled with care, with a supervisor watching over the experiment. Glassware can be broken easily and can lead to cuts, and so can the iron nails. Thus, the glassware and sharp objects should be handled carefully to avoid injury. Disposal of the acidic and basic solutions can pose danger to the environment. The waste can be stored and disposed as hazardous chemical waste. There are no ethical concerns in this experiment.

**Data Collection and Analysis:****Qualitative Observations:**

- For the extremely acidic solutions, effervescence was observed around the nail during the start of the experiment. This can be attributed to the production of hydrogen when hydrogen evolution begins. At this point, the corrosion will form some rust and hydrogen both. As the hydrogen escapes the container, the volume and mass of the solution would decrease. The drop in mass will be covered by the mathematical calculations for finding the mass for the new volume, and thus we can still find the rate of corrosion which led to the formation of rust. As time went by, the bubbles disappeared. This could be because of a layer preventing the acid from reacting with the iron. The layer is supposed to be soluble at low pH values, but it may be partially soluble, in which case some rust will still form a layer.

For this reason, the volume of the pH 2.39 solution did not drop lower than the other solutions. As the hydrogen produced was not measured, the rate of corrosion calculated would be lower than the real rate of corrosion, resulting in significant systematic error.

- Although the air conditioner was switched on, there were still slight fluctuations in the temperature from 25°C to 26°C, as the outside was hotter than the inside and the air conditioner would turn off sometimes. Thus, the temperature would rise slowly. This would not significantly impact the experiment but may create systematic error.
- The mass of one empty measuring cylinder and iron nail was recorded, and it was assumed that the other measuring cylinders and nails were identical, but they could have small differences in their masses. All nails were also assumed to have identical surface area. These assumptions can increase the random uncertainties in the experiment.

### Data Collection:

Mass of Empty Measuring Cylinder – 74.86g.

Mass of Iron Nail – 9.48g.

| (pH $\pm$ 0.01)                                    | Mass<br>( $m \pm 0.01$ ) g | Volume<br>( $V \pm 0.5$ ) cm <sup>3</sup> | Average Mass (g)  | Average<br>Volume (V) |
|----------------------------------------------------|----------------------------|-------------------------------------------|-------------------|-----------------------|
| <b>Day 0</b>                                       |                            |                                           |                   |                       |
| <b>HCl<br/>(Concentrated):<br/>2.39</b>            | 182.29                     | 100                                       |                   |                       |
|                                                    | 182.28                     | 100                                       | 182.26 $\pm$ 0.04 | 100                   |
|                                                    | 182.22                     | 100                                       |                   |                       |
| <b>HCl (Diluted):<br/>4.50</b>                     | 183.31                     | 100                                       |                   |                       |
|                                                    | 183.29                     | 100                                       | 183.29 $\pm$ 0.02 | 100                   |
|                                                    | 183.27                     | 100                                       |                   |                       |
| <b>Distilled Water:<br/>7.08</b>                   | 184.06                     | 100                                       |                   |                       |
|                                                    | 184.05                     | 100                                       | 184.04 $\pm$ 0.03 | 100                   |
|                                                    | 184.00                     | 100                                       |                   |                       |
| <b>NaOH Solution<br/>(Diluted): 9.21</b>           | 184.15                     | 100                                       |                   |                       |
|                                                    | 184.17                     | 100                                       | 184.14 $\pm$ 0.03 | 100                   |
|                                                    | 184.11                     | 100                                       |                   |                       |
| <b>NaOH Solution<br/>(Concentrated):<br/>11.16</b> | 184.29                     | 100                                       |                   |                       |
|                                                    | 184.30                     | 100                                       | 184.28 $\pm$ 0.03 | 100                   |
|                                                    | 184.24                     | 100                                       |                   |                       |
| <b>Day 3</b>                                       |                            |                                           |                   |                       |
| <b>HCl<br/>(Concentrated):<br/>2.39</b>            | 170.17                     | 87                                        |                   |                       |
|                                                    | 170.20                     | 87                                        | 170.19 $\pm$ 0.02 | 87                    |
|                                                    | 170.19                     | 87                                        |                   |                       |
| <b>HCl (Diluted):<br/>4.50</b>                     | 171.92                     | 88                                        |                   |                       |
|                                                    | 171.87                     | 88                                        | 171.90 $\pm$ 0.03 | 88                    |
|                                                    | 171.92                     | 88                                        |                   |                       |
| <b>Distilled Water:<br/>7.08</b>                   | 171.52                     | 87                                        |                   |                       |
|                                                    | 171.56                     | 87                                        | 171.55 $\pm$ 0.03 | 87                    |
|                                                    | 171.57                     | 87                                        |                   |                       |

Table continued...

| (pH $\pm$ 0.01)                                    | Mass<br>( $m \pm 0.01$ ) g | Volume<br>( $V \pm 0.5$ ) cm <sup>3</sup> | Average Mass (g)  | Average<br>Volume (V) |
|----------------------------------------------------|----------------------------|-------------------------------------------|-------------------|-----------------------|
| <b>Day 3</b>                                       |                            |                                           |                   |                       |
| <b>NaOH Solution<br/>(Diluted): 9.21</b>           | 170.61                     | 86                                        |                   |                       |
|                                                    | 170.64                     | 86                                        | 170.63 $\pm$ 0.02 | 86                    |
|                                                    | 170.65                     | 86                                        |                   |                       |
| <b>NaOH Solution<br/>(Concentrated):<br/>11.16</b> | 170.62                     | 86                                        |                   |                       |
|                                                    | 170.69                     | 86                                        | 170.65 $\pm$ 0.04 | 86                    |
|                                                    | 170.63                     | 86                                        |                   |                       |
| <b>Day 6</b>                                       |                            |                                           |                   |                       |
| <b>HCl<br/>(Concentrated):<br/>2.39</b>            | 160.08                     | 76                                        |                   |                       |
|                                                    | 160.07                     | 76                                        | 160.07 $\pm$ 0.02 | 76                    |
|                                                    | 160.05                     | 76                                        |                   |                       |
| <b>HCl (Diluted):<br/>4.50</b>                     | 159.55                     | 75                                        |                   |                       |
|                                                    | 159.50                     | 75                                        | 159.51 $\pm$ 0.03 | 75                    |
|                                                    | 159.49                     | 75                                        |                   |                       |
| <b>Distilled Water:<br/>7.08</b>                   | 160.03                     | 75                                        |                   |                       |
|                                                    | 160.08                     | 75                                        | 160.05 $\pm$ 0.03 | 75                    |
|                                                    | 160.04                     | 75                                        |                   |                       |
| <b>NaOH Solution<br/>(Diluted): 9.21</b>           | 159.09                     | 74                                        |                   |                       |
|                                                    | 159.13                     | 74                                        | 159.12 $\pm$ 0.02 | 74                    |
|                                                    | 159.13                     | 74                                        |                   |                       |
| <b>NaOH Solution<br/>(Concentrated):<br/>11.16</b> | 159.05                     | 74                                        |                   |                       |
|                                                    | 159.00                     | 74                                        | 159.01 $\pm$ 0.03 | 74                    |
|                                                    | 158.99                     | 74                                        |                   |                       |
| <b>Day 10</b>                                      |                            |                                           |                   |                       |
| <b>HCl<br/>(Concentrated):<br/>2.39</b>            | 151.14                     | 66                                        |                   |                       |
|                                                    | 151.13                     | 66                                        | 151.14 $\pm$ 0.02 | 66                    |
|                                                    | 151.16                     | 66                                        |                   |                       |
| <b>HCl (Diluted):<br/>4.50</b>                     | 149.30                     | 64                                        |                   |                       |
|                                                    | 149.24                     | 64                                        | 149.27 $\pm$ 0.03 | 64                    |
|                                                    | 149.26                     | 64                                        |                   |                       |
| <b>Distilled Water:<br/>7.08</b>                   | 150.72                     | 65                                        |                   |                       |
|                                                    | 150.71                     | 65                                        | 150.69 $\pm$ 0.04 | 65                    |
|                                                    | 150.65                     | 65                                        |                   |                       |
| <b>NaOH Solution<br/>(Diluted): 9.21</b>           | 148.74                     | 63                                        |                   |                       |
|                                                    | 148.73                     | 63                                        | 148.75 $\pm$ 0.03 | 63                    |
|                                                    | 148.78                     | 63                                        |                   |                       |
| <b>NaOH Solution<br/>(Concentrated):<br/>11.16</b> | 149.53                     | 64                                        |                   |                       |
|                                                    | 149.50                     | 64                                        | 149.50 $\pm$ 0.03 | 64                    |
|                                                    | 149.47                     | 64                                        |                   |                       |

**Table 1:** Mass and volume of the solution over 10 days for a range of values of pH

### Calculations for Table 1:

The average mass of the container was calculated through the formula:

$$\frac{m_1 + m_2 + m_3}{3}$$

Sample Calculation for HCl (Concentrated) on Day 0:

$$\frac{182.29 + 182.28 + 182.22}{3} = 182.263 \approx 182.26g$$

The average volume of the solution was calculated using the formula:

$$\frac{V_1 + V_2 + V_3}{3}$$

Sample Calculation for HCl (Concentrated) on Day 0:

$$\frac{100 + 100 + 100}{3} = 100cm^3$$

All volumes stayed the same, as the trials were conducted simultaneously due to time restrictions during the COVID-19 pandemic. Since all trials were conducted simultaneously and localized in the same area, the amount of evaporation for similar solutions remained almost identical. This led to negligible random uncertainty in the volume and improved the precision of the experiment.

The uncertainty in the mass was calculated using the formula:

$$\frac{m_{max} - m_{min}}{2}$$

Sample Calculation for HCl (Concentrated) on Day 0:

$$\frac{182.29 - 182.22}{2} = 0.035 \approx 0.04$$

| Rate of Corrosion (g/day) |                   |                   |                   |
|---------------------------|-------------------|-------------------|-------------------|
| (pH $\pm$ 0.01)           | Day 3             | Day 6             | Day 10            |
| 2.39                      | 0.218 $\pm$ 0.028 | 0.217 $\pm$ 0.013 | 0.217 $\pm$ 0.007 |
| 4.50                      | 0.162 $\pm$ 0.027 | 0.160 $\pm$ 0.013 | 0.160 $\pm$ 0.008 |
| 7.08                      | 0.158 $\pm$ 0.030 | 0.156 $\pm$ 0.014 | 0.155 $\pm$ 0.009 |
| 9.21                      | 0.154 $\pm$ 0.028 | 0.154 $\pm$ 0.013 | 0.153 $\pm$ 0.008 |
| 11.16                     | 0.120 $\pm$ 0.033 | 0.120 $\pm$ 0.014 | 0.120 $\pm$ 0.008 |

**Table 2:** Rate of corrosion (g/day) for different values of pH

### Calculations for Table 2:

The rate of corrosion was calculated using the following two formulae:

$$\left( \frac{\text{Mass on Day 0} - \text{Mass of Empty Beaker} - \text{Mass of Iron Nail}}{\text{Volume on Day 0}} \right) \times \text{Volume on Day } x$$

This would calculate the mass of the solution on Day 0 for the volume on Day  $x$  as we simply use the density of the solution and use it to find the mass for different volumes.

$$\frac{\text{Mass on Day } x - (\text{Calculated mass} + \text{Mass of Iron Nail} + \text{Mass of Empty Beaker})}{x}$$

This would give us the final increase in mass per unit time and thus give us the rate of corrosion.

Sample Calculation for concentrated hydrochloric acid on Day 3:

$$170.19 - \left( \left( \frac{182.26 - 9.48 - 74.86}{100} \times 87 \right) + 9.48 + 74.86 \right) \approx 0.218$$

The uncertainty ( $\Delta$ ) in the rate of corrosion was calculated through the following formula:

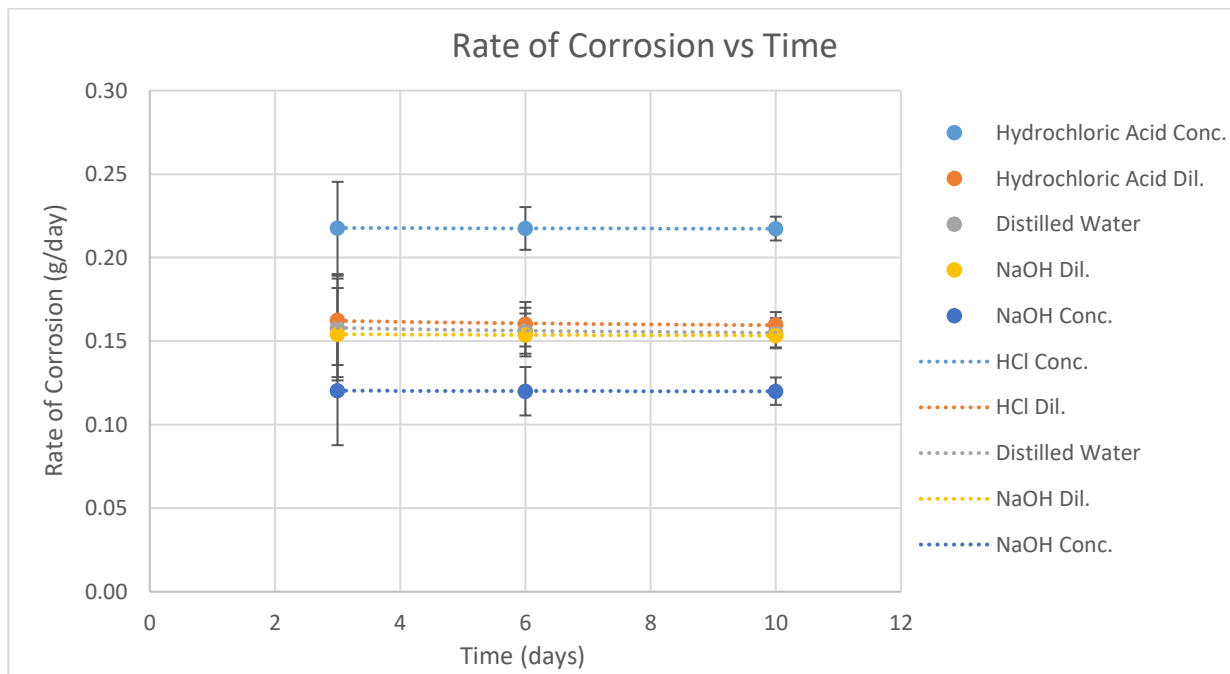
$$\frac{\left( \frac{\Delta \text{Mass on Day 0} + \Delta \text{Mass of Iron Nail} + \Delta \text{Mass of Empty Beaker}}{\text{Volume on Day 0}} \times \text{Volume on Day } x \right) + \Delta \text{Mass on Day 0} + \Delta \text{Mass of Iron Nail} + \Delta \text{Mass of Empty Beaker}}{x}$$

The uncertainty is calculated according to the following rules. When adding or subtracting the absolute uncertainties are added and when multiplying or dividing by a value with no uncertainty, the absolute uncertainty will be multiplied and divided by the same amount.

Sample Calculation for concentrated hydrochloric acid on Day 3:

$$\frac{\left( \frac{0.04 + 0.01 + 0.01}{100} \times 87 + 0.02 + 0.01 + 0.01 \right)}{3} \approx 0.028$$

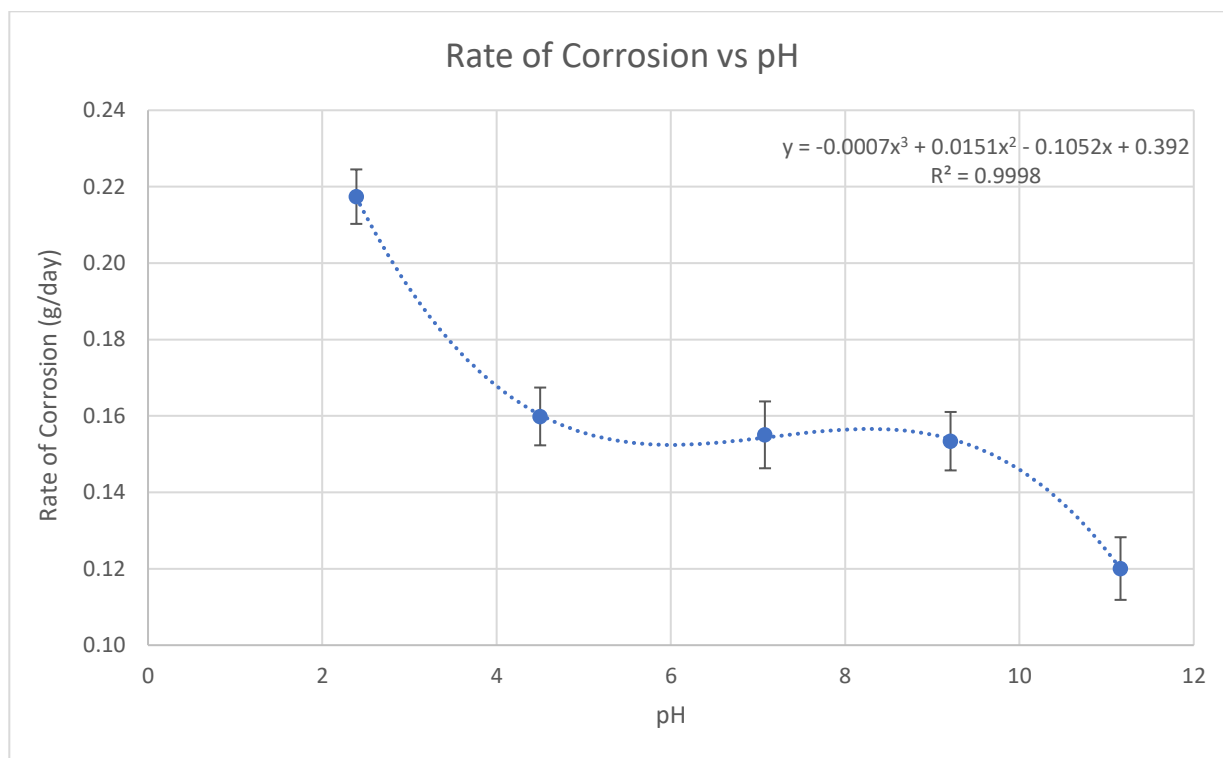
### Graphical Analysis:



**Graph 1:** Graph for rate of corrosion against time

In Graph 1, we can see that the rate of corrosion remained more or less consistent over the ten days. This could be attributed to the fact that not enough time has passed for the layers to fully form, causing the rate of corrosion to drop for all pH values. On the other hand, it could be due to the fact that, in the first three days, the layers that had to form have completely formed, and thus

the rate of reaction will not change significantly any longer. As time goes by, it can be seen that the random uncertainty considerably decreases. This can be explained by our formula, in which the absolute uncertainty in the mass increase is divided by number of days, and thus, as time passes, the uncertainty would also reduce. For this reason, the data from Day 10 is used to plot Graph 2, making the experiment more precise.



**Graph 2:** Graph for rate of corrosion for different values of pH

The rate of reaction for values from pH 4.50 to pH 9.21 are similar. There is a sudden increase in the rate of corrosion at pH 2.39 and a decrease at pH 11.16. The  $R^2$  value here holds great importance as it is the square of the coefficient of correlation and tells us the strength of the correlation of the variables. As the value is above 0.9, the variables are strongly correlated by this cubic equation, and therefore, the cubic equation is used to best fit the relationship between pH and rate of corrosion of iron. An online experiment<sup>3</sup> shows the rate of corrosion of an iron nail over ten days. The nail used is half the mass so we can approximately say it will be half the surface area as well. The value on the website for water was 0.08g/day, which we can double to use as a literature value for comparison to my nail, which gives us 0.16g/day. As we got 0.155g/day for the mass increase in distilled water over a course of 10 days we can find the percentage error to be  $\frac{0.16-0.155}{0.16} \times 100 = 3.1\%$  and thus we can see that the experiment has low systematic error.

### **Conclusion:**

After collecting and processing the data, the results support the hypothesis made. The rate of corrosion of iron did increase at low pH values and decrease suddenly at high pH values, presumably due to the increase in the formation of the passivation layer, and thus confirmed the hypothesis. From pH 4.50 to pH 9.21 there is a very slight decrease in the rate of corrosion of iron, as there are no changes in the predominant species in the Pourbaix diagram during this range of

pH. The results represented in the graphs can show the relationship between the variables and help investigate the relationship between pH and the rate of corrosion of iron.

The trendline cuts through all the error bars and has a high coefficient of correlation which show that there is low error present. However, there is some random error present in the experiment which effects precision. This is due to the limited time the experiment was conducted in, resulting in larger uncertainties. The highest percentage uncertainty was present in pH 11.16, as it had the lowest rate of corrosion. On Day 10, the percentage uncertainty for pH 11.16 was  $\frac{0.008}{0.120} \times 100 = 6.7\%$ , and the percentage uncertainty for pH 2.39 was  $\frac{0.007}{0.217} \times 100 = 3.2\%$ . While there is some random error present, mostly all values on Day 10 have low random error as enough time was given to reduce the uncertainties. On Day 3, the uncertainties were far greater, as pH 11.17 had  $\frac{0.033}{0.120} \times 100 = 27.5\%$  percentage uncertainty. The percentage error, as calculated before, is 3.1%, showing that the methodology and the design of the experiment were fairly accurate. The strengths and weaknesses of this experiment will be explored in the evaluation section below.

### **Evaluation:**

#### **Strengths of the experiment:**

The experiment has low systematic and random error, which tells us that the experiment was accurate and precise. Since there would be small amounts of rust lost if the nail were taken out of the solution for measurements, it could have significantly impacted the readings, as there were only small amounts of rust produced in the limited time. By considering this and designing the experiment to avoid this problem, the experiment was made more precise. An electronic pH meter was used instead of pH paper to give more accurate and precise results. Since all the trials were conducted simultaneously, the evaporation caused negligible random error and could be accounted for through the use of mathematics. The experiment was conducted over 10 days, which was enough time to reduce the uncertainty by a large amount.

#### **Weaknesses of the experiment:**

| <b>Evaluation</b>                                                                                                                                   | <b>Effect on Result</b>                                                                                                                                                                                                                                                                                                                                     | <b>Improvement</b>                                                                                                                                           |
|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Systematic Errors</b>                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                              |
| Hydrogen production:<br>At very low pH (2.39), hydrogen was produced due to the corrosion and escaped out of the container, which was not recorded. | High Significance: Although the hydrogen was only produced during the start of the experiment, it can cause large negative systematic error for the rate of corrosion of iron for low pH values. In reality, the corrosion due to hydrogen is faster than corrosion due to rusting and this causes the overall rate of corrosion to increase significantly. | Capture the hydrogen gas produced by using a syringe to check the amount produced. This can help find the amount corrosion which led to hydrogen production. |
| Temperature of the room: The temperature would vary between 25°C and 26°C as the AC turned off at times.                                            | Low Significance: The temperature fluctuations are too small too significantly affect the rate of corrosion of iron.                                                                                                                                                                                                                                        | Conduct the experiment in a special insulated room to avoid fluctuations in the temperature of the room.                                                     |

| Random Errors                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                          |
|---------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mass of iron nails and measuring cylinder:<br>The mass of one nail and measuring cylinder was recorded and the rest were assumed to be identical. | High Significance: The measuring cylinders were produced as a standard set and the nails were bought as a set, so there are unlikely to be differences in mass. However, even small differences in mass can cause significant random error as the increase in mass due to rust is extremely small.                                                                                           | Note down the mass of each individual container (measuring cylinder) and use an average of the mass of several nails to get more precise results.                                        |
| Weighing scale uncertainty: The measurement uncertainty of the digital weighing scale was 0.01g.                                                  | Low Significance: While the weighing scale uncertainty added almost 0.04 absolute uncertainty to the uncertainty of the rate of corrosion, this amount is significantly lessened as the uncertainty is divided by the time. Over ten days, this becomes $\frac{0.04}{10} = 0.004$ , which only contributes to 3% ( $\frac{0.004}{0.12} \times 100$ ) of percentage uncertainty for pH 11.16. | Use more precise apparatus for better results. For example, by using a weighing scale which gives values to higher decimal places, the uncertainty in the weighing scale can be reduced. |
| Measuring cylinder: The measuring cylinder had an uncertainty of $0.5\text{cm}^3$ .                                                               | Low significance: The measuring cylinder had graduations of $1\text{cm}^3$ , which made it hard to see minute differences in volume and lead to a small amount of random error. However, this amount is negligible as the containers were localized and the evaporation was consistent, and thus the volumes are most likely identical.                                                      | Use a more precise measuring cylinder with a greater number of graduations.                                                                                                              |

#### Suggestions for Extending the Research:

The rate of corrosion of other metals for different values of pH can be found out and compared with the rate of corrosion of iron to gain a more extensive knowledge on how we can combat the problem of corrosion in our communities. The rate of corrosion of iron can also be compared at different temperatures to understand how temperature can influence the relationship between pH and the rate of corrosion.

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