Personal Code- jtk011

Introduction

During my IB Chemistry class, we delved into electro crystallization reactions to understand how the size of metal crystals relates to the rate of growth when an electric current passes through a solution. We measured the crystal's weight after the current was applied. This got me thinking: what if we could calculate the metal crystal's growth rate by measuring dendrite branching and the surface area covered in the solution?

Upon additional investigation, I discovered Faraday's law of electrolysis[1]. I thought of applying it to the rate of deposition depending on the area covered by the solution because it deals with the mass of metal deposited and the quantity of metal involved. The fundamental concept of Faraday's law is charge, which is proportional to current and current density. So, by keeping the cross-sectional area of wires and electrodes constant while varying the current, I could directly investigate the relationship between these two variables.

I was particularly fascinated by the rapid expansion of crystal dendrites across the solution's surface during electro crystallization. I used a solution of $SnCl_2$, which, when dissolved in hot concentrated HCl and then in water, forms a highly ionized solution (Sn^{2+} and Cl^- ions). These ionic solutions are excellent conductors of electricity, promoting the flow of current in the circuit and thus accelerating redox reactions at each electrode. This made me wonder if increasing the flow of electrons directly impacts the rate of crystal growth.

For this experiment, I chose $SnCl_2$ solution due to its high ion concentration, which results in rapid crystal growth. This allowed me to observe and record the growing area in real-time. To process my data, I planned to use ImageJ, a software that can help me analyse the crystal images and calculate the average growth area and rate.

The software selected ImageJ is the software which will be used to analyse the growth rate of $SnCl_2$ crystals. I wanted to learn a new software due to my interest in computers. I wanted to integrate and use technology due to my profound interest in Computer Science. Using my skills to approach my investigation will motivate me to do better.

Research Question

How does the change in current (0.05, 0.10, 0.15, 0.20, 0.25, and 0.30) (in amperes) impact the average area of growth, which measures the rate of growth of Tin (Sn) crystals, keeping the concentration of Tin (II) chloride aqueous solution (0.5M) and voltage applied in the circuit (8V) constant?

Background Research

Once an electric current is sent through a $SnCl_2$ solution, something fascinating happens. Sn crystals start forming, and they grow like branching dendrites, rapidly covering a significant portion of the solution's surface. This intriguing process is known as electro crystallization, a specific type of electrolysis.[2]

Electrolysis occurs within an electrolytic cell, which typically consists of the electrolyte solution, the anode and cathode (the two electrodes), and an external power source that supplies the electric current. Usually an ionic solution is used, in which an electric current causes a reaction between non-metal and metal ions.[3]

In the case of $SnCl_2$, this electrochemical reaction leads to the formation of tin crystals at the cathode, where a reduction reaction takes place. Reduction is the process where ions gain electrons, transforming into neutral atoms. This results in the creation of solid $SnCl_2$ crystals, which can be observed at the cathode.[4]

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[1] "Faraday's Law." Chemistry Libretexts, chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Faraday's_Law. Accessed 9 Aug 2023.
[2] "Electro Crystallization." Electro Crystallization - an Overview | ScienceDirect Topics, www.sciencedirect.com/topics/chemistry/electro-crystallization. Accessed 9 Aug. 2023.
[3] "Electrolysis." Encyclopædia Britannica, Encyclopædia Britannica, inc., 29 July. 2023, www.britannica.com/science/electrolysis. Accessed 9 Aug. 2023
[4] Ibid

On the other side, at the anode, oxidation takes place. Here, ions lose electrons, which is the process of oxidation. The dendrite branches grow towards the anode, guided by the direction of the external electric current. This combination of oxidation and reduction reactions is commonly referred to as redox reactions.[5]

These reactions can be represented using the following half-equations that illustrate the gain or loss of electrons:

At the cathode (reduction): $Sn^{2+} + 2e^{-} \rightarrow Sn\ E^{\ominus}{}_{red} = -0.14V$[6]
At the anode (oxidation): $Sn^{2+} \rightarrow Sn^{4+} + 2e^{-}\ E^{\ominus}{}_{ox} = -0.16V$[7]
$Sn^{4+} + 4Cl^{-} \rightarrow SnCl_4$[8]
The "electrode potential of the reaction, a measure of energy per unit charge"[9] that may be used to drive the reaction is represented by the E° values, which stand for the standard potential.[10] Negative E° values show that the reaction needs an external electric current to start and is not spontaneous. There are two steps in the anode reaction. Initially, oxidation of Sn^{2+} ions to yield Sn^{4+} produces Tin (IV) chloride. At the end of the anode, $SnCl_4$ precipitates an insoluble substance rather than the creation of metal crystals.

During this research into electro crystallization reactions, Faraday's first law of electrolysis was explored. This law states that "the amount of substance produced at each electrode is directly proportional to the quantity of charge flowing through the cell."[11] In simpler terms, the mass of the substance produced at cathode (measured in grams) is directly linked to the charge passing through (measured in coulombs), this is linked to the current since it shows how many electrons go through over a certain amount of time.[12]

Hypothesis: The average area of growth and the rate of crystal growth will both rise in parallel with an increase in current values. It is proposed that the independent and dependent variables will interact according to Faraday's first law of electrolysis. Research by Wasekar et al. (2016)[13] 14 revealed that "a greater amount of metal disposition would be produced by an increase in current" (15). When graphed, the expected findings were thought to show a positive linear connection between the two variables.

Methodology

Independent Variable (IV)	
What will be changed?	How will it be change it?
Current	The current will vary with 6 different current values: 0.05A, 0.10A, 0.15A, 0.20A, 0.25A, and 0.30A. The investigated variable in this case will be the rise in currents obtained with the use of a rheostat.
Dependent Variable (DV)	
What needs to be measured?	How will it be measured?
Growth Rate (cm^2s^{-1}) of the $SnCl_2$ crystals.	The average area of growth (cm^2) is used to calculate the growth rate (cm^2s^{-1}). The $SnCl_2$ crystals will be impacted, depending on how much current is flowing across the circuit.

[5] Ibid
[6] FlinnScientific. "Tin Man Electrolysis." YouTube, 19 Dec. 2012, www.youtube.com/watch?v=coPGazAaVBE. Accessed 10 Oct 2023.
[7] Ibid
[8] Ibid
[9] "Electric Potential Energy: Potential Difference | Physics." Courses.lumenlearning.com, courses.lumenlearning.com/physics/chapter/19-1-electric-potential-energy-potential-difference/. Accessed 7 Oct. 2023.
[10] "13.6 Standard Electrode Potentials." Siyavula, www.siyavula.com/read/za/physical-sciences/grade-12/electrochemical-reactions/13-electrochemical-reactions-06. Accessed 9 Oct. 2023.
[11] Ibid
[12] Ibid
[13] Wasekar, Nitin P., et al. "Influence of Mode of Electrodeposition, Current Density and Saccharin on the Microstructure and Hardness of Electrodeposited Nanocrystalline Nickel Coatings." Surface and Coatings Technology, vol. 291, Apr. 2016, pp. 130–140, 10.1016/j.surfcoat.2016.02.024. Accessed 10 Oct. 2023.

Controlled Variables (CV)		
Controlled Variable	Why it needs to be controlled	How will it be controlled
Concentration of Tin (II) chloride aqueous solution	For a fair experiment the concentration of Tin (II) chloride requires to be constant as more the concentration, more particles per unit volume so more successful collision will be there which will result in faster the formation of crystals.	This variable will be held constant at 0.5M throughout the experiment.
Voltage applied in the circuit.	According to Ohm's law, $I = \frac{V}{R}$,[14] to isolate the measurement of the current, it will be required to either keep the voltage or resistance constant but since a rheostat is being used, the voltage needs to be constant.	This variable will be held constant at 8V throughout the experiment.
Internal Resistance	Internal resistance is required to stay constant as it refers to the resistance within a power source and since $\mathcal{E} = I(R + r)$,[15] with increase in internal resistance, the current would decrease.	The same power source will be used for all trials.
Cross sectional area, length, and material of wire	The cross-section area, length and material of wire is required to stay the same for all the trials as $R = \frac{\rho L}{A}$[16], if any of these 3 factors change, the resistance will change.	The same thickness will be used of the wires will be used for all trials.
Distance between camera and Petri dish	When scale is chosen in ImageJ, the same distance will guarantee that the area measured for each picture has the same unit scale.	The same tripod stand will be used where the camera is placed.
Duration of growth	We are required to keep the duration of the growth the same for all trials to make sure that we can get a trend and relationship which we can plot later with our results in regular time intervals.	A stopwatch will be used to measure the duration and as soon as the clock hits 3 minutes and I will stop the video.
Volume of the $SnCl_2$ solution	More volume will result in faster growth of crystals. The aluminium plates will also be dipped into more volume so if there is more contact of plate and solution, more crystals will get formed resulting in insignificant results.	25 cm^3 of $SnCl_2$ for each trial will be used. It will be controlled by using measuring cylinder
Petri dish	Change in size of Petri dish will result in insignificant trends as the crystals will have different areas to grow in and no consistent trend will be seen.	Same petri dish for all trials will be used, after washing and making sure it's dry.
Aluminium strip	More the cross-section area of the aluminium strip, faster the rate of reaction as surface area increases and faster the growth rate.	Mass and cross section area of the aluminium strip is the same. Mass- 10.000g Cross Section- 10x2x0.2 $\pm$0.005cm

[14] Fluke. "What Is Ohm's Law?" Fluke, www.fluke.com/en-in/learn/blog/electrical/what-is-ohms-law. Accessed Oct 16 2023.
[15] "Cells: EMF, Internal Resistance." Toppr, www.toppr.com/guides/physics/current-electricity/cells-emf-internal-resistance/#:~:text=emf%20%3D%20I%20(R%20%2B%20r,the%20internal%20resistance%20in%20ohms Accessed Oct 18 2023.
[16] "Resistance and Resistivity." Engineering Toolbox, www.engineeringtoolbox.com/resistance-resisitivity-d_1382.html Accessed Oct 18 2023.

Apparatus

Material	Name	Quantity	Uncertainty
Measuring equipment	Stopwatch	1	±0.01s
	Digital Balance	1	±0.001g
	Ruler	1	±0.05cm
Circuit Setup	Voltage Stabilizer	1	±0.01V
	Electrical Wires	5	
	Alligator Clips	10	
	Digital Voltmeter	1	±0.01V
	Digital Ammeter	1	±0.001A
	Rheostat	1	
Camera Setup	iPhone (camera)	1	±0.05s
	Tripod Stand	1	
Preparation of solution	Tin (II) Chloride ($SnCl_2 \cdot 2H_2O$)	150g	
	Volumetric Flask	$1dm^3$	$\pm 5cm^3$
	Hydrochloric Acid	$150cm^3$ x 1.0M	
	Glass stirrer	1	
	Measuring cylinder	$100cm^3$	$\pm 0.5cm^3$
	Distilled water	200ml	
General Apparatus	Measuring cylinder	$25cm^3$	$\pm 0.5cm^3$
	Petri dish	1	
	Aluminium plate	4.5x15x2.8 cm	
	Scissor	1	
	Pink Paper	A2 Size	

Preliminary Reading

To make sure there would be no problems while carrying out the experiment, multiple aspects undergo preliminary testing. Initially, Graphite(carbon) and copper rods were used as electrodes, but after fifteen minutes, there was hardly any crystal formation in either electrode. On the other hand, experiments using metallic plates serving as electrodes unexpectedly revealed almost instantaneous crystal growth, even at the lowest current. As a result, this made it possible for more effective data collecting. In addition, several metal (copper, iron, aluminium, etc.) were examined to see which one would most clearly display crystal development; aluminium plates demonstrated this growth. In order to determine if crystal development was visible, I measured voltage at various increments of 0.05 (0.05V, 0.10V, 0.15V, 0.20V, 0.25V, 0.30V). I found that crystal growth was only apparent above 0.10V.

Preparation of 0.5 molar solution of Tin (II) Chloride ($SnCl_2 \cdot 2H_2O$)

M_r of $SnCl_2$ is 225.63$gmol^{-1}$ (118.71+(2 x 35.45) +(2(2(1.01)) +16))
mass= C x M x V
mass= 0.5 x 225.63 x 1 = 113.315g

1. With the help of a digital balance, weigh 113.315 grams of $SnCl_2 \cdot 2H_2O$.
2. Add the measured $SnCl_2 \cdot 2H_2O$ into a dry beaker.
3. Add 500 cm^3 distilled water into the beaker and stir the mixture with the stirrer until all the $SnCl_2$ has dissolved completely.
4. Once the Tin (II) Chloride is fully dissolved, add $150cm^3$ of 1.0 $moldm^{-3}$ dilute Hydrochloric acid.
5. Transfer the solution to a 1.0 dm^3 volumetric flask.
6. Fill the volumetric flask with distilled water up to the mark.
7. Label the volumetric flask with the contents (0.5 M $SnCl_2 \cdot 2H_2O$).

Preparation of Circuit

1. With the help of a pair of scissors, cut out all the aluminium plates 4.5x1.5x2.8 cm. 50 pieces of aluminium plates will be required.
2. Place a Petri dish on a pink A2 sized paper.
3. Bend the aluminium cut outs so that the tip is not touching the bottom but is very close to the bottom of the petri dish.
4. Connect the alligator clips and wire at the other end of the aluminium cut outs.
5. Attach the acting cathode to the ammeter and the acting anode to the rheostat.
6. Attach the negative terminal of the power supply to the rheostat and the positive terminal of the power supply to the ammeter.
7. Lastly attach the voltmeter in parallel with the anode and cathode.

Experimental set up

(This method was developed and adapted from FlinnChemTopicTM Labs' Chemical Demonstrations of "Electrochemistry - Tin Man.")[17]

1. With a measuring cylinder measure 25cm^3 of 0.5 Molar $SnCl_2$ which was prepared.
2. Add the solution into the petri dish.
3. Set the voltage stabilizer to 8V.
4. Bend and place the aluminium cut outs so that they are dipped into the solution, but they are not touching the bottom.
5. Start the camera, turn the supply of power on and start the stopwatch simultaneously.
6. Adjust the rheostat such that the reading of the current on the ammeter is 0.05A. Keep checking the current throughout the experiment and make sure that the reading of the current is stable at 0.05A and not changing.
7. After every 30 seconds make sure to click on the click photo button.
8. Once the clock hits 180 seconds stop the recording of the video after taking the last photo, stop the power supply and stop the stopwatch.
9. Remove and replace the aluminium clips with 2 other clips.
10. Wash and dry the petri dish for a new trial.
11. Repeat steps 1 to 10 for the remaining current readings (0.10, 0.15, 0.20, 0.25, and 0.30) Ampere.
12. Repeat steps 1 to 11 for 5 trials for getting a more accurate value and take the average as the average gives more reliable data.

Safety Method

Substance	Hazard	Control Measure
0.5M Dilute HCl 2and $SnCl_2$		Direct exposure to $SnCl_2$ and HCl can pose health risks to humans. It can cause irritation to the skin, eyes, and respiratory tract upon contact or inhalation. Essential to wear protective clothing such a lab coat, gloves, and safety goggles.
Electricity (DC Current)		To avoid overheating while doing the inquiry, remember to cut off the power supply between each experiment. Long-term use of the power source might cause wire to melt, overheat, or even cause a fire owing to a possible short circuit. To reduce the danger of electrocution, make sure that all cables are properly insulated and have no exposed wires.

[17] FlinnScientific. "Tin Man Electrolysis." YouTube, 19 Dec. 2012, www.youtube.com/watch?v=coPGazAaVBE. Accessed 10 Oct 2023.

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Ethical concerns- Judicial consumption of chemicals and any environmental concern of disposing chemical is also required. To remove any lingering remnants from earlier studies, all general and measurement equipment should be carefully cleansed with distilled water before use.

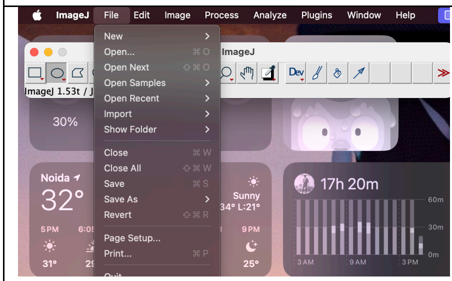
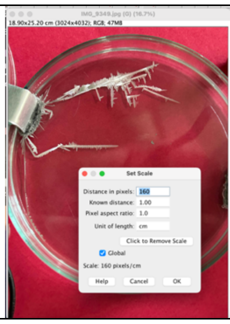
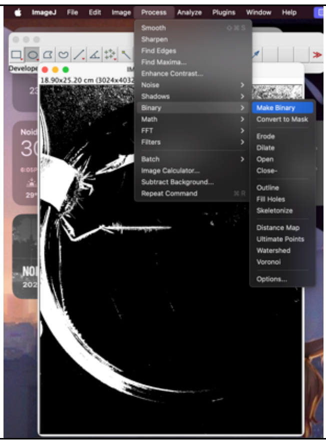
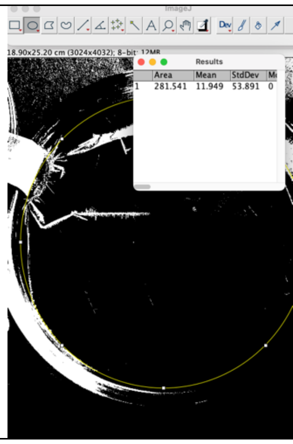
Environmental concerns- Release of Cl_2 gas is harmful for the environment, Animals that come into direct contact with HCl spills or solutions may suffer from chemical burns, irritation, and corrosion of their skin, eyes, and respiratory system. $SnCl_2$ is toxic to aquatic organisms. Correctly disposing $SnCl_2$ is required lor the safety of the marine life.

Raw and Processed Data

Qualitative analysis-

- There were no bubbles at cathode that shows the absence of chlorine or hydrogen gas.
- A milky-white precipitate, presumed to be $SnCl_4$, appeared at the anode after each trial.
- Tin crystals at the cathode displayed feather-like projections.
- Significant overhead lighting reflections were observed during many trials.
- Processing these reflections using ImageJ revealed similarities to the morphology of tin crystals.
- Crystal growth occurred at various angles, forming distinct dendritic layers and branching patterns.
- Some dendrites grew on top or perpendicular to each other, particularly noticeable at higher current intensities (e.g., 0.20A and 0.25A).

Method for finding the area using ImageJ

Step 1: Image was uploaded on ImageJ and Open was clicked where the images was selected.	Step 2: the image scale is set by going to analyse and selecting set scale, this helps in setting the distance between the camera and petri dish.	Step 3: the image gets converted into an 8-bit image.
		
Step 4: the image gets converted into a binary image for better and more accurate analysis.	Step 5: Using the ellipsis tool, outline the petri dish.	Step 6: Measure the darken area of the petri dish. This is done by clicking on analyse, then measure.
		

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Once the area is found out, 292.2mm^2 will be subtracted as the diameter of the petri dish is 93cm and area is 292.2mm^2 we can find this πr^2. Similarly, this process was followed for all trials. All the trials had resulted with the following data table:

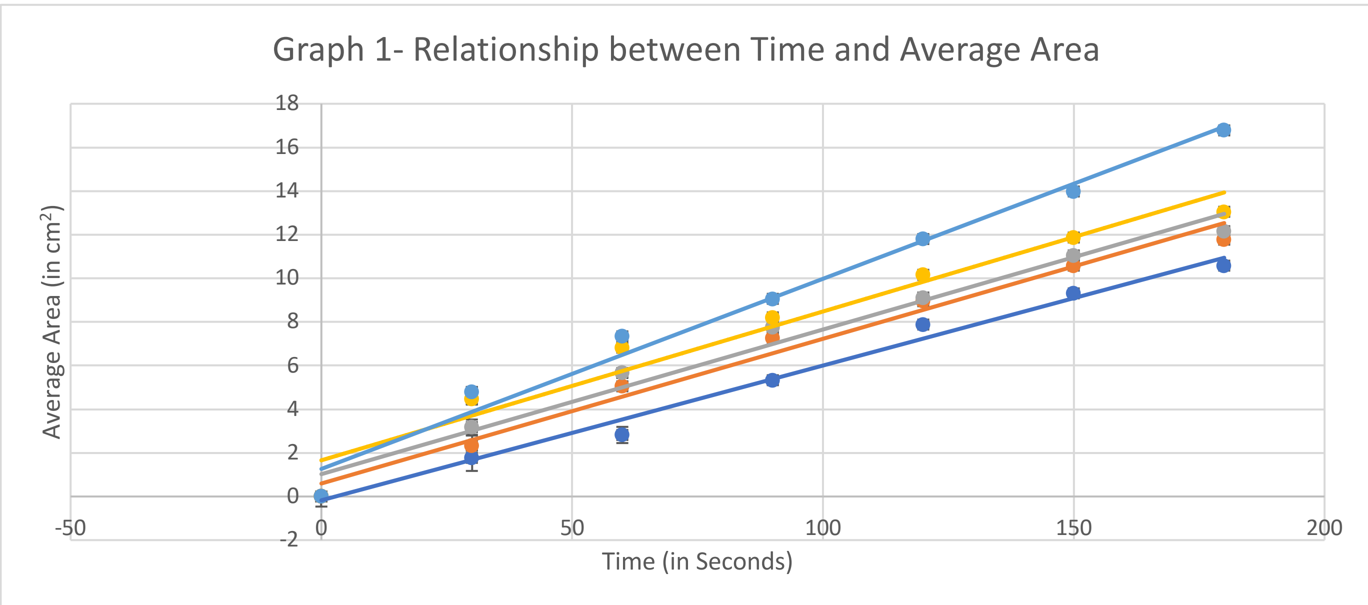
Growth Area ($\pm 0.001 cm^2$)		Time ($\pm 0.01 s$)						
Current ($\pm$0.01A)	Trial No.	0s	30s	60s	90s	120s	150s	180s
0.05A	1	0.00	1.84	2.97	5.43	7.91	9.41	10.66
	2	0.00	1.62	2.67	5.20	7.64	9.11	10.09
	3	0.00	1.81	2.81	5.31	7.87	9.36	10.53
	4	0.00	1.78	2.89	5.41	8.01	9.55	10.84
	5	0.00	1.81	2.77	5.29	7.96	9.11	10.77
	Average	0.00	1.77	2.82	5.33	7.88	9.31	10.58
0.10A	1	0.00	2.39	4.98	7.18	8.91	10.56	11.89
	2	0.00	2.45	5.18	7.45	9.02	10.72	11.91
	3	0.00	2.10	4.84	7.04	8.89	10.45	11.65
	4	0.00	2.22	4.99	7.21	8.91	10.51	11.69
	5	0.00	2.51	5.25	7.48	9.01	10.66	11.71
	Average	0.00	2.33	5.05	7.27	8.95	10.58	11.77
0.15A	1	0.00	3.11	5.56	7.61	9.12	10.92	12.12
	2	0.00	3.29	5.98	7.98	9.17	11.20	12.04
	3	0.00	3.01	5.43	7.69	9.09	10.88	12.11
	4	0.00	3.32	5.71	7.77	9.12	11.17	12.31
	5	0.00	3.18	5.61	7.73	9.11	11.08	12.21
	Average	0.00	3.18	5.66	7.76	9.12	11.05	12.16
0.20A	1	0.00	4.41	6.78	8.12	10.01	11.89	13.14
	2	0.00	4.65	6.81	8.22	10.23	11.93	13.05
	3	0.00	4.53	6.91	8.29	10.30	11.99	13.19
	4	0.00	4.46	6.84	8.25	10.17	11.86	13.01
	5	0.00	4.31	6.76	8.17	10.08	11.68	12.88
	Average	0.00	4.47	6.82	8.21	10.16	11.87	13.05
0.25A	1	0.00	4.91	7.45	9.12	11.91	14.07	16.89
	2	0.00	4.78	7.32	9.07	11.87	13.96	16.77
	3	0.00	4.81	7.35	9.11	11.88	14.00	16.82
	4	0.00	4.61	7.26	9.01	11.79	13.96	16.73
	5		4.77	7.30	8.97	11.56	13.90	16.67
	Average	00.00	4.78	7.34	9.06	11.80	13.98	16.78

Step	Measured Variables	Data Calculations	Uncertainty
Demonstrated Calculation for 0.15 A, 30 seconds			
	As shown in the table Area: 3.18$\pm$0.001cm^2 Time: 30$\pm$0.01s	Growth Rate= $\frac{Area}{Time}$ G=$\frac{3.18}{30}$ G=0.106 $\pm$ 0.00356 $cm^2 s^{-1}$	Uncertainty=$\frac{Uncertainty}{amount\ measured}$ $\frac{0.001}{3.18} = 0.000314$ $\frac{1}{30} = 0.033333$ 0.000314+0.0333=0.0336 0.0336 $\times$ 0.106= 0.00356

Demonstrated Calculation for 0.05 A			
	Time: 0 ± 0.01s Area: $0 \pm 0.001cm^2$ Time: 30 ± 0.01s Area: $1.84 \pm 0.001cm^2$ Time: 60 ± 0.01s Area: $2.97 \pm 0.001cm^2$ Time: 90 ± 0.01s Area: $5.43 \pm 0.001cm^2$ Time: 120 ± 0.01s Area: $7.91 \pm 0.001cm^2$ Time: 150 ± 0.01s Area: $9.41 \pm 0.001cm^2$ Time: 180 ± 0.01s Area: $10.66 \pm 0.001cm^2$	Growth Rate= $\frac{Area}{Time}$ $G_0 = 0$ $G_{30} = 0.0613$ $G_{60} = 0.0495$ $G_{90} = 0.0603$ $G_{120} = 0.0659$ $G_{150} = 0.0627$ $G_{180} = 0.0592$ Sum of all the values = 0.3589 Average = $\frac{0.3589}{6}$= 0.0598 0.0598 ± 0.000825	Uncertainty= $\frac{Uncertainty}{amount\ measured}$ $U_0 = 0$ $U_{30} = \frac{0.001}{1.84} + \frac{1}{30} = 0.0339$ $U_{60} = \frac{0.001}{2.97} + \frac{1}{60} = 0.0170$ $U_{90} = \frac{0.001}{5.33} + \frac{1}{90} = 0.0113$ $U_{120} = \frac{0.001}{7.88} + \frac{1}{120} = 0.00846$ $U_{150} = \frac{0.001}{9.31} + \frac{1}{150} = 0.00677$ $U_{180} = \frac{0.001}{10.58} + \frac{1}{180} = 0.00565$ Sum of all the values = 0.0831 Average = $\frac{0.0831}{6}$= 0.0138 Absolute= 0.0138×0.0598= 0.000825

Below is the Processed data table and Graph.

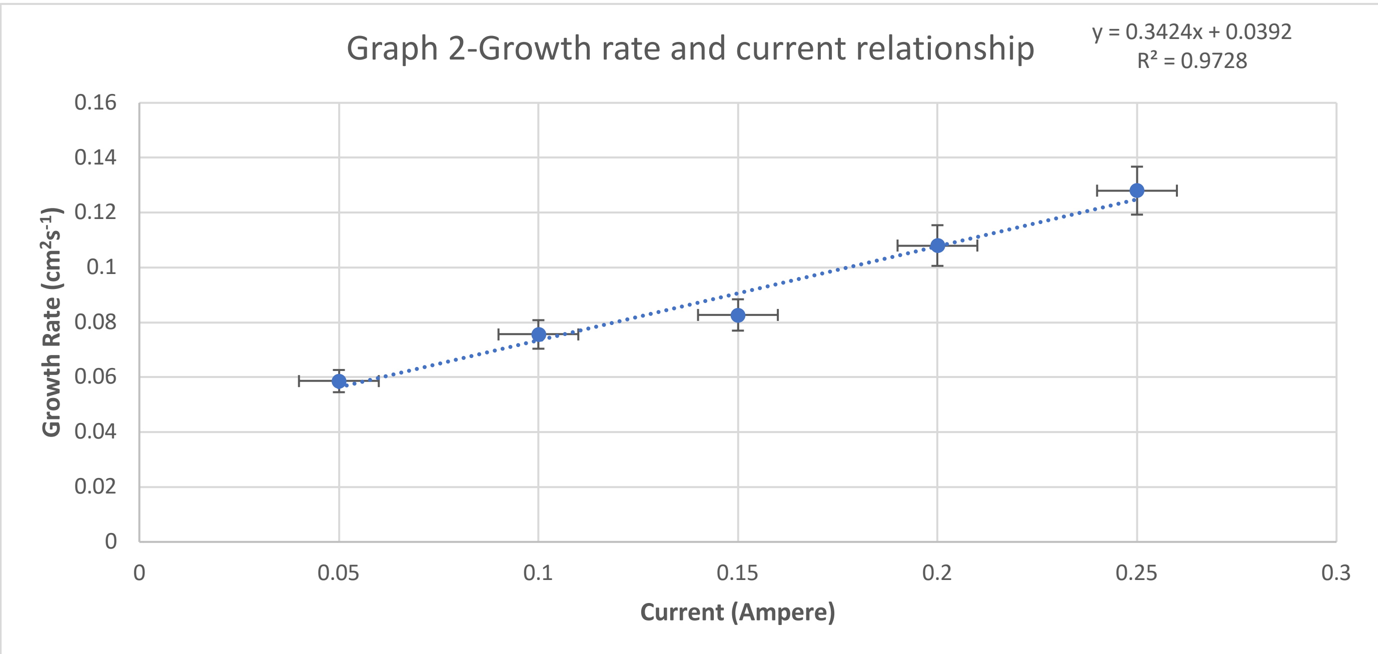
Average Growth rate	Current ($\pm$ 0.01A)				
Trial	0.05	0.10	0.15	0.20	0.25
1	0.0598 ± 0.000825	0.0756 ± 0.00104	0.0818 ± 0.00113	0.101 ± 0.00138	0.133 ± 0.00182
2	0.0562 ± 0.000781	0.0773 ± 0.00106	0.0846 ± 0.00117	0.112 ± 0.00153	0.126 ± 0.00173
3	0.0588 ± 0.000811	0.0729 ± 0.00101	0.0815 ± 0.00112	0.121 ± 0.00166	0.131 ± 0.00179
4	0.0597 ± 0.000824	0.0744 ± 0.00102	0.0833 ± 0.00115	0.108 ± 0.00148	0.123 ± 0.00169
5	0.0587 ± 0.000810	0.0776 ± 0.00107	0.0825 ± 0.00114	0.0996 ± 0.00136	0.125 ± 0.00171
Total Average	0.0586 ± 0.00405	0.0756 ± 0.00520	0.0827 ± 0.00571	0.108 ± 0.00741	0.128 ± 0.00874



This scatter plot shows the average area (in cm^2) of crystal growth over time for six different current values. Data points are collected every 30 seconds with a slight margin of error ($\pm 0.01\ seconds$), up to a total of 180 seconds. Error bars representing the standard deviation are included for each data point.

Line of best fit colour	Value of Current (in Ampere)	General equation of the line
	0.25	Y=0.0871x+1.2629 R^2 value =0.9831
	0.20	Y=0.0682x+1.6589 R^2= 0.9549
	0.15	Y=0.0663x+1.0243 R^2= 0.9756
	0.10	Y=0.0663x+0.5954 R^2= 0.9833
	0.05	Y=0.0618x-0.1743 R^2=0.9883

The data clearly shows that while using higher electrical current and let crystals grow for longer, they end up being bigger. Out of the six currents tested, the best one was 0.25 amps for 180 seconds. It helped grow crystals with an average size of 16.78 cm^2. The next best was 0.20 amps for 180 seconds, but with an average size of 13.05 cm^2. The smallest crystals, averaging only 1.77 cm^2, came from using 0.05 amps for just 30 seconds. This pattern depicts that more electricity leads to bigger crystals. This experiment was done accurately, as shown by the results. The tiny lines on the graph mean there were not big changes in our data, suggesting the measurements were pretty close to the true sizes of the crystals and not messed up by errors. Out of all the methods tried in this experiment, using 0.25 amps for 180 seconds was the best one. This trend underscores the positive correlation between current and crystal growth. All the coefficient of determination (R^2) shows the accuracy to which the experiment was performed clearly illustrating a relationship between current and growth area. The error bars in the graph are very small. Their diminutive stature hints at minimal data fluctuations, suggesting that the recorded values very close to the true crystal areas, free from significant errors.



Current's impact on crystal growth: This scatter plot depicts average crystal growth rate (cm^2s^{-1}) for six current values, using error bars for standard deviation.

Graph 2 demonstrates a stronger trendline fit with an R^2 value of 0.9728 and a y-intercept at 0.0392, suggesting that crystal growth might not occur at certain current levels. The x-intercept, near -0.15 A, implies that currents below this threshold potentially lack the electron supply to initiate a reaction at the cathode. This challenges the direct proportionality assumption between current and crystal growth, hinting at a linear relationship with a minimum current requirement for reaction. The high coefficient of determination in Graph 2's line of best-fit supports the hypothesis by indicating a relationship between the independent and dependent variables. Current measurements showed the largest amounts of uncertainty. The moderate percentage uncertainties ranged from 1.370% to 12.50% due to the ammeter's error of ± 0.01 A. This is reflected in the horizontal error bars in Graph 2. Uncertainties in time and area measurements were less occurring, as evidenced by the smaller and less visible vertical error bars.

DISCUSSION AND EVALUATION

Discussion and Evaluation of results

In this exploration, the relationship between the growth rate of $SnCl_2$ crystals and the magnitude of the current flowing through a 0.5M $SnCl_2$ solution was explored. Using current as the independent variable, five different current sizes (0.05A, 0.10A, 0.15A, 0.20A, and 0.25A) were chosen. Following Faraday's law of electrolysis, the link between magnitude of current and growth rate was found to be exactly proportionate, as predicted. The experimental results confirmed the hypothesis; as the current increased, both the average growth area and the growth rate of the crystals also increased.

In Graph 1, the error bars are not very noticeable, suggesting minimal data inconsistency and consistent collected data. Error bars in Graph 2 are barely noticeable between 0.10 and 0.15 A, but they become more noticeable between 0.15 and 0.25 A. This indicates potential data variability in the higher current range, posing a challenge to the completely support the hypothesis. However, a substantial correlation between the independent and dependent variables was confirmed by both graphs' high coefficients of determination (R^2 value), which backed up the hypothesis. Overall, the highest current value (0.25 A) resulted in the greatest average growth area and growth rate ($y = 0.0871x+1.2629$) among all current sizes, while the lowest current value (0.10 A) led to the lowest growth area and growth rate ($y = 0.0618x-0.1743$). This equation illustrates a positive linear relationship between the various opted current values and the average growth area and rate of crystals, aligning with the hypothesis. However, there were some uncontrolled variables, like light reflections, fluctuations in both voltage and current, and the free form selection in the software, ImageJ, which could have impacted the results.

Evaluation of methodology

The experiment had several strengths in its approach. Firstly, it provided a valuable opportunity for me to learn and apply Image J software, which was new to me. This helped me enhance my computer skills and gain hands-on experience in processing and calculating the growth area of crystals. The procedure was well-standardized, with controlled variables, proper use of equipment, adherence to safety protocols, and the execution of five trials. These measures ensured data consistency and minimized the potential impact of confounding variables on result validity, thereby increasing reliability.

However, a limitation surfaced during qualitative observations of the experiment's methodology. The use of pink paper as a background, intended to contrast with silver-coloured crystals, resulted in overhead lighting reflections on the Petri dish glassware. This made outlining the crystals challenging during image processing on ImageJ, potentially leading to higher-than-actual calculations. To address this, conducting the experiment in natural light and using a different electrolyte solution with a more distinctive colour, such as copper sulphate for blue crystals, could improve accuracy. Despite the five trials measuring crystal growth at 30-second intervals for 180 seconds, challenges arose with the free form selection tool in ImageJ, requiring precise outlines that were difficult to achieve with a computer cursor. Using a relatively bigger Petri dish in more experiments and increasing the values of the independent factors would enhance surface area coverage during crystal growth, improving the precision of calculations as well as confirming the trend. Time constraints limited the number of different current values in this experiment, emphasizing the need for a minimum of 7 increments in future investigations for robust data validity and reliability and to see if the trend continues.

Suggestions for procedure enhancements include alternating alligator clip wires after 3-4 trials to maintain a consistent current and voltage flow, minimizing the impact of internal resistance. Systematic errors were identified, such as potential drift in the Ammeter and Voltmeter pointers over numerous trials, suggesting the need for calibration to ensure accurate charge flow measurements. Parallax errors in using graduated cylinders could be addressed by employing more precise measuring tools like pipettes and burettes for reliable solution measurements. In summary, a wider range of present sizes in the experiment would help to clarify the correlation between current size and the average rate of crystal growth, which is the main objective of this investigation.

Literature Analysis

The majority of the resources used in this investigation are scientific journals that are published on the publication platforms Academia19[18] and ResearchGate20[19]. These platforms' submission guidelines and standards of measurement guarantee that the research journals and studies published therein are impartial and in line with scientific standards for research, lending the sources some degree of objectivity and credibility. The other materials were either from scholarly publications, research groups (LumenLearning)[20], etc. Even so, studies on electro crystallization are unorthodox and open to revision, meaning that materials from a few years ago, whether they be articles or scientific journals, may contain outdated information. As a result, it would be better to use recently published sources to get the most up-to-date and accurate information on this topic.

Error Evaluation and Improvement

Error	Significance	Improvement
Random Error: Selection of free-form in ImageJ	There's a possibility that the computer's cursor accuracy led to either selecting more surface area than the one covered by the crystals or overlapping with the crystals themselves. This discrepancy could result in recorded values that are either higher or lower than the true values.	Another image analysis tool, especially one which was observing and noticing the change after every second for a better analysis and result.
Systematic Error: Fluctuation in Voltage	The circuit may have discharged heat into the wires during the experiment as the charge passed across them. As a result, there may have been an increase in wire resistance, which would have decreased the voltage flowing through the circuit. This, in turn, would affect the flow of current and subsequently impact the crystal growth. As a result, the recorded results may show higher values than the actual ones.	Using different electrodes can facilitate easier attachment and ensure a consistent flow of charge. This, in turn, guarantees that the monitored voltage remains more stable throughout the experiment, minimizing variations.
Systematic Error: Fluctuation in Current	In every trial, the current flowing through the circuit might have gone up, despite efforts to regulate it using a Rheostat. As a result, the recorded results could be overstated, as a higher current might have been unintentionally measured.	Continuously keeping an eye on the rheostat could help in maintaining a constant current.
Systematic Error: The Room Temperature was monitored	If the room temperature goes up, there's a chance that the circuit's total resistance could also increase, leading to variations in the data. This happens because the elevated temperature might cause the current to drop, resulting in inconsistent data readings.	Measuring the temperature before every trail could be done with the help of a temperature probe.

[18] Nikolić, Nebojša D., et al. "Electrochemical and Crystallographic Aspects of Lead Granular Growth." Metallurgical and Materials Transactions B, vol. 46, no. 4, 2015, pp. 1760–1774, www.academia.edu/21893017/Electrochemical_and_Crystallographic_Aspects_of_Lead_Granular_Growth. Accessed 20 Nov. 2023.

[19] "(PDF) Electrocrystallization and Electrochemical Control of Crystal Growth. Fundamental Considerations and Electrodeposition of Metals." ResearchGate, www.researchgate.net/publication/230969784_Electrocrystallization_and_electrochemical_control_of_crystal_growth_Fundamental_considerations_and_electrodeposition_of_metals. Accessed 25 Nov. 2023.

[20] "Electrolytic Properties | Introduction to Chemistry." Courses.lumenlearning.com, courses.lumenlearning.com/introchem/chapter/electrolytic-properties/. Accessed 4 Nov. 2023.

CONCLUSION AND FURTHER INVESTIGATIONS

In conclusion, this investigation examined the relationship between current and the rate at which tin crystals form during electrolysis. As predicted, there was a direct proportionality between the current values (the independent variable) and growth rate of crystals (the dependant variable), supporting the original hypothesis. Graph 2, showcasing a trendline with a R^2 value of 0.9728 and a y-intercept at 0.0392, supports this observation. The high coefficient of determination indicates that changes in the independent variable significantly affect the variability of the dependent variable, reinforcing the hypothesis. However, the presence of error bars in Graph 2 suggests potential standardization issues in the methodology, possibly due to unaccounted systematic variables or apparatus errors. Consequently, the experimental results may not wholeheartedly substantiate the hypothesis.

The experiment supported my hypothesis by demonstrating a positive correlation between an increase in current value and a faster rate of crystal formation. The average crystal growth area (cm^2) and average growth rate (cm^2s^{-1}) were computed to evaluate this. The first graph shows that the average area of crystal growth increases with greater current sizes, notwithstanding anomalies. The second graph's line of best fit, with a strong positive linear correlation (R^2= 0.9728), reinforces the idea that the average growth rate rises with increased current values. Despite potential uncertainties, the overall trend supports the hypothesis.

Future investigations could explore the use of various solutions for the electrolyte such as Lead (II) Chloride, Zinc Chloride, Copper (II) Chloride) and compare them to the results of the solution of Tin (II) Chloride to gain a comprehensive understanding of growth rates across different solutions. Furthermore, investigating various materials used for electrodes may provide light on how electrode materials affect the formation of metal crystals, particularly in light of initial tests that showed an aluminium paperclip to be more successful than copper and carbon electrodes. It could be possible to identify the minimal decomposition potential of $SnCl_2$ more accurately by experimenting with voltage values while maintaining a constant current or by increasing the current range. Investigating the effect of current on dendrite branching could enhance comprehension of the complexities of electro crystallization. Lastly, exploring the layering of dendrites by observing the effects of current on the weight of crystals could provide valuable insights into the aspects of crystal growth.

BIBLIOGRAPHY

Canadian geochemical surveys - Les Levés Géochimiques du Canada. (n.d.-a). https://geochem.nrcan.gc.ca/ftp/data/publications/pub_02046/of_4823.pdf Accessed 12 June 2023.

"Cells: EMF, Internal Resistance." Toppr, www.toppr.com/guides/physics/current-electricity/cells-emf-internal-resistance/#:~:text=emf%20%3D%20I%20(R%20%2B%20r,the%20internal%20resistance%20in%20ohms Accessed Oct 18 2023.

“Electric Potential Energy: Potential Difference | Physics.” Courses.lumenlearning.com, courses.lumenlearning.com/physics/chapter/19-1-electric-potential-energy-potential-difference/.Accessed 7 Oct. 2023.

“Electro Crystallization.” Electro Crystallization - an Overview | ScienceDirect Topics, www.sciencedirect.com/topics/chemistry/electro-crystallization. Accessed 9 Aug. 2023.

“Electrochemical Cells.” PDF Free Download, docplayer.net/24020816-Electrochemical-cells.html Accessed 9 June 2023.

“Electrolysis.” Encyclopædia Britannica, Encyclopædia Britannica, inc., 29 July. 2023, www.britannica.com/science/electrolysis. Accessed 9 Aug. 2023

“Electrolytic Properties | Introduction to Chemistry.” Courses.lumenlearning.com, courses.lumenlearning.com/introchem/chapter/electrolytic-properties/ Accessed 4 Nov. 2023.

"Faraday's Law." Chemistry Libretexts, chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Faraday's_Law. Accessed 9 Aug 2023.

FlinnScientific. "Tin Man Electrolysis." YouTube, 19 Dec. 2012, www.youtube.com/watch?v=coPGazAaVBE. Accessed 10 Oct 2023.

Fluke. "What Is Ohm's Law?" Fluke, www.fluke.com/en-in/learn/blog/electrical/what-is-ohms-law. Accessed Oct 16 2023.

Nikolić, Nebojša D., et al. "Electrochemical and Crystallographic Aspects of Lead Granular Growth." Metallurgical and Materials Transactions B, vol. 46, no. 4,
2015, pp. 1760–1774,
www.academia.edu/21893017/Electrochemical_and_Crystallographic_Aspects_of_Lead_Granular_Growth. Accessed 20 Nov. 2023.

"(PDF) Electrocrystallization and Electrochemical Control of Crystal Growth. Fundamental Considerations and Electrodeposition of Metals." ResearchGate, www.researchgate.net/publication/230969784_Electrocrystallization_and_electrochemical_control_of_crystal_growth_Fundamental_considerations_and_electrodepo
sition_of_metals. Accessed 25 Nov. 2023.

"Resistance and Resistivity." Engineering Toolbox, www.engineeringtoolbox.com/resistance-resisitivity-d_1382.html Accessed Oct 18 2023.

The Significance of the Oxidation Reaction - Longdom.Org, www.longdom.org/open-access/the-significance-of-the-oxidation-reaction-103041.html Accessed 9 June 2023.

Wasekar, Nitin P., et al. "Influence of Mode of Electrodeposition, Current Density and Saccharin on the Microstructure and Hardness of Electrodeposited Nanocrystalline Nickel Coatings." Surface and Coatings Technology, vol. 291, Apr. 2016, pp. 130–140, 10.1016/j.surfcoat.2016.02.024. Accessed 10 Oct. 2023.

"13.6 Standard Electrode Potentials." Siyavula, www.siyavula.com/read/za/physical-sciences/grade-12/electrochemical-reactions/13-electrochemical-reactions-06. Accessed 9 Oct. 2023.

[martin_stuart_silberberg]_principles_of_general_c(bookfi.org).pdf. p.pdfkul.com. (n.d.). https://p.pdfkul.com/martinstuartsilberbergprinciplesofgeneralcbookfiorgpdf_59d821ab1723ddc80f1cf8b1.html Accessed 9 Oct. 2023.