(2988 words)

Electroplating of an iron nail with copper

How does the intensity of current (0.103A, 0.204A, 0.305A, 0.405A, 0.505A) supplied to a Copper-Iron Electrolytic Cell affect the mass of copper deposited on the Iron Nail Cathode?

Commented [A1]: Research design, first strand: The question describes the system and includes both independent and dependent variables.

Introduction

Electrolysis is the process that uses an "external source of electrical energy to bring about a redox reaction that would otherwise be non-spontaneous"[1]. In electroplating-an application of this process-, a metal layer is deposited on top of another metal or other conductive object. The anode is made of the same metal to be coated to replenish the supply of ions in the electrolyte[2].

Faraday's first law states the flow of current is proportional to the mass of material plated on the electrode[3]. During electrolysis[4], an external electric source causes an electric current to pass through an iron nail cathode, making it negatively charged. When using aqueous Copper (II) Sulphate as the electrolyte, the dissolved copper ions (Cu^{2+}) reduce at the cathode by gaining electrons to form copper deposited on the iron nail[5]. The copper foil anode is the positive electrode that oxidises itself, supplying electrons for the reaction and dissolving as Cu^{2+}[6]

The cell potential (E^ocell) is the overall value for the electrochemical cell.

$$E_{\theta\text{cell}} = E_{\theta\text{half-cell where reduction occurs}} - E_{\theta\text{half-cell where oxidation occurs}}$$

The E^o of a half- cell is the "electromagnetic force generated when it is connected to the standard hydrogen electrode by an external circuit and a salt bridge, measured under standard conditions" and it is given for the reduction reaction[7].

The electrolyte used in the experiment contains Cu^{2+}, SO_4^{2-}, OH^-, H^+ ions as water molecules autoionize and can also undergo redox reactions. The product at each electrode is determined by the relative E^o values of the ions[8], and the nature of the electrode resulting in several possible reactions.

At the cathode:

$Cu^{2+}{}_{(aq)} + 2e \text{-}\rightarrow Cu_{(s)}$ E^o= +0.34V

$2H_2O_{(l)} + 2e \text{-}\rightarrow H_{2\,(g)} + 2\ OH\text{-}_{(aq)}$ E^o = -0.83V

Metals with higher E^o values are stronger oxidizing agents so $Cu^{2+}$are more likely to reduce at the cathode[9].

At the anode:

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[1] (Brown et. al, 442)
[2] (Brown et.al,454).
[3] (Britannica)
[4] Set up under "Method"
[5] (Brown et. al, 443)
[6] (Brown et. al,450)
[7] (Brown et, al, 435-436)
[8] IB Chemistry Data Booklet
[9] (Brown ct. al, 415,441)

$Cu^{2+}{}_{(aq)} + 2e \rightarrow Cu_{(s)}$ $E^o = +0.34V$

$4H^+{}_{(aq)} + O_{2\,(g)} + 4e \rightarrow 2H_2O\ (l)$ $E^o = +1.23V$

Substances with lower E^o values are stronger reducing agents, so copper atoms are more likely to oxidise.

Commented [A2]: Research design, first strand: The relevant theory is correctly explained.

The final predicted products are:

Cathode: $Cu^{2+}{}_{(aq)} + 2e \rightarrow Cu_{(s)}$ $E^o = +0.34V$

Anode: $Cu(s) \rightarrow Cu^{2+}{}_{(aq)} + 2e^-$ $E^o = +0.34V$[10]

E^ocell = 0.34-0.34 = 0 V

Due to the overpotential of the circuit this theoretical value is not true. Overpotential "is the difference in the electrode potential of an electrode between its equilibrium potential and its operating potential when a current is flowing.", with "extra energy needed to force the electrode reaction to proceed at a required rate (or its equivalent current density) "[11].

Commented [A3]: Research design, first strand: Overpotential is beyond the syllabus and adds value to the background theory.

Using Faraday's first law, where the amounts of products at the electrodes depend on the quantity of electric charge passed through the cell, the charge can be quantified by multiplying the current and duration of the electrolysis. The ratio between the number of electrons and copper produced allows to calculate the mole, and thus, the mass of copper produced:

$$m = \frac{ItM}{Fz}$$

Where:

m = Mass of Copper produced, I= Current, t= Time, M = Molar mass of Copper, the product that is electroplated = 63,546 $gmol^{-1}$,F Constant = 96485 C/mol, z = Charge of ion = 2

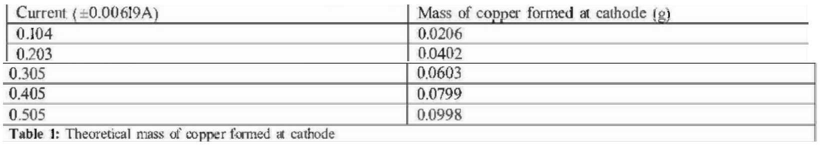
I considered that the experimental results would be similar to the theoretical values as calculated below, and the mass of copper formed at the cathode would increase linearly with the current supplied to the reaction.

Mass of copper formed at cathode at 0.104A

$$\frac{ItM}{Fz} = \frac{0.104 \times 63546 \times 600}{96485 \times 2} = \frac{3981898}{192970} = 0.0206g$$

Commented [A4]: Data analysis, second strand: The candidate calculates theoretical values to support their hypothesis.

Commented [A5]: Data analysis, first strand: The data are clearly reported.



Current (±0.00619A)	Mass of copper formed at cathode (g)
0.104	0.0206
0.203	0.0402
0.305	0.0603
0.405	0.0799
0.505	0.0998

Table 1: Theoretical mass of copper formed at cathode

Method

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[10] Values correspond to standard conditions. The collected data show differences are not substantial.

[11] (Lou. Huang, 4)

I conducted a pilot aiming to adjust the circuit's current by manipulating the resistance level with a rheostat. Unexpectedly, the current gradually increased with time from the original value. This could result from the increasing amount of copper deposits that made the nail lumpy, with a larger surface area. Larger surface areas lead to less resistive current paths, and an increased current[12]. However, this is difficult to resolve as interfering with the deposits on the nail may disrupt the circuit.

I wanted to use a galvanostat to automatically maintain a constant current and voltage by altering the resistance, but none was available at school. I was limited to a variable resistor, where the current was indirectly kept constant by manually increasing the resistance every time the current exceeded the intended value.

Commented [A6]: Research design, second strand: The report includes an explanation of the selected equipment used.

The circuit required around ten seconds to adjust the current to the intended value, but copper deposits were already visible when the current was adjusted. This leads to inaccurate results as the products of electrolysis were affected by another current.

Commented [A7]: Evaluation, first strand: A weakness limitation is explained.

Commented [A8]: Research design, second strand: Careful attention is given to factors affecting validity of results.

Variables

Independent - The range of current was chosen as the digital current logger device had a precision of 0. 00619A.The mean values resulted in increments of 0.103A, 0.204A, 0.305A, 0.405A and 0.505A. I used 3 significant figures as it was enough to differentiate current levels between the various increments.

Commented [A9]: Research design, second strand: Methodological considerations include the selection of range and its justification.

Dependent - Mass of the copper deposited. Because copper deposits were either stuck to the iron nail, or did not adhere to it I opted for the mass difference method.

Commented [A10]: Research design, second strand: The report includes the method used for measuring the dependent variable.

Methodological considerations include the range of the independent variable.

Variables controlled during the procedure:

Temperature: The "electrolysis process is much more efficient at raised temperatures[13]." An increase in temperature favours the collisions between ions in the electrolyte, reducing electrical resistance and increasing ionic conductivity, resulting in increased efficiency[14] and more copper deposited. Trials were conducted in the same room and the temperature of the electrolyte measured with a thermometer. The range of temperature remained in 296.05 to 297.05K ±0.05K[15].

Pressure, measured with a barometer, remained constant at 101.325 ±0.001kPa.

The metals used in the electrodes were chosen considering their level of activity, electrical resistance and corrosion resistivity[16]. The voltage was kept at 12.00V to provide an equal amount of energy for reduction and oxidation reactions.

Commented [A11]: Research design, second strand: The methodological considerations are thorough and the candidate has monitored any factors that were relevant and could not be controlled.

The resistance was modified to keep the current at the desired values, and I also considered that:

$$R = \frac{\rho l}{A}$$

where A is the cross-section area, ρ is the material resistivity, R is the electrical resistance, and l is the length of the current path[17]. Reducing the distance between electrodes, lowers the electrical

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[12] (Bahlake, 1738)

[13] (Nikolic et. al., 3316)

[14] (Buelvasl et. al.)

[15] It can be assumed that the temperature is constant throughout the experiment.

[16] (Nikolic et. al., 3321)

[17] (Nikolic et. al., 3316)

resistance, and increases the current of ions in the electrolyte, enabling Cu^{2+} to travel efficiently across electrodes[18]. An electrode holder was used to hold the electrode in the right position.

Size and alignment of the electrodes: 80 mm iron identical nails were selected to control surface area and of similar size as foil to avoid anode polarisation. 20x80 mm copper pieces were cut from the same foil with a constant thickness, as larger surface areas lead to less resistive current paths[19]. Higher electrode height leads to additional power dissipation in a cell, and it forms a larger volume of void fraction[20]. Edges were rounded off to improve current distribution. All pieces washed in Gateros light alkaline cleaner (30 min), rinsed with distilled water and dried in oven at 348K for 2.5 hours to improve adherence[21].

Commented [A12]: Research design, second strand: This is very well done, including factors not often considered at this level.

Electrolyte's concentration: In Faraday's law, the mass of substance deposited is only affected by current and time, but the equation only applies when the current efficiency (CE) of the metal deposition reaction is 100 %. If the concentration of metal ion in the electrolyte decreases throughout electrolysis, the electrode potential will increase and may lead to parasitic reactions, lowering the CE[22]. This should not be a problem for this investigation because the anode dissociates into the same cation with the electrolyte, so each Cu^{2+} reduced at the cathode is replenished with a copper atom oxidised into a Cu^{2+}.

Duration of electrolysis: Longer periods increase the charge passed through the circuit, modifying the amount of copper produced. I chose 600 seconds- measured with the time against current datalogger- because the school's available balance has a ±0.001g precision so this time allowed for a reasonable mass of copper.

Materials

95.765 g of $CuSO_4$ (±0.003g), 6000.0 Distilled Water (±1.5cm^3), 2000 cm^{3}Volumetric flask, 250 cm^{3}Beaker, 30 pieces of 20x80 mm, 1,600 mm Copper Foil (±100mm), 30 Iron Identical Nails. Sand Paper, Electrode Holder (2 Crocodile Clips, 1 wooden block), 8 Wires, 4 Variable Resistors, a 12.00 V D.C. Power Generator(±0.01V), Scissors, ruler,Computer, Vernier (Current and Time) Logger (±0.00619A, ±1s), Filter Paper, Evaporating dish,338K oven, Thermometer (±0.05°C), 50.000 cm^3 Pipette (±0.050 cm^3), Balance (±0.001g), Gateros® light alkaline cleaner

Procedure[23]

I. 0.1moldm^3 $CuSO_4$ solution: Measure 31.922g of $CuSO_4 . 5 H_2O$, dissolve with distilled water in 2000cm^3 volumetric flask. Repeat 3 times.[24]

Commented [A13]: Research design, third strand: The number of repetitions will result in sufficient data. The candidate explains the choice.

2. Electrolyte: Using a pipette, measure and transfer 50.00 cm^3 of $CuSO_4$ solution into a 250 cm^3 beaker. Repeat 4 times.

3. Electrodes: Measure thirty pieces of metal (20mm x 80 mm) with a ruler and cut from the same piece of copper foil.

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[18] (Nikolic et. al. 3319)
[19] (Nikolic et. al. 3319)
[20] (M. Canaro, 2003)
[21] (SPC, 2021)
[22] (Padyala, 2015)
[23] All variables controlled as previously described
[24] Repetitions look to reduce random errors. Number limited by time constraints.

Thirty identical iron nails: Sand each to remove impurities.

4. Homemade Electrode Holder:

Two crocodile clips were hot glued onto the opposite sits of a piece of wood in a parallel direction at 30mm distance. This ensures identical surface area of electrodes immersed in the electrolyte and identical alignment in the electrolyte.

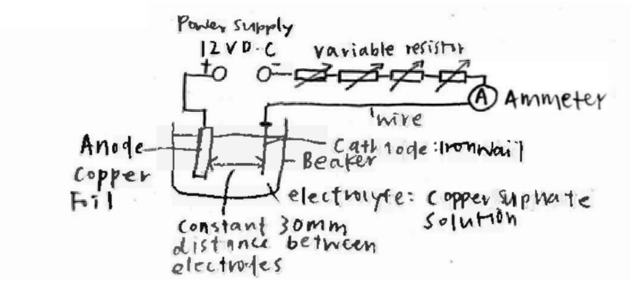

Diagram 2: Circuit Setup

Commented [A14]: Research design, third strand: The method is clearly communicated and the diagram is helpful. The procedure can be repeated.

Current datalogger: Used to regulate current level against time, acting as a stopwatch.

Ohm's Law indicates that "Voltage(V) = Current (I)x Time(t)" [25] so the variable resistors are used to alter the resistance.

5. Procedure summary

a. Setup One

Connect the circuit and adjust the variable resistor until the target current is reached. Turn off the power and discard both electrodes and electrolyte.

b. Setup two

Insert new electrodes and electrolyte. Once the circuit is connected, start current datalogger, which generates a current against time table, logging the current of the circuit every *10^{-1} s. The current of the cell will begin by being identical to the intended current. When the current begins increasing, reduce it back to original desired current. By 600 seconds, turn off the power.

7.Mass Recording

Mass an evaporating dish and a piece of filter paper. Fold the filter paper into a funnel and place it on the opening of a conical flask. Place the copper-plated iron nail on the filter funnel, while pouring the electrolyte into it to collect any copper suspended in the electrolyte. Rinse nail and copper deposits with distilled water. Place the filter paper on the previously massed evaporating dish into the oven, drying them at 348K for 3 hours. The temperature was used as it "this indicates the very slow rate" of copper oxidation when compared to temperatures from 373 to 423K[26]. This prevents

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[25] (Tsokos, 207),

[26] (Pinnelet.al, 575)

the mass of the copper deposits to be affected. The dish is massed and returned into the oven and process repeated until constant mass (difference within ±0.001g uncertainty range of the balance). The time intervals were sufficient for efficient drying while avoiding rusting.

Commented [A15]: Research design, second strand: The methodological considerations are thoroughly addressed and explained.

Risk Assessment

$CuSO_4$ "can irritate and burn the skin and eyes"[27]: gloves, goggles and lab coat should be worn to prevent skin contact with the solution.

The experiment was completed in a lab with an insulated plastic floor and the bench was kept dry, while gloves insulated from electricity. The electrolytic cell was always attended, and only one trial was done at a time.

The solution, copper foil and iron nails were recycled for use at lower levels[28].

Commented [A16]: Research design, second strand: Safety and environmental issues are nicely addressed.

Data Analysis

Qualitative data

As the circuit was connected, a brown layer (copper) was immediately formed on the initially grey iron nail. The deposits thickened overtime, and grew to be flakier, in particular for setups at 0.4A and 0.5A. The deposits lost adhesion to the nail, becoming suspended in the electrolyte. Small amounts of bubbles emerged on the nail, at around 400 seconds for setups at 0.4A or above. The foil became thinner. The blue intensity of the electrolyte remained the same.

Commented [A17]: Data analysis, first strand: Relevant qualitative data are clearly communicated.

Data Quantitative

The current was recorded every $*10^{-1}$ s during 600 seconds:

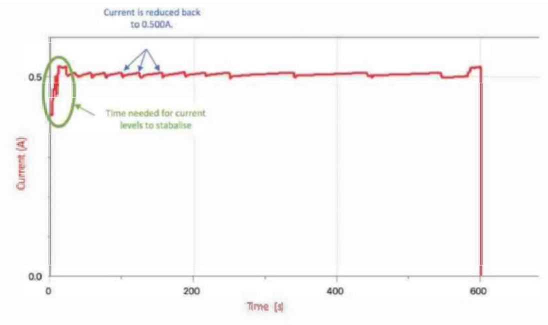

Diagram 3: Current-Time Graph of 0.505A Trial 3 experiment

As the current fluctuated throughout the experiment, I calculated the average:

Average current per trial= $\frac{\Sigma current\ each 10\ \hat{}{-1}\ \mathrm{s}}{6000}$

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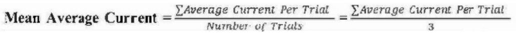
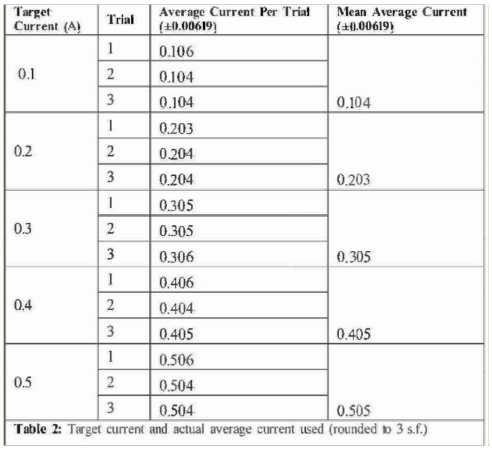
[27] (NJ Health, I)

[28] $CuSO_4$ affects bodies of water



$$\text{Mean Average Current} = \frac{\sum \text{Average Current Per Trial}}{\text{Number of Trials}} = \frac{\sum \text{Average Current Per Trial}}{3}$$



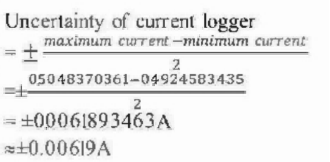
Target Current (A)	Trial	Average Current Per Trial (±0.00619)	Mean Average Current (±0.00619)
0.1	1	0.106	
	2	0.104	
	3	0.104	0.104
0.2	1	0.203	
	2	0.204	
	3	0.204	0.203
0.3	1	0.305	
	2	0.305	
	3	0.306	0.305
0.4	1	0.406	
	2	0.404	
	3	0.405	0.405
0.5	1	0.506	
	2	0.504	
	3	0.504	0.505

Table 2: Target current and actual average current used (rounded to 3 s.f.)

Current Uncertainty

The uncertainty of the datalogger is not reported by the company. Following the circuit setup of the experiment without the electrode and electrolyte component, the current was initially set to 0.497A, then left alone for 600 seconds. The maximum and minimum current reached were 0.505A and 0.492A respectively. The uncertainty of the apparatus was then found using the following equation (Tsokos, I):

Commented [A18]: Data analysis, first strand: The recording of the data is clear and precise. The candidate has previously clarified why data will be reported to three decimal places.



Uncertainty of current logger

$$= \pm \frac{\text{maximum current} - \text{minimum current}}{2}$$

$$= \pm \frac{05048370361 - 04924583435}{2}$$

$$= \pm 0{,}0061893463\text{A}$$

$$\approx \pm 0.00619\text{A}$$

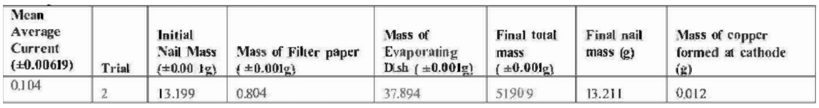
Final total mass = Final $_{\text{nail mass}}$ + mass $_{\text{evaporating dish}}$ + mass $_{\text{filter paper}}$

Final nail mass = Final $_{\text{total mass}}$ - mass $_{\text{evaporating dish}}$ - mass $_{\text{filter paper}}$. Since the initial mass of the nail has been measured, the change in mass of the nail, namely the mass of copper produced on the iron nail cathode is:

Mass of Copper Formed at Cathode = Change in mass of nail = Final $_{\text{Nail Mass}}$-Initial $_{\text{Nail Mass}}$

Sample Calculations for Trial 2 of 0.1 A:

Commented [A19]: Data analysis, first strand: The processing of the data is both clear and precise.



Mean Average Current (±0.00619)	Trial	Initial Nail Mass (±0.00 1g)	Mass of Filter paper (±0.001g)	Mass of Evaporating Dish (±0.001g)	Final total mass (±0.001g)	Final nail mass (g)	Mass of copper formed at cathode (g)
0.104	2	13.199	0.804	37.894	51909	13.211	0.012

Final $_{\text{Nail Mass}}$ = 51,909- 37.894 0.804 =13.211g

Mass of Copper Formed at Cathode =13.211-13,199 =0.012g[29]

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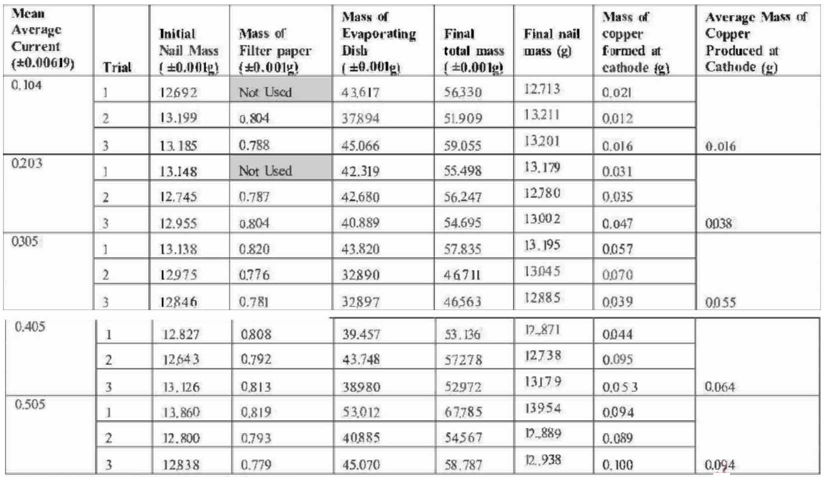
[29] Please observe calculated uncertainties below



Mean Average Current (±0.00619)	Trial	Initial Nail Mass (±0.001g)	Mass of Filter paper (±0.001g)	Mass of Evaporating Dish (±0.001g)	Final total mass (±0.001g)	Final nail mass (g)	Mass of copper formed at cathode (g)	Average Mass of Copper Produced at Cathode (g)
0.104	1	12692	Not Used	43.617	56330	12.713	0.021	0.016
	2	13.199	0.804	37.894	51.909	13.211	0.012	
	3	13.185	0.788	45.066	59.055	13201	0.016	
0203	1	13.148	Not Used	42.319	55.498	13.179	0.031	0038
	2	12.745	0.787	42.680	56.247	12.780	0.035	
	3	12.955	0.804	40.889	54.695	13.002	0.047	
0305	1	13.138	0.820	43.820	57.835	13.195	0.057	0.055
	2	12.975	0.776	32890	46711	13.045	0.070	
	3	12.846	0.781	32.897	46.563	12.885	0.039	
0.405	1	12.827	0.808	39.457	53.136	12.871	0.044	0.064
	2	12.643	0.792	43.748	57278	12.738	0.095	
	3	13.126	0.813	38980	52972	13.179	0.053	
0.505	1	13.860	0.819	53.012	67.785	13954	0.094	0.094
	2	12.800	0.793	40.885	54.567	12.889	0.089	
	3	12.838	0.779	45.070	58.787	12.938	0.100	

Table 3: Raw and Processed Quantitative Data

$U_{\text{final nail m}} = U_{\text{total m}} + U_{\text{m evaporating dish}} + U_{\text{m filter paper}} = 0.001 + 0.001 + 0.001 = 0.003$ g

$U_{\text{m copper formed at cathode}} = U_{\text{final m nail}} + U_{\text{initial m nail}} = 0.003 + 0.001 = 0.004$g

For trials 1 of 0.104 A and 0.203A, since the filter paper was not used, the uncertainty is as follows:

$U_{\text{final m nail}} = U_{\text{final total m}} + U_{\text{m evaporating dish}} = 0.001 + 0.001 = 0.002$ g

$U_{\text{m copper formed at cathode}} = U_{\text{final m nail}} + U_{\text{initial m nail}} = 0\ 002 + 0.001 = 0.003$g

$U_{\text{Average mass copper formed at cathode per current increment}} = \frac{\Sigma m\ copper\ formed\ cathode}{Number\ of\ trials}$

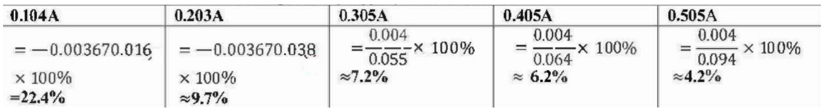
0.104A and 0.203A:

$U_{\text{Average mass copper formed at cathode}} = \frac{0.003+0.004+0.004}{3} = 0.00367$g

0.3054, 0.4054, 0.505A:

$U_{\text{Average mass copper formed at cathode}} = \frac{0.004+0.004+0.004}{3} = 0.004$g

$\% U_{\text{Average mass copper formed at cathode}} = \frac{\text{U Average mass copper formed at cathode}}{\text{Average mass copper formed at cathode}}$

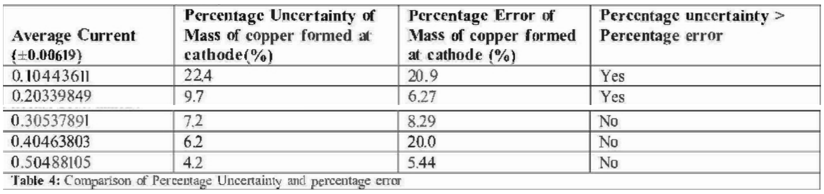


0.104A	0.203A	0.305A	0.405A	0.505A
$= -0.003670.016 \times 100\%$ **=22.4%**	$= -0.003670.038 \times 100\%$ **≈9.7%**	$= \frac{0.004}{0.055} \times 100\%$ **≈7.2%**	$= \frac{0.004}{0.064} \times 100\%$ **≈ 6.2%**	$= \frac{0.004}{0.094} \times 100\%$ **≈4.2%**

$$\frac{|Experimental\ Value - Theoretical\ Value|}{Theoretical\ Value|} \times 100\%$$

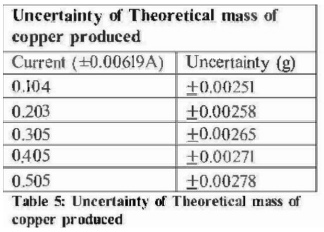
Sample Calculation for Data set of 0.104A:

Percentage Error = $\frac{I0.0163-- 0.0206I}{I0.0206I}$ x 100 = 20.9%



Average Current (±0.00619)	Percentage Uncertainty of Mass of copper formed at cathode(%)	Percentage Error of Mass of copper formed at cathode (%)	Percentage uncertainty > Percentage error
0.10443611	22.4	20.9	Yes
0.20339849	9.7	6.27	Yes
0.30537891	7.2	8.29	No
0.40463803	6.2	20.0	No
0.50488105	4.2	5.44	No

Table 4: Comparison of Percentage Uncertainty and percentage error



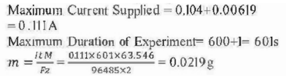
Uncertainty of Theoretical mass of copper produced	
Current (±0.00619A)	Uncertainty (g)
0.104	±0.00251
0.203	±0.00258
0.305	±0.00265
0.405	±0.00271
0.505	±0.00278

Table 5: Uncertainty of Theoretical mass of copper produced

The values of time and current possess uncertainty, the theoretical value of the mass of copper produced, calculated by It/M also has uncertainty. The uncertainty of the current is said to be +0.00619A, while an absolute error of ±1 second is used to represent the human reaction time in disconnecting the circuit to halt electrolysis when reaching 600s.

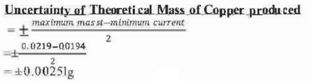
Uncertainty of mass of copper produced:

$$\frac{\max m\ of\ Cu\ prod - \min m\ of\ Cu\ produced}{2}$$



Maximum Current Supplied = 0.104+0.00619
= 0.111A
Maximum Duration of Experiment= 600+1= 601s

$$m = \frac{ItM}{Fz} = \frac{0.111 \times 601 \times 63.546}{96485 \times 2} = 0.0219\text{g}$$

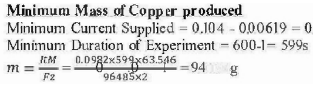


Uncertainty of Theoretical Mass of Copper produced

$$= \pm \frac{maximum\ mass\ t - minimum\ current}{2}$$

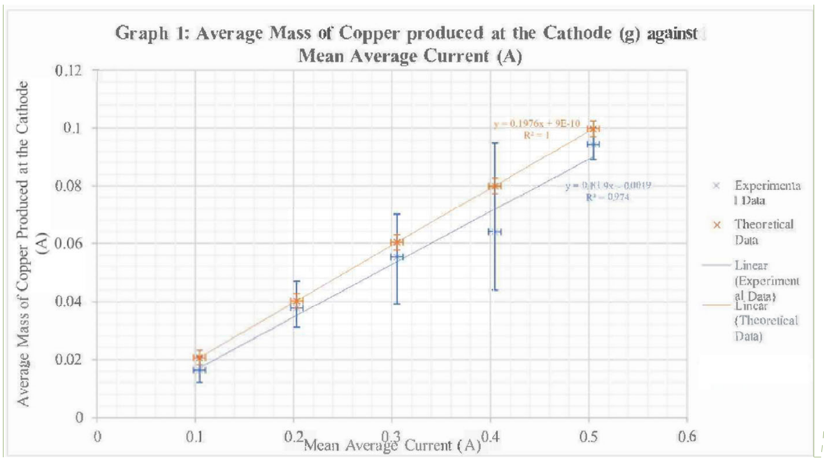
$$= \pm \frac{0.0219 - 00194}{2}$$

$$= \pm 0.00251\text{g}$$



Minimum Mass of Copper produced
Minimum Current Supplied = 0.104 - 0.00619 = 0
Minimum Duration of Experiment = 600-1= 599s

$$m = \frac{ItM}{Fz} = \frac{0.0982 \times 599 \times 63.546}{96485 \times 2} = 94\ [illegible]\ \text{g}$$

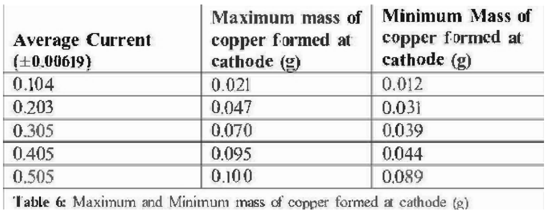


Commented [A20]: Data analysis, third strand: The processing includes the equation for both functions.

Error Bar Values: Horizontal are ±0,00619A for both experimental and theoretical data (they represent the uncertainty of the current datalogger).

Vertical Error Bars - experimental data

Commented [A21]: Data analysis, second strand: Both horizontal and vertical error bars are explained. This is not a requirement, but is allowed and helpful in some investigations.



Average Current (±0.00619)	Maximum mass of copper formed at cathode (g)	Minimum Mass of copper formed at cathode (g)
0.104	0.021	0.012
0.203	0.047	0.031
0.305	0.070	0.039
0.405	0.095	0.044
0.505	0.100	0.089

Table 6: Maximum and Minimum mass of copper formed at cathode (g)

The error bars are used to show t range of data for each increment of current. The initial current values were not considered for the maximum and minimum value to provide the current logger with time to stabilize.

Vertical Error Bars - theoretical data

The error bars are the length of the masses' uncertainty

Evaluation and conclusion

Error bars display a range of possible values for the given variable. The horizontal error bars, representing the uncertainty of current, are small and do not overlap. The bars are the same for both experimental and theoretical data, and the increments of current are clearly differentiated from one another for both contexts The vertical error bar of the theoretical mass of copper produced at the cathode were also small and did not overlap, suggesting difference between the data. However, the vertical error bars for the mass of copper produced at the cathode were large, suggesting a large variability and large range of data. Although the error bars for the mass at 0.505A do not overlap with 0.104, 0.203 and 0,305A, other error bars overlap with one another Thus, I cannot be certain that the mass of copper produced between 0.203, 0.305, 0.405A are entirely different. It is also uncertain whether the mass of copper produced at 0.405 and 0.505 are different as the error bars of 0.405A completely overlapped the one of 0.505A. Though a generally positive

Commented [A22]: Conclusion, first strand: The conclusion is based on the results. There is a good analysis of the impact of errors on these. The correlation is correctly identified.

correlation can be seen between current and mass of copper with the data points that do not overlap, the line of best fit is not linear like Faraday's law as other types of lines can be drawn within the error bars.

Commented [A23]: Conclusion, second strand: The relevant theory is considered and the candidate bases the justifications on it.

All data points for experimental data lay below the theoretical data. The calculations of percentage uncertainty and error show that the uncertainty of measurements cannot explain the percentage error of all data sets of 0.305, 0.405 and 0.505A, meaning there are systematic errors resulting in a lower mass of copper produced than expected.

Commented [A24]: Conclusion, first strand: The conclusion includes the discrimination between systematic and random errors. R^2 values are correctly used.

It is impossible to differentiate between several data points, and there are errors in the accuracy of measurements, but the experimental data's line of best fit displays a positive linear correlation between the two variables. The line passes through all of the error bars and the R^2 value of 0.974, suggest that the data points fall along the trendline rather precisely. This agrees with Faraday's first law to a certain extent. However, the line has a gentler slope as is only applicable when the current efficiency is 100%. Current Efficiency is defined as "a fraction, usually expressed as a percentage, of the current passing through an electrolytic cell (or an electrode) that accomplishes the desired chemical reaction".[30] The mass of copper produced at the cathode should become lower for all data due to inefficiencies in the current adjustments.

An alternative redox reaction, seems to have taken place before any current has passed the circuit. Since Iron is above Copper in the reactivity series, Iron will oxidise into ions, entering the solution while Cu^{2+} from the solution become reduced into solid copper[31]. This may have affected the measurements for the mass of copper because some copper resulted from reactions other than electrolysis, while the final mass of iron nail may have decreased due to ionization. The Iron ions contaminated the electrolyte causing a linear decrease in current efficiency, thus m_{exp} is less than m_{theor}[32]. These factors cannot be controlled in available conditions

Commented [A25]: Evaluation, first strand: A methodological weakness is identified and explained.

According to a similar research completed by Sigit et. al. on the electroplating of uranium on to a platinum cathode, the uranium attached to the cathode increased with a peak at 1 hour of electrolysis, when it decreased due to "reduced attracting power of the positive ions when the cathode surface is already covered by a layer of uranium deposit.", causing "previously attached uranium dissolves back into UO: ion solution, or the weakly attached uranium releases from the Pt cathode." This may have occurred at an earlier stage, considering Cu^{2+} have a lower molar mass than Uranium ions. This systematic error, is especially applicable to the higher levels of current as the nails would have been more quickly covered with copper, causing a Cu^{2+}reduction of attraction at earlier stages, especially at current levels above 0.305A. This also explains why more copper deposits were suspended in the electrolyte as the current level increased. I may reduce the error by lowering duration and using multiple filters to collect deposits simultaneously to minimise the time for copper deposits in the solution to oxidise back into ions. Using plating grade materials is not an option due to school's budget.

Commented [A26]: Conclusion, second strand: The candidate uses relevant scientific context to justify the weakness in the method.

Commented [A27]: Evaluation, first strand: The methodological weakness is explained.

Evaluation, second strand: A realistic improvement for a previously identified weakness is explained.

The bubbles observed at 0.4054 and 0.505 A, are most probably Hydrogen as its evolution is common at high current densities because H^+ are highly mobile in aqueous solutions, making them kinetically favoured over Cu^{2+} transport[33]. The systematic error lowers the mass of copper because the current is used to operate in a side reaction for the reduction of water molecules.

Commented [A28]: Evaluation, first strand: The methodological weakness is supported by qualitative data and well explained.

Evaluation, second strand: The improvement to previous weakness is realistic and well explained.

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[30] (Lou, Huang, 3)
[31] (Nuffield Foundation)
[32] (Sterten)
[33] (Azzam)

This error could be reduced by providing larger electrodes to reduce current density, and lowering the voltage to below 1.23 V.[34]

For the setups of trial 1 for 0.104A and 0.203A, the electrolytes were not filtered as there were no visible deposits. This caused a systematic error that lowered the mass of copper deposited because, there may be copper deposits left in the solution. However, their small mass unlikely to be detected by the balance. The inconsistent initial surface area of the electrodes is a random error caused by the inaccurate measurements of electrode length and width using a ruler. Small changes in surface area can alter the resistance of the electrode, which leads to inconsistent current and resistance levels between trials recommending the use of a Vernier calliper instead.

Commented [A29]: Evaluation, first strand: This is a methodological weakness.

Evaluation, second strand: The candidate explains a realistic improvement.

During electroplating under described conditions, an increase in current leads to an increase in the mass of copper deposited at the cathode, thus obeying Faraday's law to a certain extent. However, the linearity between the two variables is not proven due to the sizeable overlapping error bars between data points. Nonetheless, a positive linear trendline is proposed with a slope gentler than in the theoretical trendline to consider the reduced current efficiency in executing Faraday's first law of electrolysis with the proposed methodology.

Commented [A30]: Conclusion, first strand: The candidate shows awareness that the investigation does not result in definite conclusions, but the efforts to interpret results and justify discrepancies through correct use of methodological limitations and weaknesses is rewarded.

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[34] Equation presented in background(Mazloomi, 3315)

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