

The Effect of the Duration of Maintaining a Closed Circuit in a Single-Celled Galvanic Cell  
( $\pm 0.01$  s) on the Change in Mass of the Zinc Metal Anode ( $\pm 0.02$  g)

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**Nomenclature**

Symbol	Measurement	SI Base Units
$A$	Area	$\text{m}^2$
$C$	Molar concentration	$\text{mol}\cdot\text{dm}^{-3}$
$E$	Potential difference	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-3}\cdot\text{A}^{-1}$
$F$	Faraday constant	$9.65 \times 10^{-34} \text{ A}\cdot\text{s}\cdot\text{mol}^{-1}$
$G$	Gibbs free energy	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$
$H$	Enthalpy	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}\cdot\text{mol}^{-1}$
$I$	Electric current	A
$l$	Length	m
$m$	Mass	kg
$n$	Amount of substance	mol
$P$	Electric power	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-3}$
$Q$	Reaction quotient	Dimensionless
$q$	Electric charge	$\text{A}\cdot\text{s}$
$R$	Electrical resistance	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-3}\cdot\text{A}^{-2}$
$\bar{R}$	Gas constant	$8.31 \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-2}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
$S$	Entropy	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}\cdot\text{K}^{-1}$
$T$	Temperature	K
$t$	Duration/time	s
$V$	Volume	$\text{m}^3$
$z$	Anode oxidation number	Dimensionless
$\rho$	Electrical resistivity	$\text{kg}\cdot\text{m}^3\cdot\text{s}^{-3}\cdot\text{A}^{-2}$

## Introduction

The voltaic or galvanic cell is an electrochemical cell which depends on two separate half-cells to drive a spontaneous oxidation-reduction reaction, which is abbreviated as redox (Voltaic Cells, 2019). Primary and secondary batteries comprised of various metals are based on the scientific theory of a voltaic cell to convert chemical energy into electricity and power numerous electronic devices like cell phones, laptops, and automotive vehicles. Although batteries have become more efficient over time by reducing size, minimizing manufacturing costs, and maximizing energy output, they still require two cells to drive the spontaneous reaction. Complete redox reactions may take place in a single cell under circumstances that are fundamentally similar, yet differently organized compared to an ordinary galvanic cell. This raises the question on whether single-celled voltaic cells, abbreviated as VHCs, may be a reliable source of electrical energy that also reduces expenses due to their smaller sizes and fewer materials compared to the  $\$176 \text{ (kWh)}^{-1}$  needed to produce lithium-ion batteries: the most common type of electrochemical cell (Goldie-Scot, 2019).

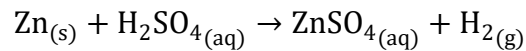
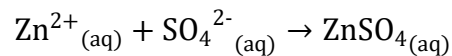
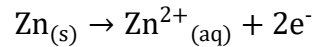
Exploring the chemical properties and consequences of VHCs, such as the maximum electrical current, its lifespan, or any health risks, may encourage effective evaluation of how batteries may be improved to decrease expenses and improve customer satisfaction.

## Research Question

*To what extent does the duration of maintaining a closed circuit in a copper-zinc half-voltaic cell (s) affect the change in mass of the zinc anode (g)?* Accordingly, the chosen real-life issue will be approached from the perspective of the lifespan of these VHCs, specifically the lifespan of its electrodes that are needed to maintain a potential difference and current.

### Scientific Background

Consider a single beaker containing dilute sulfuric acid known as the electrolyte, a solution containing dissociated ions, with two electrodes submerged in it: a zinc anode and a copper cathode. The zinc anode in contact with sulfuric acid develops an electrical potential on its valence electrons:  $-0.76\text{ V}$  (Haynes, 2017). The negative voltage indicates that zinc metal is at a lower potential relative to hydrogen atoms in the electrolyte per the electrochemical series, where hydrogen's potential is  $0.00\text{ V}$  (Haynes, 2017). Per the second law of thermodynamics, the total entropy, or disorder, of an isolated system never decreases with time. Thus, to achieve a lower energy state, zinc metal reacts with sulfuric acid to produce zinc sulfate solution by displacing the hydrogen atoms bound to the sulfate ion (Bylikin, Horner, Murphy, & Tarcy, 2014). Zinc metal oxidizes into a soluble cation that can ionically bond to the sulfate anion (Kshetrapal, Voltaic Cell Working, 2018). As the cation dissolves, the anode's mass decreases. The two electrons lost during oxidation travel up the zinc electrode to maintain the  $-0.76\text{ V}$ .



The copper cathode in contact with sulfuric acid develops a potential difference of  $+0.34\text{ V}$  on its valence electrons (Haynes, 2017). Copper is at a higher potential than the hydrogen atoms in the sulfuric acid. For zinc metal to oxidize and lose two electrons, it must be connected to the copper electrode via a metal wire with a resistive load. The load prevents a high electrical current that dangerously releases thermal energy according to the proportionality between power and resistance (Bowen-Jones & Homer, 2014).

$$P \propto I \propto R$$

This wire establishes the electrode potential differences between zinc and copper. Zinc can lose its electrons to copper and become a cation, whereas copper metal is reduced and becomes an anion (Kshetrapal, Voltaic Cell Working, 2018). For each coulomb of negative charge transferring from zinc to copper, its energy transitions from  $-0.76\text{ V}$  to  $+0.34\text{ V}$ . Hence, the electromotive force of the VHC is  $1.10\text{ V}$  (Haynes, 2017).

$$\begin{aligned}
 E^{\circ}_{\text{cell}} &= E_{\text{cathode}} - E_{\text{anode}} \\
 &= E_{\text{Cu}} - E_{\text{Zn}} \\
 &= +0.34\text{ V} - (-0.74\text{ V}) \\
 &= +1.10\text{ V}
 \end{aligned}$$

Since no input energy is required for the reaction, it is spontaneous (Bylikin, Horner, Murphy, & Tarcy, 2014). The entropy and enthalpy of dissolution of zinc metal in sulfuric acid are positive and negative respectively (Owen, 2014). This increases the VHC's temperature since thermal energy is released per the exothermic reaction. Also, since the standard potential difference is positive, the reaction is spontaneous (Bylikin, Horner, Murphy, & Tarcy, 2014). Gibbs free energy is defined as the maximum reversible work performed by a thermodynamic process (Owen, 2014). Thus, a negative free energy conveys a spontaneous reaction.

$$\Delta G^{\circ} = -nFE^{\circ}$$

$$E^{\circ} = 1.10\text{ V}$$

$$E^{\circ} > 0$$

$$\therefore \Delta G^{\circ} < 0$$

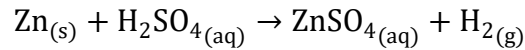
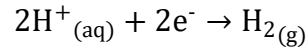
$$\Delta G^{\circ} = \Delta H^{\circ} - T\Delta S^{\circ}$$

$$\Delta S^{\circ} > 0$$

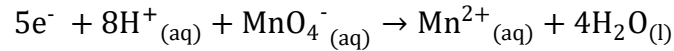
$$\Delta H^{\circ} < 0$$

$$\therefore \Delta G^{\circ} < 0$$

Copper does not dissolve since the electrons transferred to it bind to hydrogen cations in the sulfuric acid solution. Hydrogen is reduced and the reaction produces hydrogen gas that escapes from the solution via bubbles (Kshetrapal, Voltaic Cell Working, 2018).



Adding an oxidizing agent in the electrolyte like permanganate ( $\text{MnO}_4^-_{(\text{aq})}$ ) produces liquid water as its oxygen atoms react with the produced hydrogen gas (Owen, 2014).



Impurities or bubbles formed on the copper surface increase the internal resistance of the cell since the transferred electrons are blocked from reducing the hydrogen atoms. This results in energy loss due to heat and the half-cell becomes a poor electrical conductor (Tsokos, 2014). Using an oxidizing agent maximizes the efficiency of the electrochemical cell by not producing gas bubbles.

Ultimately, as the hydrogen ions are oxidized, the negatively charged sulfate ion travels towards the zinc anode to form zinc sulfate as it reacts with the cations. This movement of negative charge in the solution maintains a closed circuit. Electrons travel from zinc to copper, and sulfate ions travel from copper to zinc to produce an electrical current (Tsokos, 2014).

$$E = I \cdot (R_{\text{internal}} + R_{\text{wire}} + R_{\text{load}}), R_{\text{wire}} \approx 0 \, \Omega$$

The electrical current is sustained until either the sulfuric acid or the zinc anode is exhausted and a break in the circuit occurs (Kshetrapal, Voltaic Cell Working, 2018). As the electrolyte concentration decreases, the electrode potentials decrease since there is fewer hydrogen atoms that can be reduced.

The two metal electrodes are connected to each other using an electrically conductive wire that contains a resistive load with resistance  $R_{\text{load}}$ , such as a resistor, voltmeter, lamp, or any electronic device. Electrical resistances of wires are negligible as they are near-perfect electrical conductors (Bowen-Jones & Homer, 2014).



$$R_{\text{wire}} = \frac{\rho l}{A}$$

Where  $\rho \approx 0 \Omega \cdot \text{m}$  since the wire's delocalized electrons in its metallic structure provide an avenue for electron flow (Owen, 2014). As electrons travel from copper to zinc through the electrolyte, they collide with atoms and ions that resist their movement. This resistance inside the VHC produced by the electrolyte is the internal resistance of the cell. It is proportional to the electrical resistivity of the electrolyte, as well as the length of the path that the electrons travel through in the solution since a longer path increases the number of ions they will collide with (Tsokos, 2014). Internal resistance is inversely proportional to the cross-sectional area of the electrons' path, which is the surface area of the electrode submerged in the electrolyte that faces the other metal (Bowen-Jones & Homer, 2014). Larger surface areas increase the space that electrons can travel through to avoid collisions that increase resistance (Kshetrapal, Voltaic Cell Internal Resistance, 2018).

$$R_{\text{internal}} = \frac{\rho l}{A} \Rightarrow R_{\text{internal}} \propto \frac{l}{A}$$

Furthermore, it is proportional to the electrolyte concentration. With a greater concentration, more ions will be present to impede the charges from travelling through the solution (Kshetrapal, Voltaic Cell Internal Resistance, 2018). However, resistance is inversely proportional to the electrolyte temperature. The higher the temperature, the more kinetic energy and velocity, each electrolyte ion has, and the higher the probability they ricochet off each other to become separated and provide an unobstructed avenue for electron flow (Kshetrapal, Voltaic Cell Internal Resistance, 2018). The thermal energy of the molecules converts into potential energy in their intermolecular forces to separate from each other (Tsokos, 2014).

$$R_{\text{internal}} \propto \frac{C}{T}$$

A lower resistance produces a higher electrical current since they are inversely proportional to each other (Bowen-Jones & Homer, 2014). However, at a constant cell potential, the VHC current is proportional to the heat released due to electron flow (Bowen-Jones & Homer, 2014). As heat due to current and the spontaneous dissolution of zinc increases, the electrolyte temperature increases, thus, decreasing resistance, increasing current, and generating more heat. This feedback cycle repeats until the electrochemical cell is damaged by melting the electrodes or the wire, evaporating the solution, or breaking the container. To prevent the battery from breaking, the cell should be placed in a well-ventilated area or a cooling bath to transfer the produced thermal energy via convection or conduction respectively (Nichols, 2019).

$$E = IR \Rightarrow I \propto \frac{1}{R}$$

$$P = EI \Rightarrow P \propto I$$

Current is the rate of electron flow, however, in a VHC, it is defined as the rate of oxidation since electrons are liberated from the anode and transferred to the cathode (Owen, 2014). Therefore, the number of electrons released from the anode is proportional to its change in mass, and a change in rate of oxidation corresponds to a change in rate of the change in mass with respect to time. The change in mass of the anode is abbreviated as AMC.

$$\Delta m \propto \Delta q$$

$$\frac{\Delta m}{t} \propto \frac{\Delta q}{t}$$

$$\frac{dm}{dt} \propto \frac{dq}{dt}$$

$$\frac{dm}{dt} \propto I$$

## Variables

### Independent

Table 1. The manipulated variable of the investigation.

Definition	Settings	Protocol
The duration of maintaining a closed circuit in the copper-zinc VHC (s). Symbol: $t$	0.00 (control test), 30.00, 60.00, 90.00, 120.00, 180.00 $\pm 0.01$ s	A control test ( $0.00 \pm 0.01$ s) was implemented to verify that the change in the anode's mass is proportional to the dependent variable to an extent. The relatively wide range of the chosen settings allowed any uncontrolled variables to demonstrate their effect on the dependent variable. The times were monitored and verified using a digital stopwatch ( $\pm 0.01$ s), which was started when the wire-connected electrodes were placed in the half-cell for three trials of each setting.

### Dependent

Table 2. The measured variable of the investigation influenced by the manipulated variable.

Definition	Protocol
The change in mass of the zinc anode in the copper-zinc VHC (g), abbreviated as AMC. Symbol: $\Delta m$	The initial mass of the zinc anode was measured using a digital balance ( $\pm 0.01$ g) before submerging it in the electrolyte. After the respective duration time passed, the zinc anode was removed from the cell and its final mass was measured using the digital balance ( $\pm 0.01$ g). The change in mass of the respective electrode ( $\pm 0.02$ g) was calculated by subtracting the final mass from the initial mass.

### Controlled

Table 3. Variables that were controlled to provide an opportunity for impartially investigating the relationship between the independent and dependent variables for all trials. Controlling these variables maintained a constant current, which is proportional to the rate of AMC.

Definition	Protocol	Significance
Electrolyte substance (sulfuric acid)	Using the same chemical composition of the electrolyte ( $\text{H}_2\text{SO}_{4(\text{aq})}$ ).	Since the ionic radii of the electrolyte's ions were constant due to a controlled chemical structure, the probability of flowing electrons colliding with the ions

Definition	Protocol	Significance
Electrolyte initial concentration ( $6 \text{ mol}\cdot\text{dm}^{-3}$ )	Pouring the acid from a bottle labelled as: $6 \text{ mol}\cdot\text{dm}^{-3}$ purified sulfuric acid.	in the solution remained constant alongside the initial internal resistance and current (Tsokos, 2014). Since the number of electrolyte ions in a specific volume inhibiting the flow of electrons was constant, the initial internal resistance and current were also constant (Bowen-Jones & Homer, 2014).
Electrolyte volume ( $75.0 \pm 0.5 \text{ cm}^3$ )	Measured using an analogue graduated cylinder ( $100 \pm 0.5 \text{ cm}^3$ ) to pour into the glass beaker ( $200 \pm 13 \text{ cm}^3$ )	The volume of the electrolyte affects the height of the electrode surface submerged in the solution; subsequently, the surface area and volume that electrons can travel through to avoid inhibition by the ions (Kshetrapal, Voltaic Cell Internal Resistance, 2018). Controlling the volume maintained the initial resistance and current.
Electrode materials (metal zinc anode, metal copper cathode)	Connecting a zinc sheet to the common socket, and a copper sheet to the voltage socket in the digital multimeter ( $\pm 0.01 \text{ V}$ ).	The standard electrode potentials, initial cell potential, and current of the VHC were constant; thus, maintaining electrical current (Bowen-Jones & Homer, 2014).
Electrolyte initial temperature ( $24.00 \pm 0.01 \text{ }^\circ\text{C}$ )	Monitored using a digital temperature probe ( $0.01 \text{ }^\circ\text{C}$ ) to ensure that it started at a constant temperature before submerging the electrodes.	Controlling the potential energy of the electrolyte's intermolecular forces and molecule separation maintained the initial resistance and current as the avenue for electron flow was constant (Owen, 2014).
Furthest distance between the electrodes ( $3.0 \pm 0.1 \text{ cm}$ )	The electrodes were placed parallel to each other and the constant distance between them was verified using an analogue ruler ( $30.0 \pm 0.5 \text{ cm}^3$ ) as they were submerged in the electrolyte.	The length of the electron's path in the electrolyte is proportional to the number of electrolyte ions that impede charge flow (Kshetrapal, Voltaic Cell Internal Resistance, 2018). Controlling length maintained the initial internal resistance and current.
Surface area of the electrodes submerged in the electrolyte ( $10.6 \pm 0.3 \text{ cm}^2$ )	The width and height of the electrodes surface areas pointing towards each other inside the electrolyte were calculated and maintained using an analogue ruler ( $30.0 \pm 0.5 \text{ cm}^3$ ). The electrodes were also submerged perpendicular to the base of the glass beaker at the bottom.	A greater surface area implies a greater volume that the electrons can travel through the electrolyte to avoid colliding into its ions (Tsokos, 2014). Maintaining surface area controlled the initial internal resistance and current.

## Uncontrolled

Table 4. Variables that were monitored instead of controlled due to limitations in the apparatus.

Definition	Significance	Protocol
Temperature of VHC electrolyte (°C)	<p>Since the electric current is linearly proportional to the heat produced by the movement of electrons, if a conductive wire is connected between the electrodes and a closed circuit is formed, heat will constantly be supplied to the VHC and the temperature will continuously increase (Bowen-Jones &amp; Homer, 2014). This decreases the internal resistance due to an increase in the potential energy of the electrolyte's intermolecular forces and avenue for electron flow. Thus, as current increases, oxidation rate increases and AMC rate decreases (Owen, 2014).</p> <p>Moreover, due to the current, heat, and resistance feedback loop, the current was constantly increasing while the resistance decreased throughout the trial at a different rate, which resulted in a non-constant potential difference across the half-cell (Tsokos, 2014): <math>E = IR</math>. Additionally, according to the Nernst equation, an uncontrollably increasing temperature resulted in an uncontrollably decreasing VHC voltage (Nernst Equation, 2019).</p> $E_{\text{cell}} = E^{\circ}_{\text{cell}} - \frac{\bar{R}T}{zF} \ln Q$	<p>To maintain the electrolyte temperature, the internal resistance would have to increase dynamically with time; either by increasing the electron path length or decreasing the surface area of the electrode dipped in the solution. Thus, as internal resistance increases while heat is supplied, the ratio of the proportionalities relative to the current at a constant voltage would be controlled and a constant current would be produced.</p> $I \propto \frac{P}{R}$ <p>However, the current and produced heat cannot be calculated in real-time to deduce an appropriate resistance, thus, the temperature of the half-cell cannot be controlled. Additionally, a cooling bath cannot be used since the rate of cooling cannot be ensured to match the rate of heating (Nichols, 2019).</p> <p>The temperature will be monitored using a digital temperature probe (<math>\pm 0.01</math> °C) and a Vernier LabQuest.</p>
Molar concentration of VHC electrolyte ( $\text{mol} \cdot \text{dm}^{-3}$ )	<p>The molar concentration of the electrolyte decreases with time. As the number of zinc sulfate molecules produced due to the redox reaction increases, the number of sulfuric acid molecules</p>	<p>The electrolyte concentration could not be calculated nor monitored in real-time, therefore, it cannot be controlled by adding new solute as the old one reacts with the zinc anode.</p>

Definition	Significance	Protocol
	<p>and its number of moles decreases (Bowen-Jones &amp; Homer, 2014). Since the volume of the electrolyte is constant, a smaller number of moles of the solute results in a lower concentration (Bylikin, Horner, Murphy, &amp; Tarcy, 2014).</p> $C = \frac{n_{\text{solute}}}{V_{\text{solution}}} \Rightarrow C \propto n_{\text{solute}}$ <p>As the concentration decreases, the number of electrolyte ions inhibiting the transfer of electrons through the solution decreases. Therefore, the internal resistance of the VHC decreases, and the electric current of the cell increases relative to time. Thus, the rate at which zinc metal oxidizes and its mass decreases changes as well (Owen, 2014).</p>	

### Educated Hypothesis

It is predicted that as the duration of maintaining a closed circuit in the VHC (s) increases, the magnitude of the change in mass of the anode between closing and breaking the circuit (g) will increase directly and non-linearly (Owen, 2014). The final mass of the zinc anode is predicted to continually decrease relative to its initial mass as time increases since it is oxidizing and dissolving with time (Owen, 2014). Although the change in mass will decrease as it becomes more negative with time, its magnitude will increase.

The relationship is expected to have a  $\Delta m$ -intercept of 0.00 g, hypothesizing a direct proportionality due to a point of (0.00 s, 0.00 g) on the plot. If the circuit is closed for zero seconds, no potential difference is developed on the electrodes, and the zinc metal does not oxidize to lose electrons and dissolve in the electrolyte (Bylikin, Horner, Murphy, & Tarcy,

2014). Since the anode mass will not change under this control, the plot of time against AMC will intersect the origin.

Moreover, the relationship between the independent and dependent variables is hypothesized to be non-linear due to the changing internal resistance with respect to time. If resistance is constant, current would also be constant, thus, the rate at which electrons flow and zinc oxidizes is controlled (Tsokos, 2014). A constant rate of changing the anode's mass produces a linear relationship between mass and time:

$$\int \left( \frac{dm}{dt} \right) dt = \int (kI) dt \quad \left\{ \frac{dm}{dt} \propto I \right\}$$

$$\therefore \Delta m = kIt + c, \text{ where } k, c \in \mathbb{R}.$$

However, resistance is continually changing as the circuit is closed due to the increase in electrolyte temperature and decrease in electrolyte concentration, which are both uncontrolled variables (Kshetrapal, Voltaic Cell Internal Resistance, 2018). Consequently, current, as well as the AMC, is continually changing with respect to time. Therefore, the anti-derivative of this non-constant rate produces a non-linear relationship between the investigated variables. Since the electrolyte concentration is not monitored, the rate of change in internal resistance cannot be calculated with respect to time. Therefore, the relationship between the variables cannot be hypothesized any further. This investigation attempts to identify the relationship between duration and mass change under the circumstance of an uncontrolled internal resistance.

### Materials and Apparatus

Table 5. Required items to conduct the experiment and investigate the relationship between the independent and dependent variables while controlling or monitoring unwanted influences.

Quantity	Item	Capacity and Uncertainty
1	Digital balance	$\pm 0.01$ g
1	Digital stopwatch	$\pm 0.01$ s
1	Digital temperature probe	$\pm 0.01$ °C
1	Digital multimeter	$\pm 0.01$ V
1	Analogue ruler	$30.0 \pm 0.5$ cm <sup>3</sup>
1	Analogue graduated cylinder	$100 \pm 0.5$ cm <sup>3</sup>
1	Glass beaker	$200 \pm 13$ cm <sup>3</sup>
1	Glass beaker	$50 \pm 5$ cm <sup>3</sup>
1	Glass dropper	5 cm <sup>3</sup>
15	Solid copper metal sheet	$1.9 \pm 0.1$ cm width
15	Solid zinc metal sheet	$1.9 \pm 0.1$ cm width
15	6 mol·dm <sup>3</sup> sulfuric acid	$75.0 \pm 0.5$ cm <sup>3</sup>
2	Metal lead	
2	Alligator clip	
1	Vernier LabQuest	
1	AC power outlet	
1	Laboratory bench	
1	Laboratory apron	
1	Splash goggles	
2	Nitrile glove	
1	Tap water	
1	Hand soap	
1	Paper towel roll	
1	Garbage waste container	
1	Acid/oxidizer waste container	



## **Precautions**

### **Ethical**

No ethical precautions exist since the dissociation of a metal in an electrolyte, the transfer of electrons, and the generation of a potential difference do not directly nor indirectly raise any moral dilemmas that differ between cultures and societies.

### **Environmental and Ecological**

A concentration of at least  $2.8 \mu\text{g}\cdot\text{dm}^{-3}$  of sulfuric acid solution is toxic to aquatic life, and the acid may decompose into sulfur oxides, which are more toxic than the original reactant (Sulfuric Acid: Safety Data Sheet, 2018). It is also a groundwater pollutant, mild water pollutant, and causes a pH shift in these areas (Sulfuric Acid: Safety Data Sheet, 2018). Zinc sulfate also exhibits similar ecological effects (Zinc Sulfate: Safety Data Sheet, 2014). Sulfuric acid and zinc sulfate solutions were disposed in the acid/oxidizer waste container to prevent releasing them into the environment. This waste container was used since sulfuric acid is an Arrhenius acid (Sulfuric Acid: Safety Data Sheet, 2018)

### **Health and Safety**

Sulfuric acid is corrosive and causes severe skin burns and eye damage (Sulfuric Acid: Safety Data Sheet, 2018). Zinc sulfate is corrosive, an irritant that can cause eye damage, and exhibits acute toxicity via oral intake, dermal intake, or inhalation (Zinc Sulfate: Safety Data Sheet, 2014). Safety nitrile gloves, splash goggles, and an apron were worn to prevent dangerous contact with these acids.

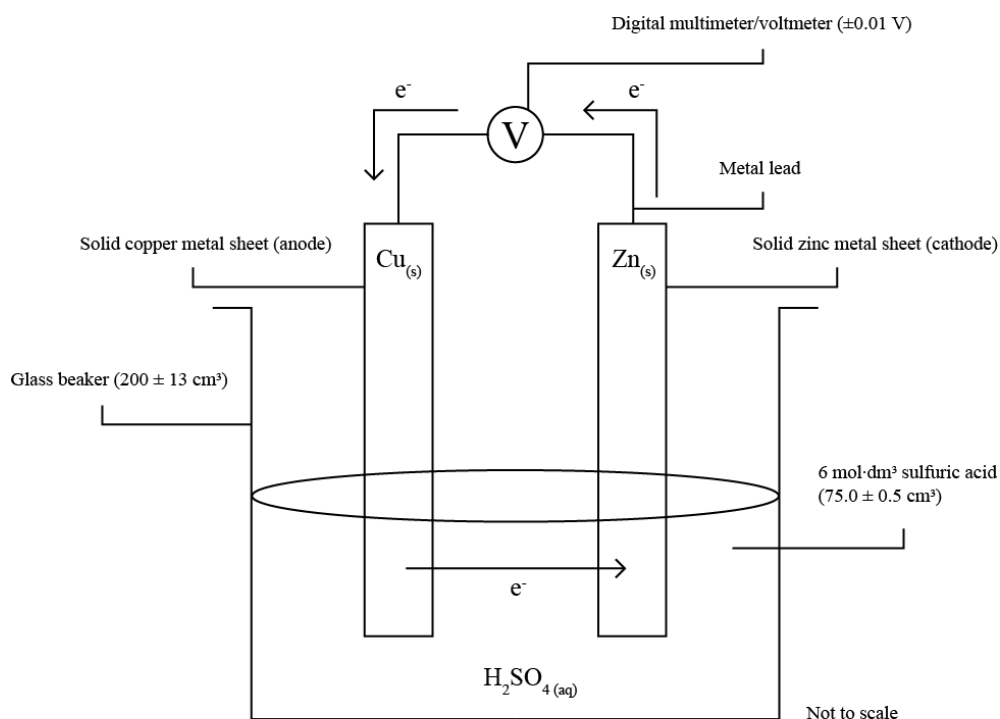
### Procedure

1. A pair of nitrile safety gloves, safety goggles, and a laboratory apron were worn in this order, and the laboratory bench was prepared with the required materials.
2. The Vernier LabQuest was connected to an AC power outlet and turned on.
3. The digital temperature probe ( $\pm 0.01\text{ }^{\circ}\text{C}$ ) was connected to the LabQuest through the digital port.
4.  $75.0 \pm 0.5\text{ cm}^3$  of  $6\text{ mol}\cdot\text{dm}^{-3}$  sulfuric acid was poured into and measured using an analogue graduated cylinder ( $100 \pm 0.5\text{ cm}^3$ ). A glass dropper ( $5\text{ cm}^3$ ) was used to finely place acid into the cylinder.
5. The  $75.0 \pm 0.5\text{ cm}^3$  of  $6\text{ mol}\cdot\text{dm}^{-3}$  sulfuric acid was poured into a glass beaker ( $200 \pm 13\text{ cm}^3$ ).
6. A copper sheet was submerged in the acid in the beaker until the bottom of the electrode touched the bottom of the beaker perpendicularly.
7. The copper sheet was removed from the beaker and the length and width of the area of one side of the sheet covered in acid was measured using an analogue ruler ( $30.0 \pm 0.5\text{ cm}^3$ ).
8. The surface area of one side covered in sulfuric acid was calculated by multiplying the measured length and width by each other.
9. The initial mass of a solid zinc sheet was measured using a digital balance ( $\pm 0.01\text{ g}$ ).
10. The two metal leads were connected to the multimeter ( $\pm 0.01\text{ V}$ ) via the voltage and common sockets respectively.
11. Each alligator clip was clipped onto the end of a metal lead. The other ends were clipped onto the copper sheet (voltage socket) and the zinc sheet (common socket) respectively.

12. The digital temperature probe ( $\pm 0.01\text{ }^{\circ}\text{C}$ ) was placed in the sulfuric acid in the glass beaker ( $200 \pm 13\text{ cm}^3$ ).
13. When the probe reported an acid temperature of  $24.00 \pm 0.01\text{ }^{\circ}\text{C}$ , the digital stopwatch ( $\pm 0.01\text{ s}$ ) and LabQuest data logging were started simultaneously and both metal sheets were submerged in the glass beaker ( $200 \pm 13\text{ cm}^3$ ) such that they were parallel to each other and touching the bottom of the beaker perpendicularly.
14. The distance between the two metal sheets was measured using an analogue ruler ( $30.0 \pm 0.5\text{ cm}^3$ ) and controlled to  $3.0 \pm 0.1\text{ cm}$ .
15. After  $0.00 \pm 0.01\text{ s}$  on the stopwatch, the metal sheets were removed from the beaker and placed on the lab bench, and the digital stopwatch and LabQuest data logging were stopped.
16. Any sulfuric acid on the zinc sheet was wiped off using paper towel from the roll to not consider its mass when calculating the AMC.
17. The digital temperature probe was removed from the beaker and wiped off using the same paper towel.
18. The respective paper towel was disposed in the garbage container.
19. The metal sheets were disconnected from the alligator clips.
20. The final mass of the zinc sheet was measured using a digital balance ( $\pm 0.01\text{ g}$ ).
21. The change in mass of the anode was calculated by subtracting the final mass from the initial mass.
22. The copper and zinc electrodes were placed in a glass beaker ( $50 \pm 5\text{ cm}^3$ ).
23. The sulfuric acid in the glass beaker ( $200 \pm 13\text{ cm}^3$ ) was disposed in the acid/oxidizer waste container.
24. Steps 4 to 23 were repeated for two more trials.

25. The sample mean and standard deviation for the AMC of the setting were calculated.
26. Steps 24 to 25 were repeated for durations 30.00, 60.00, 90.00, 120.00, 180.00  $\pm$  0.01 s.
27. The bench was cleared from materials and cleaned using paper towel wetted in tap water.
28. The nitrile gloves and paper towel were disposed in the garbage container, and the goggles and apron were removed.
29. The investigator's hands were washed using tap water and hand soap.
30. The mean changes in mass ( $\pm$ 0.02 g) were plotted against the duration of maintaining a closed circuit ( $\pm$ 0.01 s).
31. The curve of best fit between the change in mass and duration was sketched onto the plot.

### Protocol Diagram



Protocol diagram by M20 IB DP candidate 002952-0023 (2020)

Figure 1. Experiment setup illustrating the beaker, electrolyte, electrodes, multimeter setting, and required electron flow direction.

**Raw Data****Qualitative**

Table 6. Qualitative states of the sulfuric acid electrolyte, zinc anode, copper cathode, and the VHC at different stages of maintaining a closed circuit for all settings and trials (s).

Quality	Description of Qualitative Data		
	Before Closed Circuit	During Closed Circuit	After Closed Circuit
State of matter of the electrolyte	Aqueous solution	Aqueous solution	Aqueous solution
State of matter of the anode	Solid	Solid, bottom of electrode was a thick, concentrated aqueous solution	Solid, bottom of electrode was a thick, concentrated aqueous solution
State of matter of the cathode	Solid	Solid	Solid
Color of the electrolyte	No color; clear; transparent	Clear, turning black	Very light grey
Color of the anode	Silver; light grey, white tint	Silver; light grey, white tint, bottom of electrode was dark grey	Silver; light grey, white tint, bottom of electrode was dark grey
Color of the cathode	Reddish brown, green tint	Reddish brown, green tint	Reddish brown, green tint
Odor of the electrolyte	Odorless	Odorless	Odorless
Odor of the anode	Odorless	Odorless	Odorless
Odor of the cathode	Odorless	Odorless	Odorless
Odor of the VHC	Odorless	Pungent	Odorless
Mixture type of the electrolyte	Homogenous solution	Heterogenous solution containing black pieces from anode and gas bubbling out	Heterogenous solution containing black pieces from anode
Viscosity of the electrolyte	Water-like viscous	Water-like viscous	Water-like viscous
Touch of the conductive wire	Neutral	Consistent, weak electric tingling	Neutral
Vigorousness of the reaction	No reaction	Slightly vigorous	No reaction

**Quantitative**

Table 7. The initial and final masses of the zinc metal anode ( $\pm 0.01$  g) within maintaining a closed circuit in the copper-zinc voltaic half-cell ( $\pm 0.01$  s) for all settings and trials.

Duration of Maintaining Closed Cell Circuit ( $\pm 0.01$ s)	Mass of Zinc Anode within Maintaining a Closed VHC Circuit ( $\pm 0.01$ g)					
	Trial 1		Trial 2		Trial 3	
	Initial	Final	Initial	Final	Initial	Final
0.00	10.24	10.24	9.32	9.32	10.55	10.55
30.00	8.89	8.87	11.21	11.20	10.76	10.74
60.00	12.44	12.38	13.27	13.24	14.40	14.20
90.00	9.98	9.90	8.42	8.38	7.50	7.49
120.00	8.21	8.13	7.08	7.01	14.52	14.34
180.00	11.12	11.11	9.40	9.35	11.48	11.30

**Processed Data****Quantitative**

Table 8. The change in mass of the zinc metal anode ( $\pm 0.02$  g) after maintaining a closed circuit in the copper-zinc voltaic half-cell ( $\pm 0.01$  s) for all settings and trials.

Cell Closed Cell Circuit Time ( $\pm 0.01$ s)	Change in Mass of Zinc Anode within Maintaining a Closed VHC Circuit ( $\pm 0.02$ g)			Sample Arithmetic Mean of AMC ( $\pm 0.02$ g)	Sample Standard Deviation of AMC (g)
	Trial 1	Trial 2	Trial 3		
0.00	$\pm 0.00$	$\pm 0.00$	$\pm 0.00$	$\pm 0.00$	0.00
30.00	-0.02	-0.01	-0.02	-0.02	0.007
60.00	-0.06	-0.03	-0.20	-0.10	0.09
90.00	-0.08	-0.06	-0.01	-0.05	0.04
120.00	-0.08	-0.07	-0.18	-0.11	0.06
180.00	-0.01	-0.05	-0.18	-0.08	0.09

**Sample Calculations**

Select a certain closed-circuit duration (independent variable):

$$t = 30.00 \pm 0.01 \text{ s}$$

$$N = 3 \text{ trials}$$

Calculate AMCs:

$$\begin{aligned}\Delta m_{\text{trial 1 value}} &= m_{\text{f trial 1 value}} + m_{\text{i trial 1 value}} \\ &= 8.87 \text{ g} - 8.89 \text{ g} \\ &= -0.02 \text{ g}\end{aligned}$$

$$\begin{aligned}\Delta m_{\text{trial 1 uncertainty}} &= m_{\text{f trial 1 uncertainty}} + m_{\text{i trial 1 uncertainty}} \\ &= 0.01 \text{ g} + 0.01 \text{ g} \\ &= 0.02 \text{ g}\end{aligned}$$

$$\Delta m_{\text{trial 1}} = \Delta m_{\text{trial 1 value}} \pm \Delta m_{\text{trial 1 uncertainty}}$$

$$\therefore \Delta m_{\text{trial 1}} = -0.02 \pm 0.02 \text{ g}$$

$$\Delta m_{\text{trial 2}} = -0.01 \pm 0.02 \text{ g}$$

$$\Delta m_{\text{trial 3}} = -0.02 \pm 0.02 \text{ g}$$

Calculate sample arithmetic mean of AMC to evaluate the accuracy of the apparatus:

$$\overline{\Delta m} = \frac{1}{N} \sum_{i=1}^N \Delta m_{\text{trial } i}$$

$$\begin{aligned}
&= \frac{1}{3} \sum_{i=1}^3 \Delta m_{\text{trial } i} \\
&= \frac{\Delta m_{\text{trial } 1} + \Delta m_{\text{trial } 2} + \Delta m_{\text{trial } 3}}{3} \\
&= \frac{(-0.02 \pm 0.02 \text{ g}) + (-0.01 \pm 0.02 \text{ g}) + (-0.02 \pm 0.02 \text{ g})}{3} \\
&= \frac{-0.05 \pm 0.06 \text{ g}}{3} \\
&= -0.02 \pm 0.02 \text{ g}
\end{aligned}$$

Calculate sample standard deviation of AMC to propagate errors and evaluate data precision:

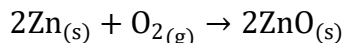
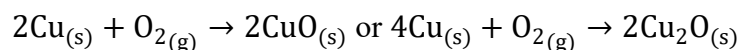
$$\begin{aligned}
s &= \sqrt{\frac{\sum_{i=1}^N (\Delta m_{\text{trial } i} - \bar{\Delta m})^2}{N - 1}} \\
&= \sqrt{\frac{\sum_{i=1}^3 (\Delta m_{\text{trial } i} - (-0.02 \text{ g}))^2}{3 - 1}} \\
&= \sqrt{\frac{\sum_{i=1}^3 (\Delta m_{\text{trial } i} + 0.02 \text{ g})^2}{2}} \\
&= \sqrt{\frac{(\Delta m_{\text{trial } 1} + 0.02 \text{ g})^2 + (\Delta m_{\text{trial } 2} + 0.02 \text{ g})^2 + (\Delta m_{\text{trial } 3} + 0.02 \text{ g})^2}{2}} \\
&= \sqrt{\frac{(-0.02 \text{ g} + 0.02 \text{ g})^2 + (-0.01 \text{ g} + 0.02 \text{ g})^2 + (-0.02 \text{ g} + 0.02 \text{ g})^2}{2}} \\
&= \sqrt{\frac{0.0001 \text{ g}^2}{2}} \\
&= 0.007 \text{ g}
\end{aligned}$$



## Data Analysis

### Qualitative Analysis

The state of matter of the electrolyte was aqueous throughout the trial since by its Arrhenius definition, sulfuric acid is a compound that increases the concentration of hydrogen ions in an aqueous solution (16.1: Arrhenius Theory: A Brief Review, 2016). Zinc and copper were solids since their metallic structure of electrostatic attractions between metal cations and delocalized electrons result in a high boiling point and low volatility (Owen, 2014). The bottom of the anode was a concentrated aqueous solution since zinc was dissolving as it oxidized (Owen, 2014). The electrolyte was initially clear since it was purified, but it was turning black since pieces of zinc were chipped from the anode as it was dissolving (Sulfuric Acid: Safety Data Sheet, 2018). These large pieces may act as impurities that increase the VHC internal resistance before they dissolve due to increased collisions. Zinc and copper had colors due to their unbound valence electrons in their d-orbitals, however, their tints indicate metal oxides on their surfaces (Owen, 2014). Since copper is multivalent, it produced two oxides (Haynes, 2017).



During zinc's oxidation, there was a pungent smell, however, since hydrogen gas, sulfuric acid, and the metals are odorless, the odor may come from impurities reacting with produced zinc sulfate or hydrogen gas in the VHC (Owen, 2014). Gas bubbles emerged from the electrolyte during the closed circuit, indicating that hydrogen gas was produced from the redox reaction (Owen, 2014). The tingling from touching the alligator clip ends after submerging the electrodes indicates a closed circuit. The reaction vigorousness during the closed circuit conveys that zinc began to oxidize after the cell voltage relative to the electrolyte was established.

### Quantitative Graphs

Refer to the Appendix for plots of the VHC electrolyte temperatures ( $\pm 0.01$  °C) against the duration of maintaining a closed cell circuit ( $\pm 0.01$  s) in Figures 4-18.

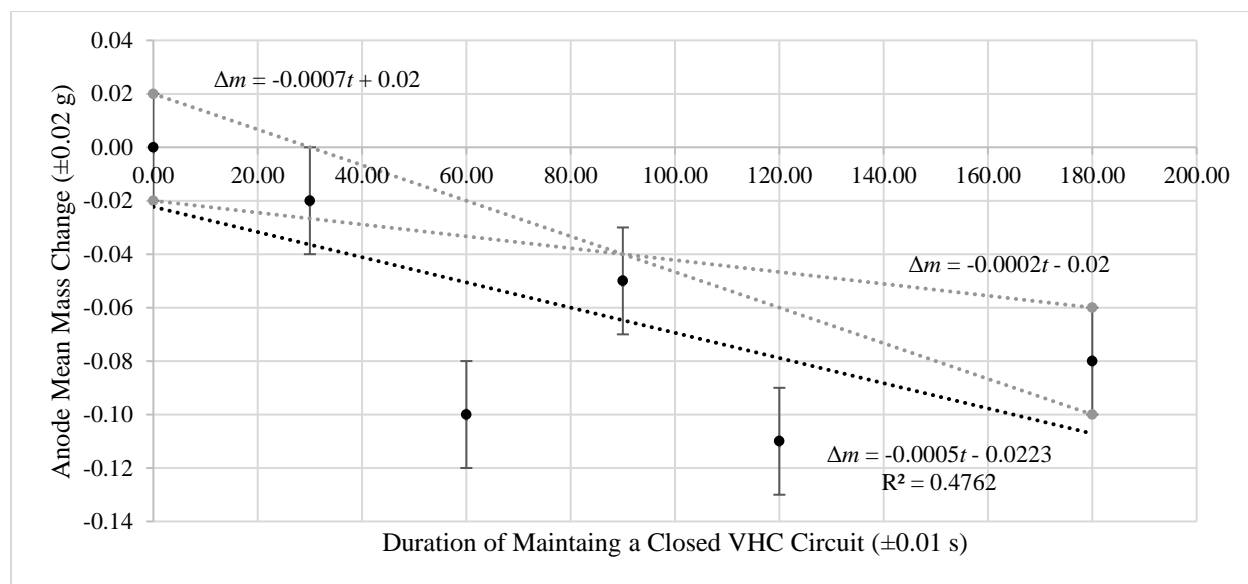


Figure 2. The change in mass of the zinc anode ( $\pm 0.02$  g) after maintaining a closed circuit in a copper-zinc voltaic half-cell ( $\pm 0.01$  s) for all settings and trials. Data from Table 8.

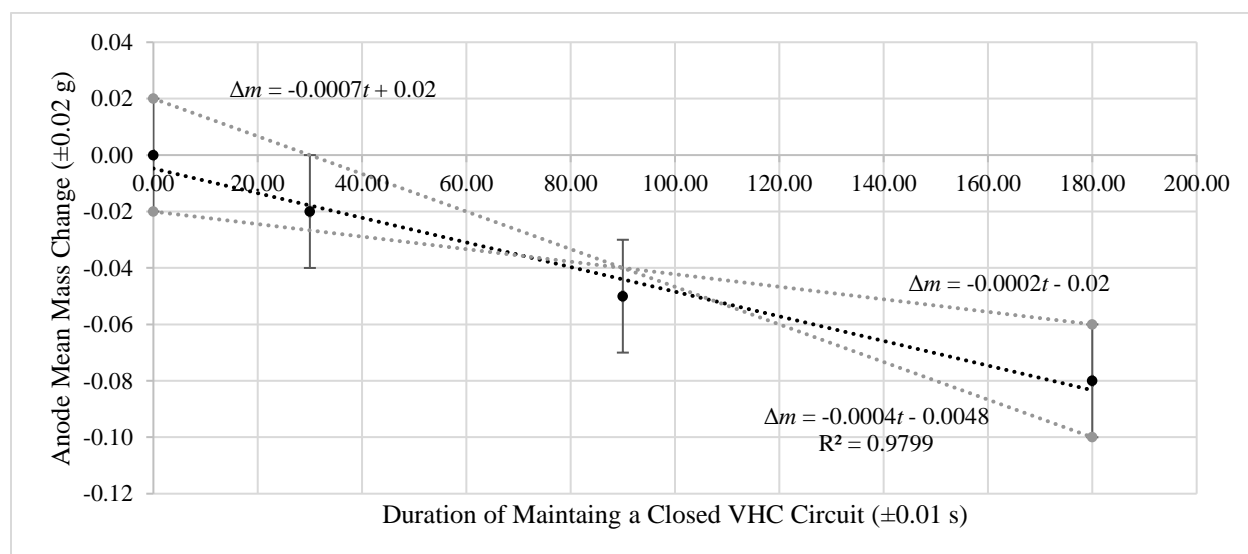


Figure 3. The change in mass of the zinc anode ( $\pm 0.02$  g) after maintaining a closed circuit in a copper-zinc voltaic half-cell ( $\pm 0.01$  s) for non-outlier settings and trials. Data from Table 8.

### Quantitative Analysis

The coefficient of determination in Figure 2 was appropriately 47.62% in linear regression. However, sketching the maximum and minimum slope lines conveyed the presence of outliers at  $t = 30.00, 60.00 \pm 0.01$  s as their error bars did not fit within the lines. The coefficient in Figure 3 was 97.99%, indicating  $\Delta m \propto t$ , which does not support the formulated hypothesis, thus, suggesting systematic errors and inaccurate apparatuses. If  $\Delta m = \alpha t + \beta$ :

$$\begin{aligned}
 \alpha_{\text{avg.}} &= \frac{\alpha_{\text{max}} + \alpha_{\text{min}}}{2} & \alpha_{\text{uncert.}} &= \left| \frac{\alpha_{\text{max}} - \alpha_{\text{min}}}{2} \right| \\
 &= \frac{-0.0002 + (-0.0007)}{2} & &= \left| \frac{-0.0002 - (-0.0007)}{2} \right| \\
 &= -0.0004 & &= 0.0002 \\
 \beta_{\text{avg.}} &= \frac{\beta_{\text{max}} + \beta_{\text{min}}}{2} & \beta_{\text{uncert.}} &= \left| \frac{\beta_{\text{max}} - \beta_{\text{min}}}{2} \right| \\
 &= \frac{-0.02 + 0.02}{2} & &= \left| \frac{-0.02 - 0.02}{2} \right| \\
 &= 0.00 & &= 0.02
 \end{aligned}$$

$$\begin{aligned}
 \therefore \Delta m &= (-0.0004 \pm 0.0002)t + (0.00 \pm 0.02) \\
 &= (-0.0004 \pm 0.0002)t \pm 0.02
 \end{aligned}$$

Additionally, due to the possible presence of outliers, overfitting the graph using a polynomial function of any degree formulates an overexaggerated, incorrect relationship between the variables. Also, the highest standard deviation was 112.5% of the mean, indicating that the data was imprecise. Since the slope is the average change in mass with respect to time, for each second that passes after establishing a closed circuit, the anode mass decreases by an average of 0.0004 g. The fact that it decreases with time conveys that zinc is being oxidized and the fundamental scientific theory is correct. A  $\Delta m$ -intercept of approximately 0.00 g conveys a

direct relationship. However, when considering the range of  $\Delta m$  to be 0.11 g, a vertical shift uncertainty of 0.02 g (18% of the range) suggests an influence of random and systematic errors. Since the vertical error bars of all the points overlap each other and the mass change uncertainty is equal to the  $\Delta m$ -intercept uncertainty ( $\pm 0.02$  g), systematic errors were present. Due to the relatively small duration uncertainty of 0.01 s and lack of horizontal error bars visible on the graph, there exists an issue with gathering data on the dependent variable rather than the independent one. Lastly, since there are no accepted values nor literature relationships between the investigated variables, the percentage error of the rate could not be calculated.

However, when referring to the electrolyte temperature with respect to time as well as the qualitative analysis, the relationship could be considered linear. Firstly, the relationship between temperature and time is quadratic (increasing), however, this may be overfitted and inconclusive since the linear and exponential regressions were similar, the temperature was fluctuating, and there existed many plots with coefficients of determination that were significantly less than 50%. Therefore, there existed many systematic errors. As the VHC current increases, heat is released and the rate of AMC increases, thus, increasing the rate of change in enthalpy of zinc. This increasing rate of heat produces a non-linear relationship. As temperature increases with time, internal resistance decreases, and the rate of AMC increases, thus, the vigorousness of the redox reaction increases to accommodate for the increasing rate of electron flow. Qualitatively, the vigorous reaction releases larger pieces of zinc into the solution which act as impurities that impede electron flow before they dissolve. These impurities increase resistance, decrease current, and return the rate of AMC back to the initial rate. Therefore, an average change in AMC rate of  $0.00 \text{ g}\cdot\text{s}^{-2}$  conveys a linear relationship:

$$\iint (0.00 \text{ g}\cdot\text{s}^{-2}) dt = \Delta m = kt + c, \text{ where } k, c \in \mathbb{R}.$$

## Evaluation

### Alternative Methods

Since no available literature values exist for the relationship between the AMC and reaction time, a dataset experiment could not be conducted. On the other hand, a simulation may have been carried out to eliminate any systematic errors, however, that would defeat the purpose of applying scientific theories and evaluating any unknown influences that may not be accommodated in the simulation before conducting a laboratory experiment.

### Limitations

Numerous systematic errors were present during the investigation that equally shifted the data points. Granular zinc pieces were removed from the anode as the redox reaction was carried out vigorously. They acted as impurities impeding electron flow through the electrolyte, thus, increasing the internal resistance and decreasing the current and the rate of AMC relative to time.

Based on qualitative analysis, a pungent smell was present as the closed circuit was maintained. However, since all the reactants and products due to the redox reaction are odorless, impurities must have been in the glass beaker ( $200 \pm 13 \text{ cm}^3$ ). The sulfuric acid was odorless due to its clear color indicating its purity, but the electrodes had metal oxides on their surfaces according to the colored tints (Sulfuric Acid: Safety Data Sheet, 2018). Zinc oxide reacted with sulfuric acid to produce aqueous zinc sulfate, but copper(I) oxide and copper(II) oxide both produced copper(II) sulfate (copper(I) sulfate is chemically unstable), which are all odorless (Copper(I) sulfate, 2019). Therefore, unknown, pungent impurities that existed in the glass beaker ( $200 \pm 13 \text{ cm}^3$ ) must have escaped via the hydrogen gas bubbles to convey the smell. The presence of these impurities and hydrogen gas may inhibit electron flow in the electrolyte, thus, increasing resistance and decreasing electrical current and the rate of AMC (Tsokos, 2014).

Lastly, due to the increasing electrolyte temperature and decreasing electrolyte concentration, the internal resistance, potential difference, and current were changing with respect to time, thus, influencing the rate of AMC.

### **Improvements**

To decrease the vigorousness of the reaction and the amount of granular zinc pieces, a lower concentration of sulfuric acid may be used as the electrolyte. Less sulfuric acid molecules reduces the probability of the oxyacid interacting with the anode to oxidize zinc, thus, decreasing reaction vigorousness and the amount of impurities formed (Owen, 2014). The metal electrodes may be cleaned and polished from oxide impurities using steel wool (Copper(I) sulfate, 2019). Using an oxidizing agent like permanganate can maximize the efficiency of the electrochemical cell as the produced hydrogen gas bubbles react with activated oxygen to produce liquid water, thus, minimizing electrical resistance (Owen, 2014). Underneath the fume hood before each trial, the glass beaker ( $200 \pm 13 \text{ cm}^3$ ) should be rinsed off at least three times with tap water, ethanol, and deionized water in this order to remove any water-soluble or insoluble solutions, and strong and weak acids and bases that may act as impurities (Helmenstine, 2019).

Since the electrolyte temperature was increasing non-linearly with time, a cooling bath would be ineffective since the rate of heat transfer from the solution to the ice cannot be dynamically controlled to counteract the heating (Nichols, 2019). Although concentration cannot be measured nor calculated in real-time to add solute at the same rate as the rate of changing concentration, the concentration of hydrogen protons of the solution may have been monitored using a digital pH probe to calculate the electrolyte concentration over time after the trial (The Hydronium Ion, 2019). Nonetheless, the electrolyte's average kinetic energy and concentration were uncontrolled variables.

### Discussion

This investigation explored the extent to which the duration of maintaining a closed circuit in the VHC affects the change in the zinc anode's mass. Unlike galvanic cells which rely on two half-cells, a single voltaic cell is sensitive to more variables like the distance between the electrodes and their surface areas submerged in the electrolyte since it involves an internal resistance (Kshetrapal, Voltaic Cell Internal Resistance, 2018). Therefore, there were more controlled variables and a more thorough procedure that accommodated them. However, there were also uncontrolled variables like the electrolyte temperature and concentration, which formed the basis for systematic errors and prevented the gathered data from supporting the formulated hypothesis.

It was hypothesized that the relationship between the variables would be direct and non-linear due to a theorized change in rate of the anode's mass change with respect to time since the internal resistance continually changes. The processed data contained outliers and the general relationship with the highest coefficient of determination was linear if not overfitted. However, due to uncontrolled variables and systematic errors, the data is not be reliable to formulate a confident conclusion. Fortunately, due to the decreasing anode mass and appropriate qualitative data, the fundamental theories behind the voltaic cell is clearly reflected in this investigation.

Nonetheless, investigating VHCs is significant as it creates opportunities to further explore different structures of electrochemical cells and their physical and chemical properties in areas of engineering, science, or simply for the excitement of exploring electrochemistry. More efficient structures and materials of batteries in terms of energy and manufacturing costs may be studied and evaluated.

### References

*16.1: Arrhenius Theory: A Brief Review.* (2016, February 8). Retrieved from Chemistry

LibreTexts:

[https://chem.libretexts.org/Bookshelves/General\\_Chemistry/Map%3A\\_General\\_Chemistry\\_\(Petrucci\\_et\\_al.\)/16%3A\\_Acids\\_and\\_Bases/16.1%3A\\_Arrhenius\\_Theory%3A\\_A\\_Brief\\_Review](https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_General_Chemistry_(Petrucci_et_al.)/16%3A_Acids_and_Bases/16.1%3A_Arrhenius_Theory%3A_A_Brief_Review)

Bowen-Jones, M., & Homer, D. (2014). *Physics Course Companion*. Oxford: Oxford University Press.

Bylikin, S., Horner, G., Murphy, B., & Tarcy, D. (2014). *Chemistry Course Companion*. Oxford: Oxford University Press.

*Copper(I) sulfate.* (2019, June 4). Retrieved from Wikipedia The Free Encyclopedia:

[https://en.wikipedia.org/wiki/Copper\(I\)\\_sulfate](https://en.wikipedia.org/wiki/Copper(I)_sulfate)

Goldie-Scot, L. (2019, March 5). *A Behind the Scenes Take on Lithium-ion Battery Prices.*

Retrieved from BloombergNEF: <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/>

Haynes, W. (2017). *CRC Handbook of Chemistry and Physics*. Boca Raton: Taylor and Francis Group.

Helmenstine, A. M. (2019, August 7). *How to Clean Laboratory Glassware*. Retrieved from ThoughtCo.: <https://www.thoughtco.com/how-to-clean-laboratory-glassware-606051>

Kshetrapal, P. (2018, February 8). *Voltaic Cell Internal Resistance*. Retrieved from YouTube:

<https://www.youtube.com/watch?v=8IZYQ3pvO44>

Kshetrapal, P. (2018, February 8). *Voltaic Cell Working*. Retrieved from YouTube:

<https://www.youtube.com/watch?v=6jKM9Gf9sC0>



*Nernst Equation.* (2019, June 5). Retrieved from LibreTexts:

[https://chem.libretexts.org/Bookshelves/Analytical\\_Chemistry/Supplemental\\_Modules\\_\(Analytical\\_Chemistry\)/Electrochemistry/Nernst\\_Equation](https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Nernst_Equation)

Nichols, L. (2019, August 18). *1.3J: Cooling Baths*. Retrieved from Chemistry LibreTexts:

[https://chem.libretexts.org/Bookshelves/Organic\\_Chemistry/Book%3A\\_Organic\\_Chemistry\\_Lab\\_Techniques\\_\(Nichols\)/1%3A\\_General\\_Techniques/1.3%3A\\_Heating\\_and\\_Cooling\\_Methods/1.3J%3A\\_Cooling\\_Baths](https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Book%3A_Organic_Chemistry_Lab_Techniques_(Nichols)/1%3A_General_Techniques/1.3%3A_Heating_and_Cooling_Methods/1.3J%3A_Cooling_Baths)

Owen, S. (2014). *Chemistry for the IB Diploma*. Cambridge: Cambridge University Press.

*Sulfuric Acid: Safety Data Sheet.* (2018, January 23). Retrieved from LabChem:

<http://www.labchem.com/tools/msds/msds/LC25550.pdf>

*The Hydronium Ion.* (2019, September 29). Retrieved from 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)

Tsokos, K. (2014). *Physics for the IB Diploma*. Cambridge: Cambridge University Press.

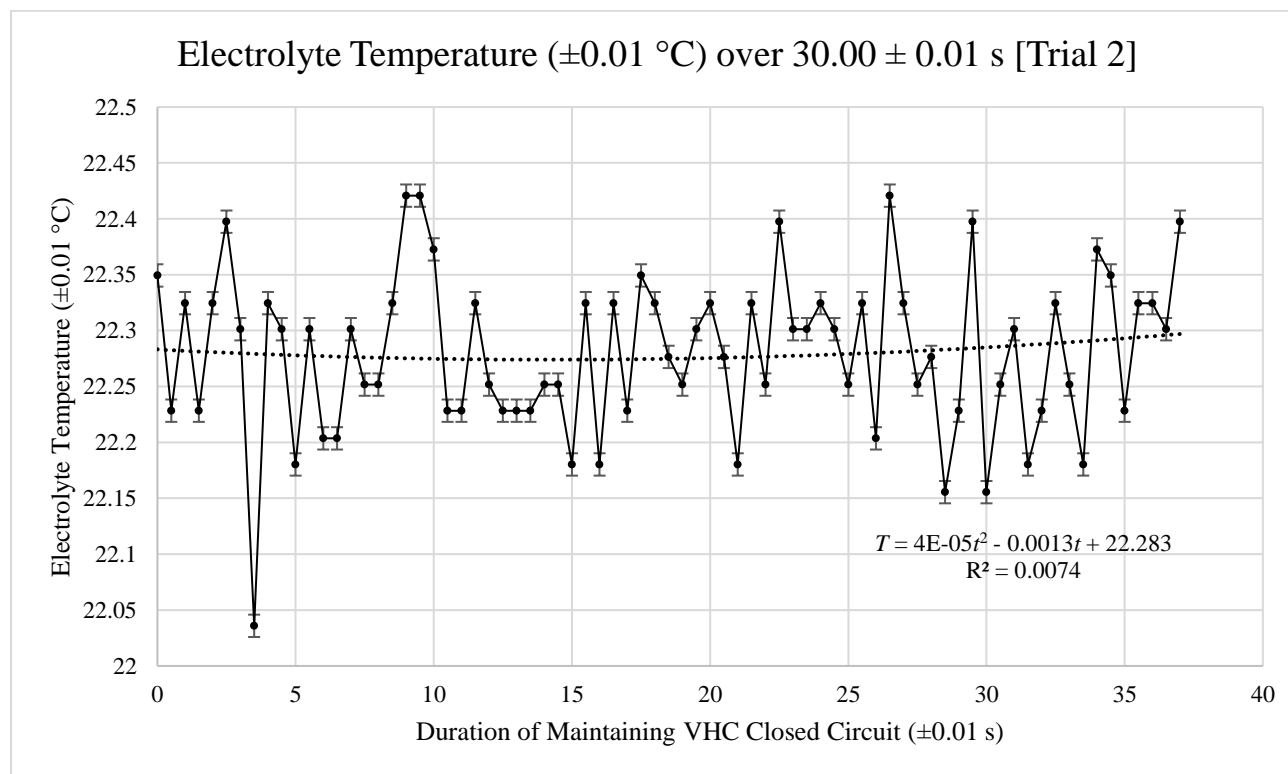
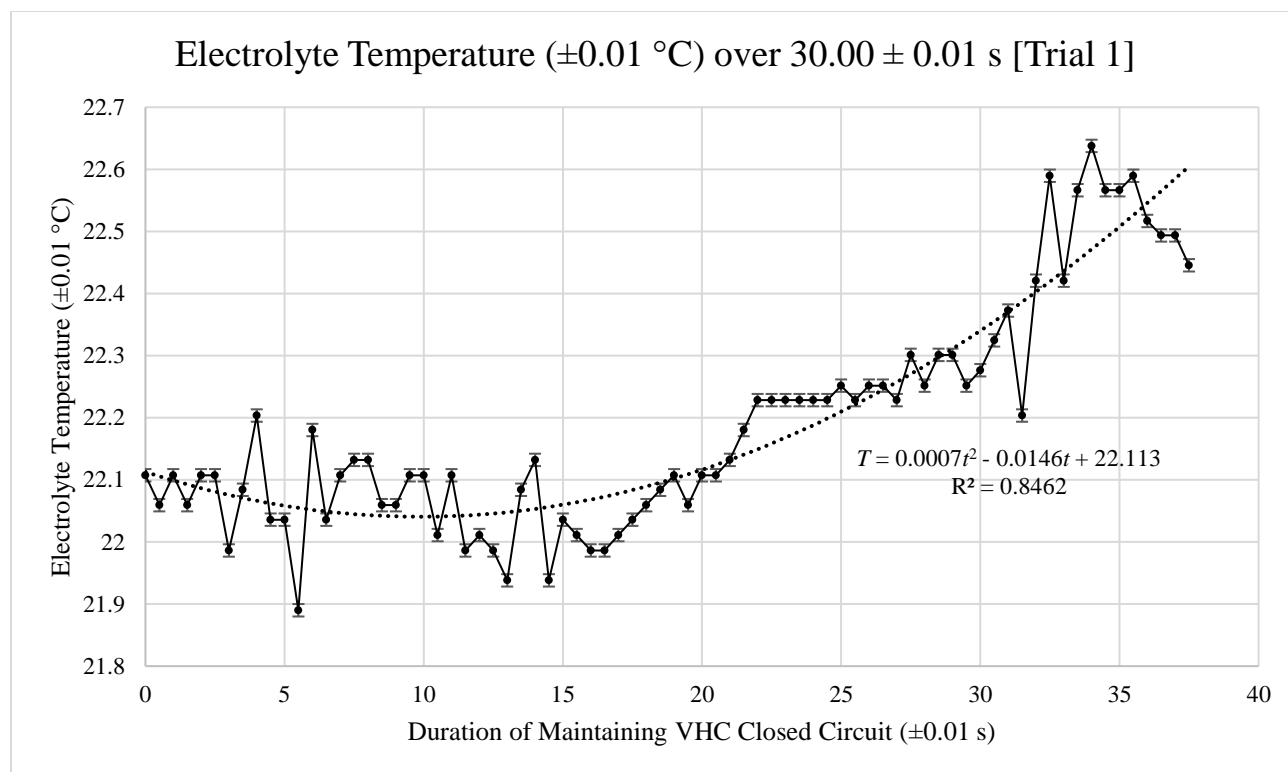
*Voltaic Cells.* (2019, June 5). Retrieved from Chemistry LibreTexts:

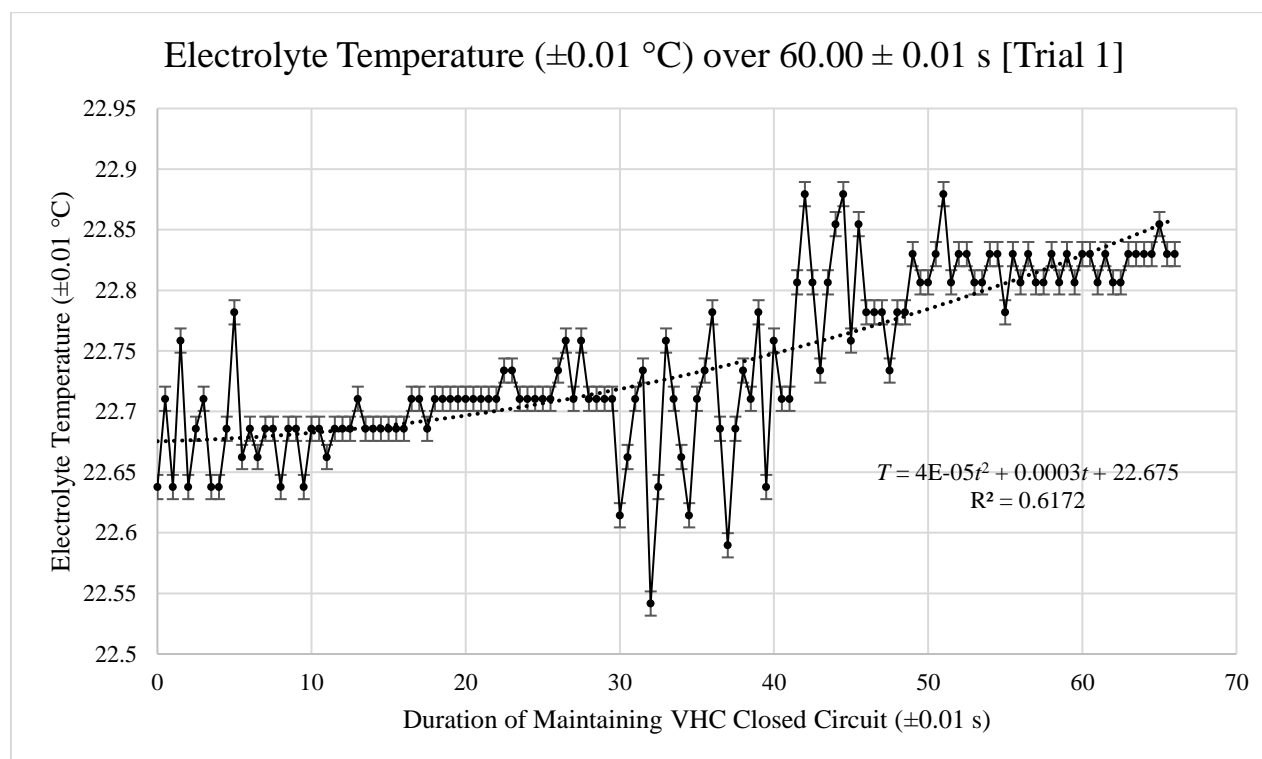
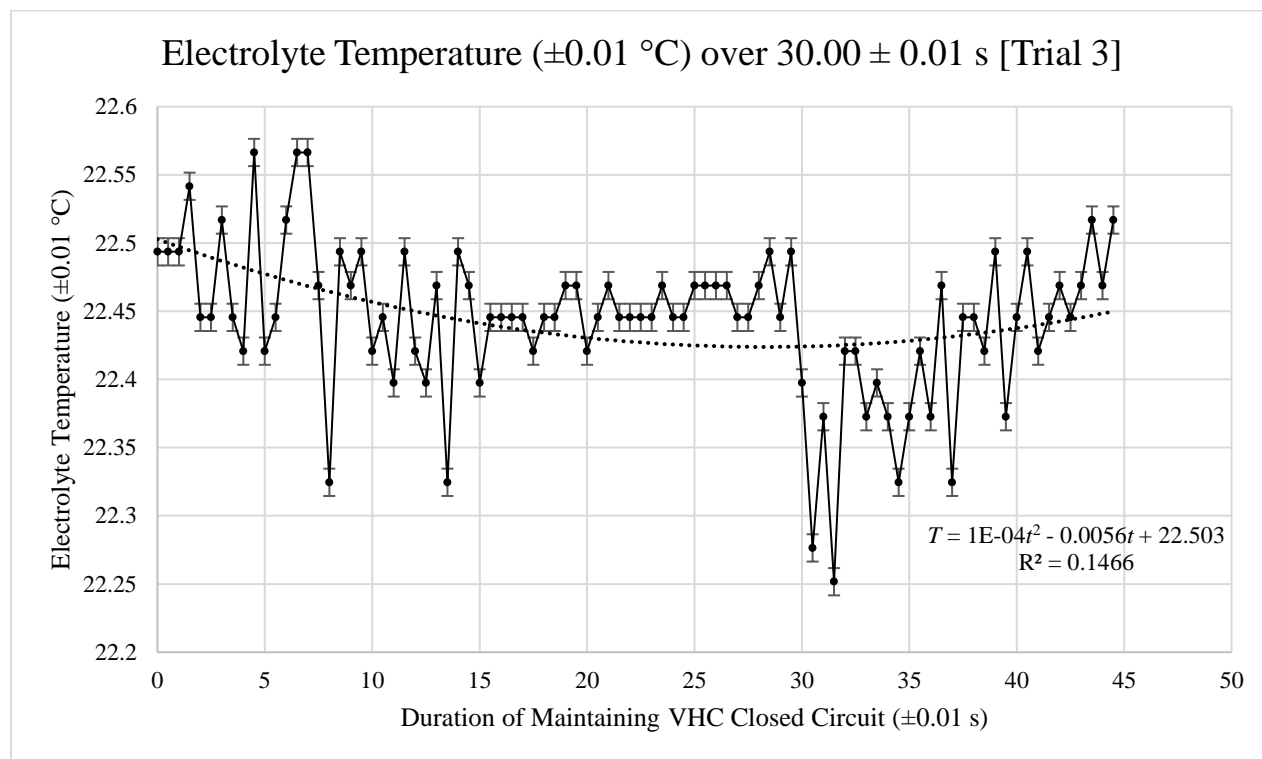
[https://chem.libretexts.org/Bookshelves/Analytical\\_Chemistry/Supplemental\\_Modules\\_\(Analytical\\_Chemistry\)/Electrochemistry/Voltaic\\_Cells](https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Voltaic_Cells)

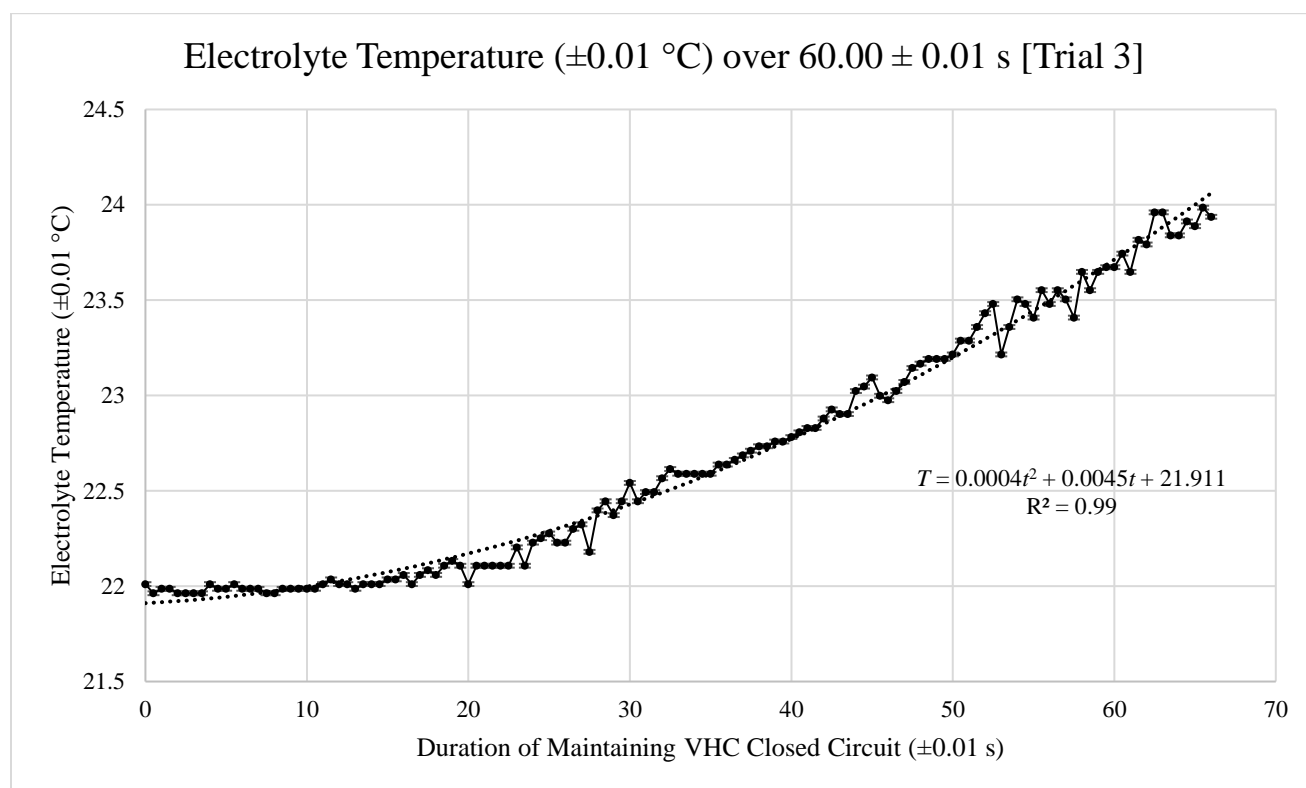
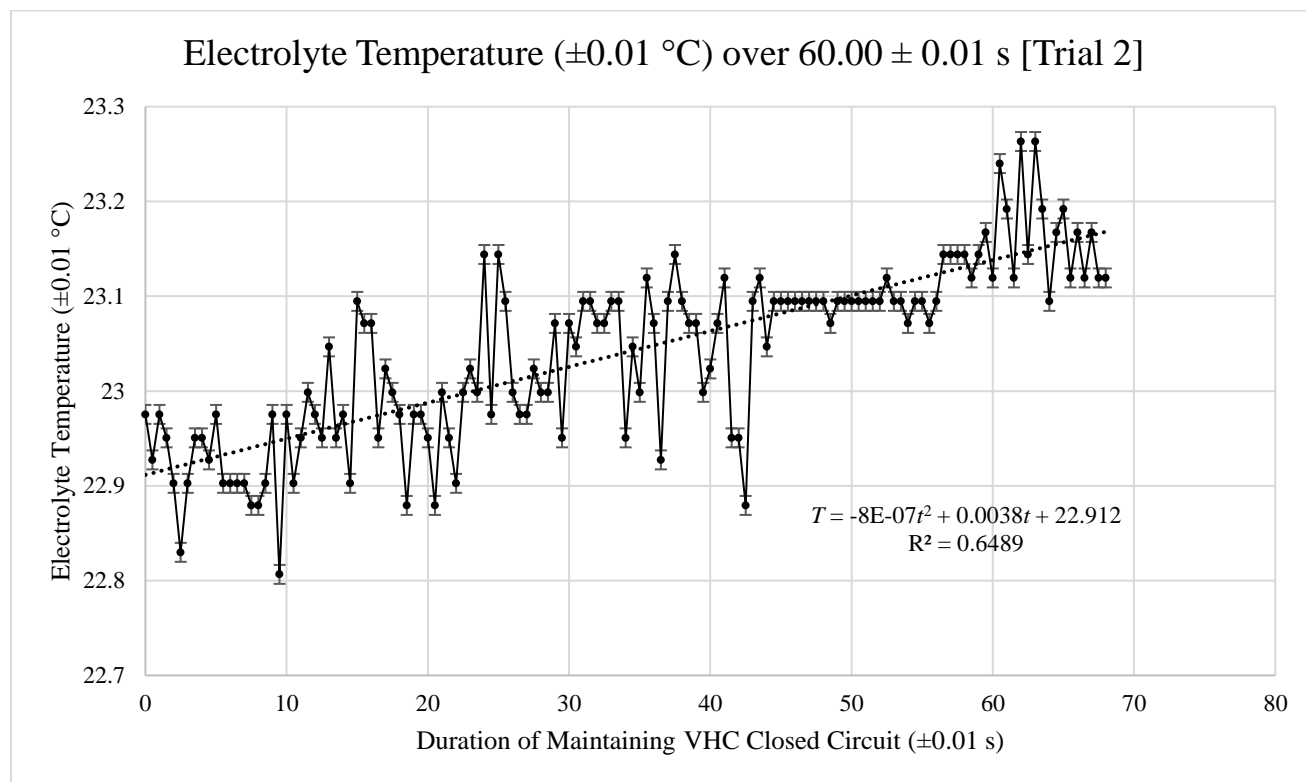
*Zinc Sulfate: Safety Data Sheet.* (2014, October 24). Retrieved from Fisher Science Education:

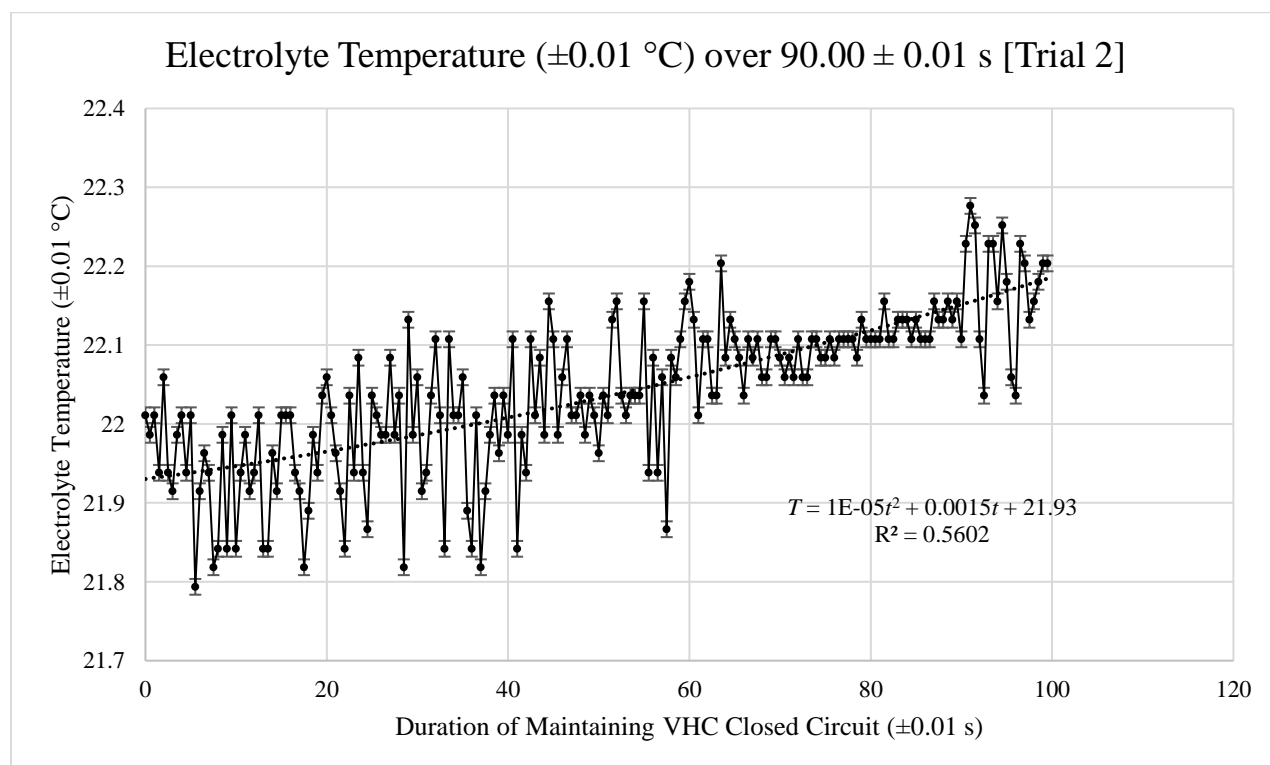
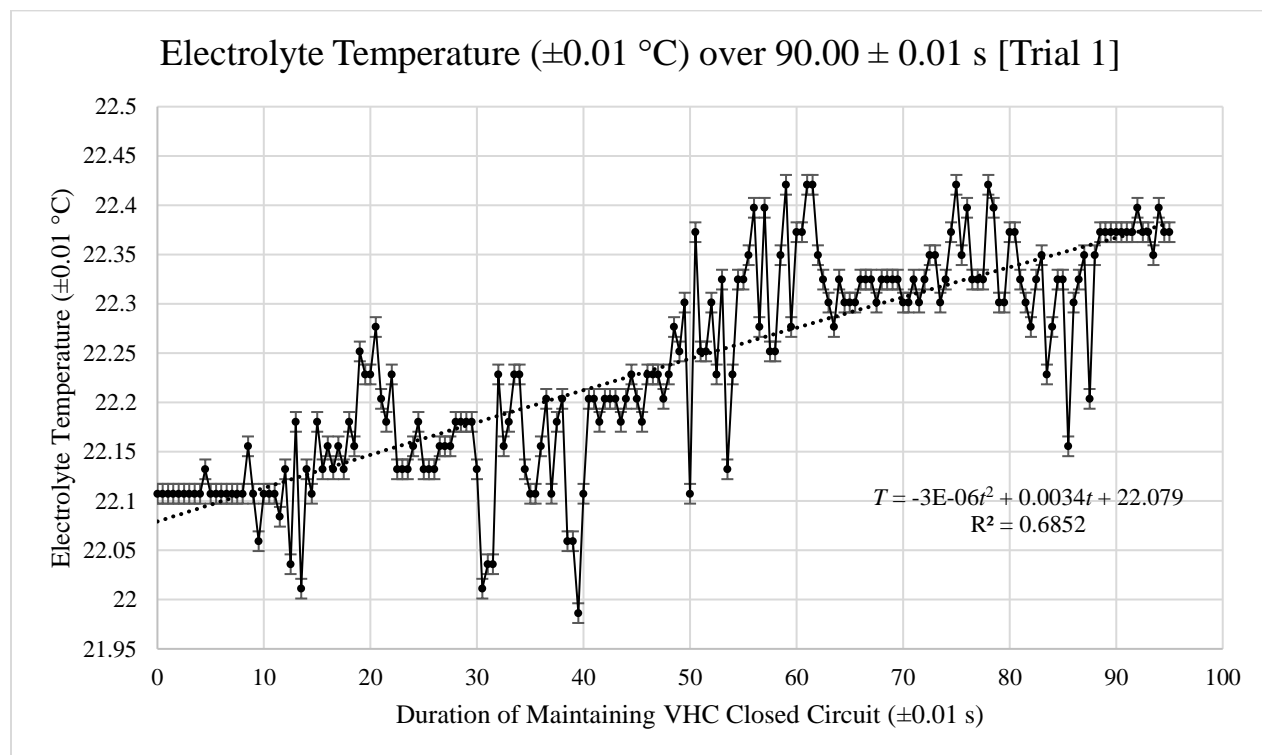
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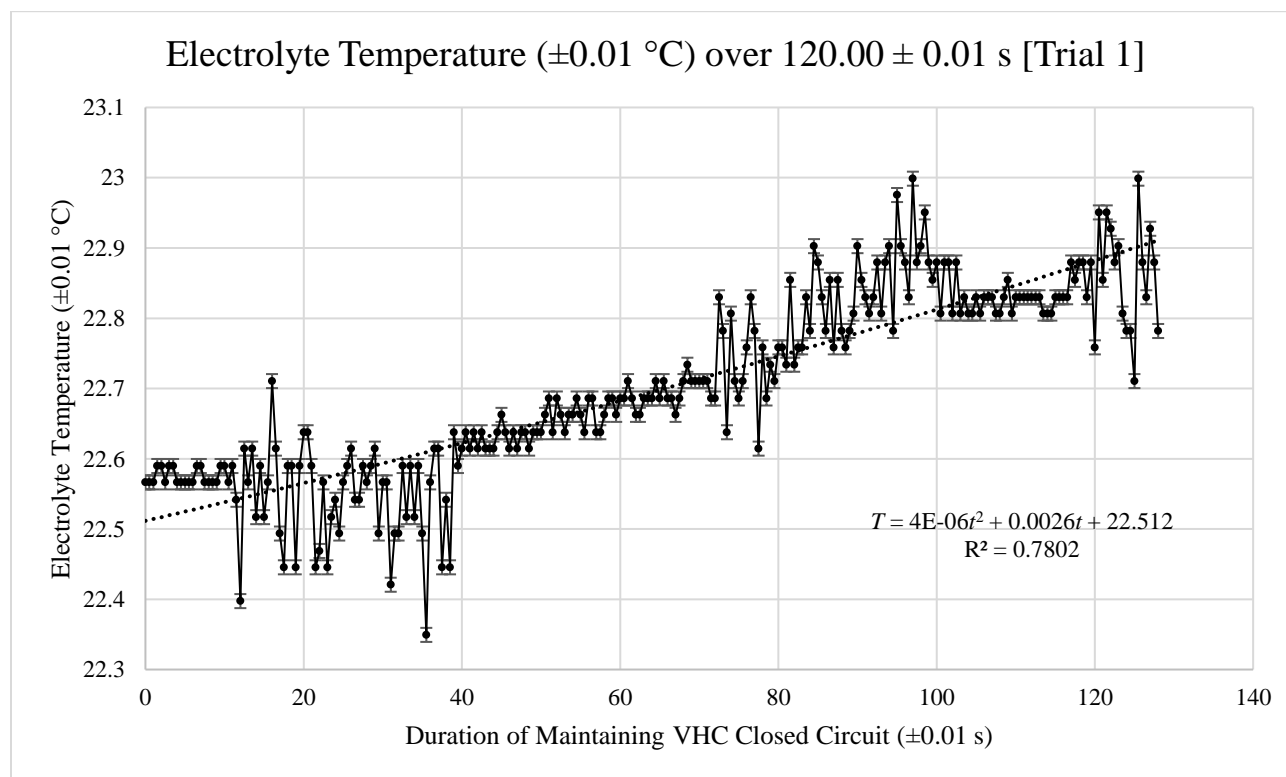
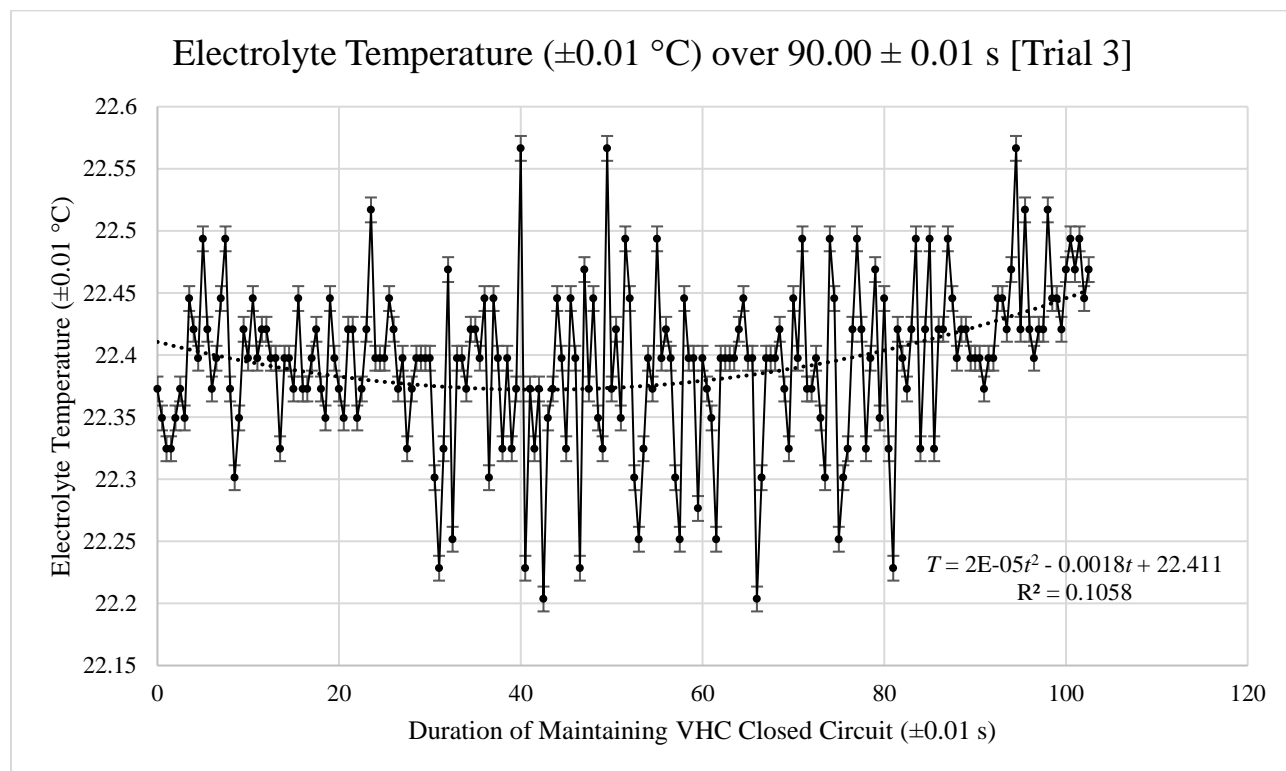
## Appendix

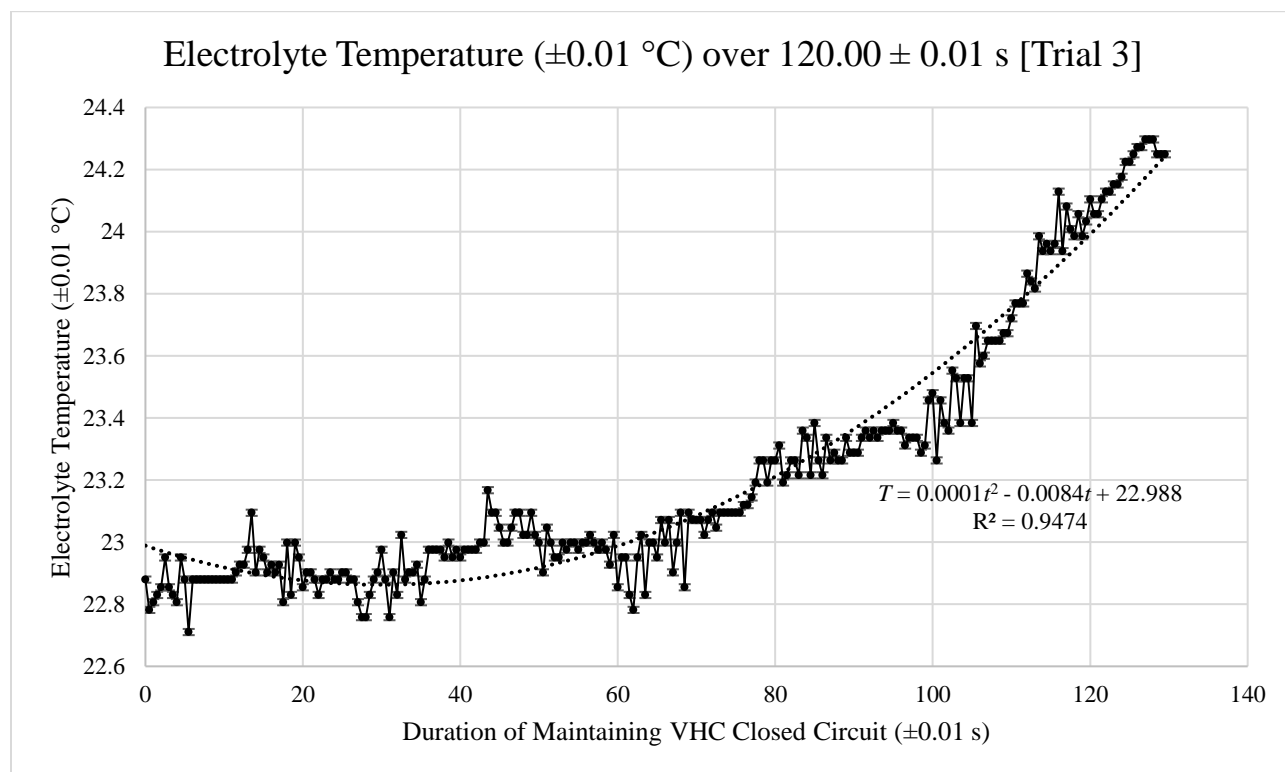
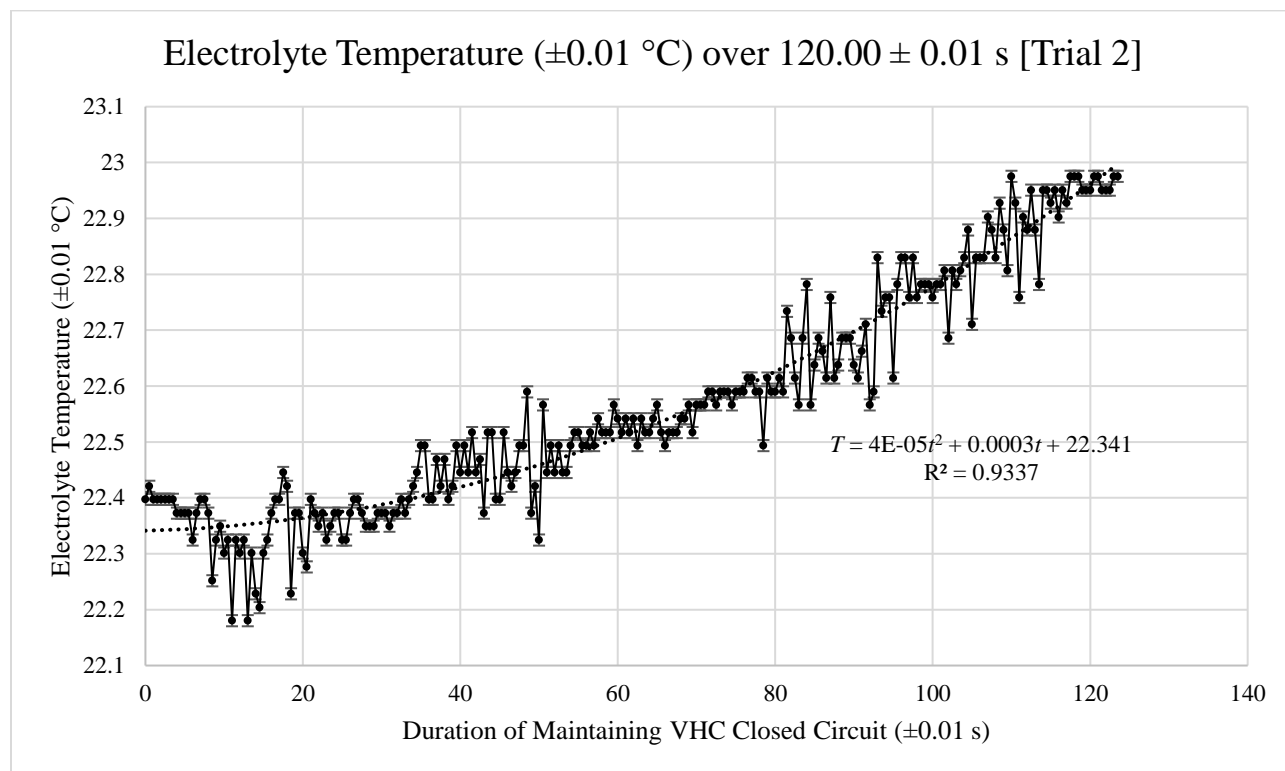


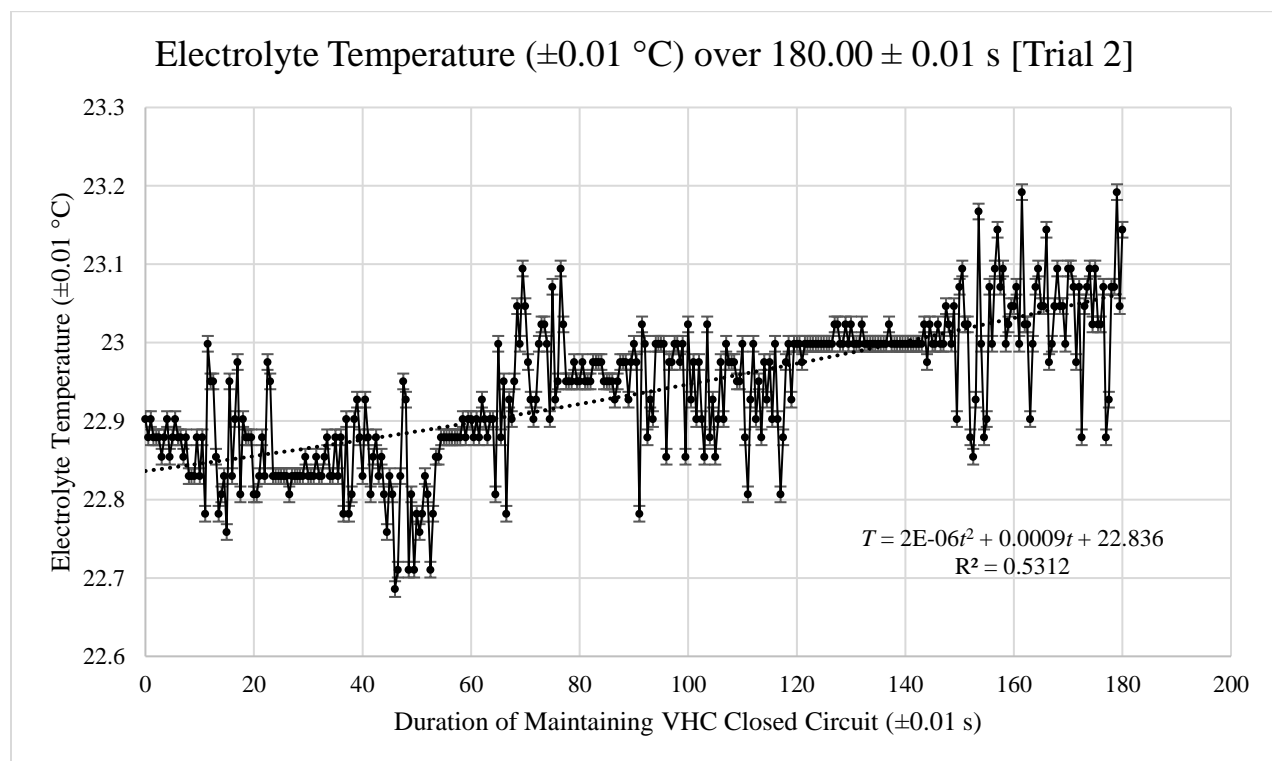
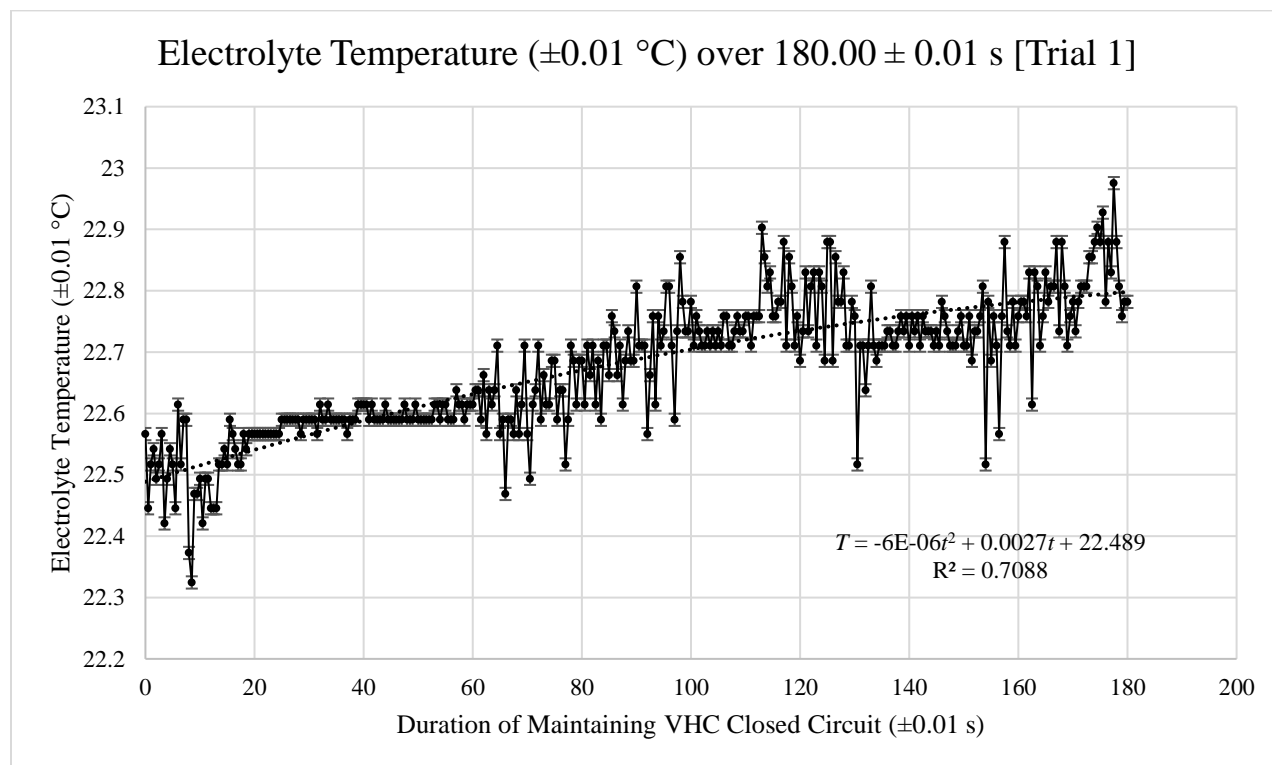




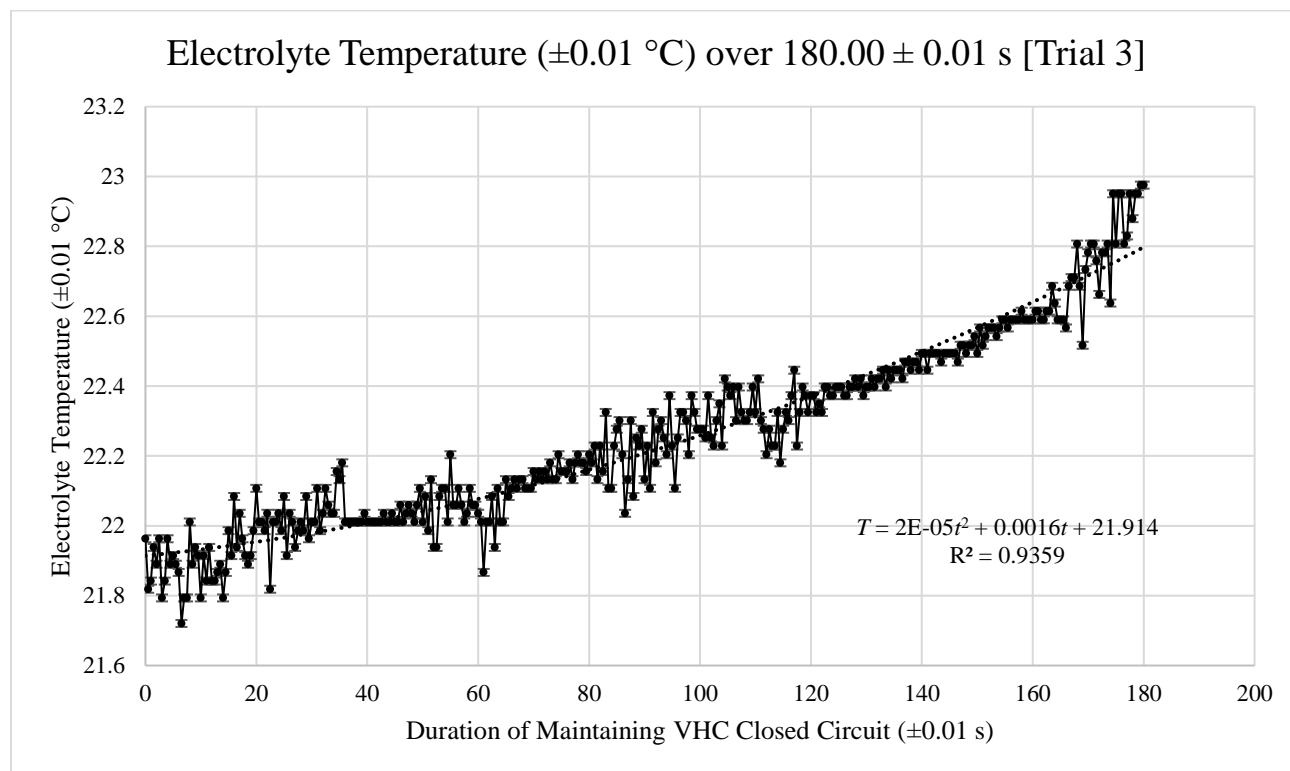












Figures 4-18. The temperature of the electrolyte ( $\pm 0.01$  °C) after maintaining a closed VHC circuit for all settings and trials of the duration ( $\pm 0.01$  s).