International Baccalaureate

Higher Level Chemistry Extended Essay

Investigation of the relation between anodization and leaching of aluminium in cooking scenarios

"How does the anodization of an aluminium electrode affect its rate of leaching when left in Citric Acid for an hour at different temperatures and under constant pressure measured via weight loss?"

Word Count: 3922

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Anodizing is a simple procedure used in very diverse fields with both industrial and personal uses. Anodizing is used in many industries which includes the production of general metal appliances, marine pipelines, general metal colourings and many more. Anodization is a type of electrochemical conversion which leads to an oxide layer being formed on the anode [1] which in most cases are aluminium. The aim of this research is to find out how the anodization of an aluminium electrode affects its rate of corrosion when its left in citric acid. The results of this research can be interpreted for the food industry. Excessive amounts of aluminium can cause serious health issues in humans such as dementia [2] and most of the cooking products we use are made from aluminium. Aluminium cook wares can get abraded by contact with other hard kitchen utensils such as metal spatulas, spoons and forks, aluminium cook wares can also get corroded with the effect of heat, acidity, and salinity. Both situations cause the ingestion of excess aluminium which can be hazardous. The study focuses on the difference between corrosion and leaching when the aluminium is used as it is or anodized. The study was carried out in the direction of measuring the mass values realized by immersing the aluminium in citric acid solutions prepared at 100.0 ^{0}C differences between 60.0 ^{0}C and 100.0 °C. The results of the study showed that the anodized aluminium was leached more in food since the oxide layer on it reacts with the citric acid found in the solution the form aluminium ions.

Introduction

1.1 Research Question

How does the anodization of an aluminium electrode affect its rate of leaching when left in (1M) Citric Acid for an hour at different temperatures (60.0 ^{0}C, 70.0 ^{0}C, 80.0 ^{0}C, 90.0 ^{0}C, 100.0 ^{0}C) and constant pressure measured via weight loss?"

1.2 Context

Aluminium is one of the most abundant elements on Earth which is found mostly as insoluble aluminosilicate and oxides [3]. It is almost used everywhere in daily life since it's abundant and versatile. An example to the vast uses of aluminium is its anodization. Anodization is basically forcing an oxide layer on top of the aluminium so that the corrosives cannot reach the aluminium as easily. Anodized aluminium is used in many industries such as the ship industry where it's used to build the hull of the ship, in the automotive industry and in the pipeline industry. The reason anodized aluminium is used in all these industries is because it is corrosion resistant. Non-Anodized aluminium cannot be used for these situations because it is easily corroded with the effect of acidity, temperature, and salinity. Aluminium also has a variety of effects on the human body. While the human body needs aluminium, an excess amount of it is known to play an effective role in dementia [2].

The main sources of aluminium for a human are reported to be beverages and cereals which are all intended, but there are some unintended aluminium sources as well. These are mostly from the aluminium cook wares, aluminium foils, and other utensils we use. The aluminium used in cook wares and utensils tend to be coated, but the coating can wear over time with the effect of scratching on their surface and elevated temperature. If the coating of an aluminium pan gets undone, it can cause excessive intake of aluminium which can lead to health issues mentioned before. The excess aluminium from the cook wares and foils are caused from the leaching of aluminium into the food. Most food is acidic, and leaching occurs when the acidic content of the food causes the uncoated aluminium the corrode, which releases aluminium into the food.

Background Information

To measure the amount of aluminium leached into the acid at any given temperature, a weight loss measuring method was used. The aluminium sheet was weighed on a sensitive lab scale before etching it in sodium hydroxide to clear its surface, then it was weighed after etching, after anodizing and after it has been soaked in acid for an hour. The weight difference between the time after anodizing and after the acid bath was used to derive the amount of aluminium leached/corroded into the acid.

To anodize the aluminium sheet, the aluminium was used as the anode of the electrolytic cell to form an oxygen layer on top of it.

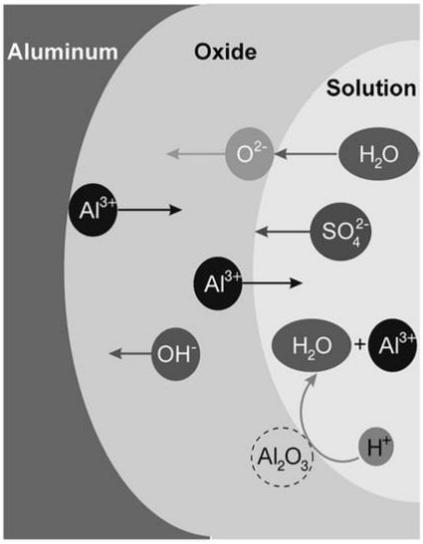


Figure 1: Illustration of ion movement and dissolution of oxide in sulfuric acid solution during aluminium anodization. [4]

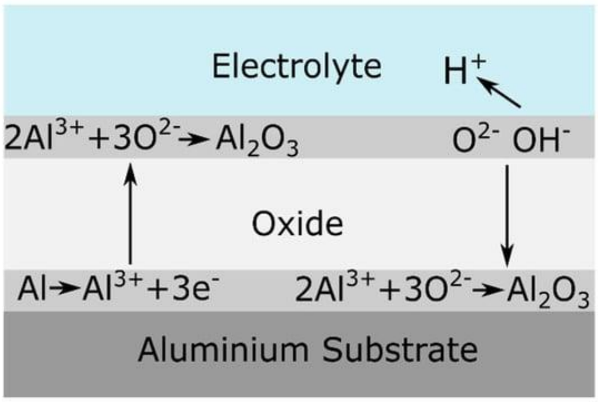


Figure 2: Ionic processes taking place during the anodization of aluminium. [5]

For the anodization process to be most effective, the aluminium needs to be prepared for the process by clearing and treating its surface. To prepare the aluminium sheet for anodization, it was first sanded down using sandpaper to get rid of any physical impurities, and then it was etched in 5M sodium hydroxide which reacts with any leftover acidic substances such as fats and leftover acids by reacting with them and producing corresponding salts.

$(NaOH + Acid \rightarrow Salt + Water)$.

As shown in the figures above, the anodization process consists of a few parts. First, the aluminium is oxidized, turning the Al to Al^{3+}ions and producing 3 electrons in the process. At the same time, H_2O molecules are electrolyzed to form O^{2-} and OH^- ions. Then the Al^{3+}ions and the O^{2-} ions combine with the balanced equation $2Al^{3+}+3O^{2-} \rightarrow Al_2O_3$ the Al_2O_3 coat the aluminium sheets surface to form the "oxide layer" which is the result of the anodization. The Al_2O_3 coating on the aluminium sheets also cause the sheet to gain mass since there is weight being added to it in form of oxygen molecules. The increase in mass values is a significant one which can be observed using a digital lab scale. So, the added weight had to considered for calculations.

In the second part of the experiment, the aluminium samples were left in 1M Citric acid for an hour at different temperatures, the aim of this procedure was to simulate cooking at different temperatures. Citric acid is an organic acid which is abundant in foods we eat. Since the aim of this step was to simulate cooking, it was a desirable choice since cooking materials such as lemon, oranges and tomatoes have different kinds of weak acids in them. For this experiment citric acid was chosen, but for further investigations other types of acids could be used to compare the effectiveness.

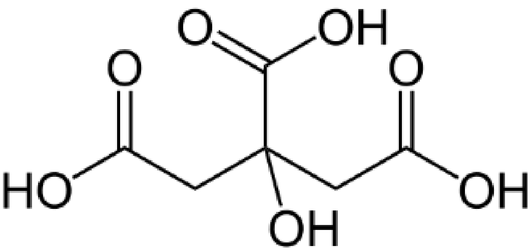


Figure 3: Skeletal structure of citric acid.

The reason for the aluminium leaching which occurs in this process, is the acidic medium. The H^+ ions in the citric acid react with the Al_2O_3 formed from the anodization process to form aluminium ions and water. The balanced equation for this step is $Al_2O_3 + 6H^+ \rightarrow 2Al^{3+} + 3H_2O$. The reason the anodized aluminium sheet loses more weight than the non-anodized sheet of aluminium is exactly this.

Preliminary Trials

A lot of preliminary trials were done using different methods. At first, aluminium foil was used instead of solid aluminium sheets. Foil was chosen for the preliminary trials because it simulated the cooking environment better. When we wrap our food in aluminium foil for its cooking process in the oven, aluminium leaching occurs, making us take more than necessary amounts of aluminium. The aim of this experiment was to simulate that, but since the aluminium foil is very fragile, physical tears and rips were observed during the procedure, rendering the trial useless. Because of this, aluminium sheets were used to simulate the cooking process in a pan rather than in an oven. The aluminium sheet represents the cooking utensils such as a spatula or the pan itself.

Another set of preliminary trials used 8.00 volts during the anodization process instead of 5.00 volts which was used as the final value. 8.00 volts were found to be less stable than 5.00 volts. 8.00 volts sometimes created unpredictable problems such as uneven coating during the anodization process. It sometimes made no coating at all.

Another preliminary trial was about using hydrochloric acid instead of citric acid. The hydrochloric acid was diluted with distilled water so that the pH level was 2.00 before being used. The pH level 2.00 was used because the pH of citruses used for cooking is around the same level. While the hydrochloric acid produces comparable results with the citric acid, The citric acid was preferred since it simulated the cooking process with actual citrus better. This is because hydrochloric acid is a strong acid by its nature while the citric acid found in the citrus is a weak one.

Initially, the independent variable of the experiment was chosen to be the pH value of the acid which the aluminium was going to be bathed in, but the temperature inside the water bath made the control of the pH values very difficult. I tried using different concentrations of hydrochloric acid solutions for different pH values, I scrapped the idea since it was very difficult to control the different pH values inside the water bath.

Experimental Variables

4.1 Independent Variables

4.1.1 Temperature

The temperature which the aluminium sheet was bathed in the 1M citric acid solution was chosen as the independent variable of the experiment. While there were many reasons for this, the main one is related to the experiments real-life situation. While cooking, the effect which changes the most is the temperature at which we cook meals at. While some meals are slow-cooked with low heat and relatively low temperature, some are seared with the highest heat possible such as meat which uses the technique "reverse-searing" which is essentially cooking the meat in the oven and then searing it as fast as possible in a pan without cooking its inside.

The temperature was chosen as the independent variable and the values 60.0 ^{0}C, 70.0^{0}C, 80.0^{0}C, 90.0^{0}C and 100.0^{0}C were chosen since they are the temperatures most meals are cooked at.

4.1.2 Anodization

The other independent variable of the experiment was the anodization process itself. The experiments aim was to see how treating and anodizing the surface of an aluminium sheet would affect its corrosion and leaching of it in high-heat, acidic cooking scenarios. For this reason, both non-anodized and non-surface-treated and anodized aluminium sheets were subjected to the same tests under the same circumstances.

4.2 Dependent Variables

The dependent variable of this experiment is the rate of corrosion/ leaching of the aluminium sheets. The rate of reaction changes according to both the anodization and the temperature.

4.3 Controlled Variables

Controlled variable	Reason for control	Method of control
Pressure	Difference in pressure affects the rate of corrosion/leaching by shifting the reactions balance towards the side with less gas according to Le Chatelier's principle since more gas causes more pressure.	The same laboratory was used for all the takes. The pressure of the lab was checked through a barometer present in the lab.
Time (1.0 hour)	The time that the aluminium sheets were bathed in the acid was kept constant because the time directly affects the amount of weight lost through leaching.	A stopwatch was used to time the process which was started at the instant when the beaker full of the acid and the aluminium was put inside the water bath. Although the beaker and the acid doesn't reach the temperature of the water bath instantly, the time is the same for all samples.
Chemicals	Chemicals from different batches could affect the results of the experiment in an unpredicted way, so all the takes were done with the chemicals prepared from the same batch.	Chemicals were all taken from the same batch then diluted at the same time as a single batch to keep them constant.
pH	The pH of the citric acid itself has a big effect on the rate of leaching so it had to be kept constant without counting in the effects of the temperature of the water bath	The citric acid was always used from the same batch so that there would be no differences between the pH or any other property. The pH was checked using a pH meter which was around 2.15 $\pm$0.01.
The Cathodes	The zinc cathodes used were kept constant with dimensions 7.5x4 cm. They needed to be the same because different cathodes could potentially have different reduction potentials and therefore could affect the anodization quality.	The zinc cathodes were kept constant by using the same two cathodes for every anodization take.

Table 1: Controlled variables of the experiment, their reason for control and their method of control.

Apparatus and Methodology

5.1 Apparatus and Chemical List

Equipment and Glassware	Sandpaper	7.5x4 cm Aluminium Sheet x2	Sensitive Digital Lab Scale (±0.001g)	DC Power Supply	Alligator-Alligator copper wire
	Power Supply-Alligator copper wire x2	Lab Stand	Lab Parafilm	7.5x4 cm Zinc Cathodes x2	Water Bath
	Stopwatch (±0.2s Human reflex time)	Glass Dishes x2	Weighing boats	25mL Beakers x2	50mL Beaker
	1L Beaker	Large Washbowl	Funnels x2	1L Volumetric Flasks x4	1L Graduated Cylinders x2
Chemicals	Distilled Water	412.5mL ≥99.5% Sulfuric Acid (H_2SO_4) (98.079 g/mol)	625mL 5M Sodium Hydroxide (NaOH) (39.997g/mol)	625mL Technical Grade Acetone (CH_3COCH_3) (58.08 g/mol)	1250mL 1M Citric Acid $(HOC(COOH)$ $(CH_2COOH)_2)$ (192.124g/mol)

Table 2: Table of chemicals , equipment and glassware used.

5.2 Methodology

5.2.1 Preparation of the 2M Diluted Sulfuric Acid

All of the following is done under a fume hood for safety reasons.

1. Fill the large washbowl with tap water and ice. This will be necessary to fasten ad to control the dilution process where it is seriously exothermic.

2. Using a funnel, pour 110mLs of concentrated sulfuric acid to the graduated cylinder and seal it using laboratory parafilm.

3. Using another funnel, pour 890mL of distilled water in another 1L graduated cylinder. Then, pour the distilled water into the volumetric flask. Pouring the water first is a must for safety reasons to control the amount of acid reacting with water.

4. Put the volumetric flask in the washbowl and using the funnel which was used for pouring sulfuric acid pour half of the sulfuric acid into the flask. Seal the flash and swirl to dilute the added sulfuric acid completely. The flask should warm up since the reaction between the acid and the water is an exothermic one. Swirl for 5 seconds and put the flask in the washbowl. Let it cool down completely.

5. After the flask has cooled down completely, using the funnel, add the remaining sulfuric acid, seal the flask, swirl for 5 seconds and then put in back in the washbowl to let it cool down.

Repeat steps 2-5 until there is 3750mL of diluted 2M Sulfuric Acid in total.

5.2.2 Anodization Process

1. Use sandpaper to remove the outer surface of an aluminium sheet until it is consistent in colour.

2. Put the aluminium sheet in 25mL 5M Sodium Hydroxide in a fume hood to be safe from the aluminium fumes. Let it sit in the sodium hydroxide for 5 minutes. This step is essential to clear the surface of the aluminium from any contaminants before the anodization process.

3. After 5 minutes, rinse the aluminium in distilled water and acetone. Acetone is a powerful solvent which cleans the surface from any leftover chemicals. Then pat it dry gently with paper towels. Weigh the weighing boat first then, weight the aluminium sheet on the digital scale and record the value in milligrams and subtract the weight of the weighing boat.

4. Using the lab stand as support, connect one alligator-power supply wires to one of the zinc cathodes, and connect the alligator-alligator wire to both cathodes. Then position them to be on the opposite sides of the beaker without touching it.

5. Connect the other alligator-power supply wire to the aluminium anode and position it in the middle of the two cathodes without touching either of them or the beaker.

6. Pour 750mL of 2M Sulfuric Acid into the beaker without spilling on the wires. Sulfuric acid is the electrolyte solution for this anodization cell which provides the ions needed for electrical current to form.

7. Turn on the power supply and set it to 5.00 volts. Then connect the anode to the + side and the cathodes to the - side. Wait for 15 minutes.

8. After 15 minutes, shut the power supply down, and carefully take the aluminium anode out. After taking it out, rinse it using distilled water and acetone and then dry it by gently patting with a paper towel. After making sure it is completely dry, weigh the aluminium anode using the digital scale and record the value. The value should be 30-50 mg more than the previous value, indicating the oxide layer forming.

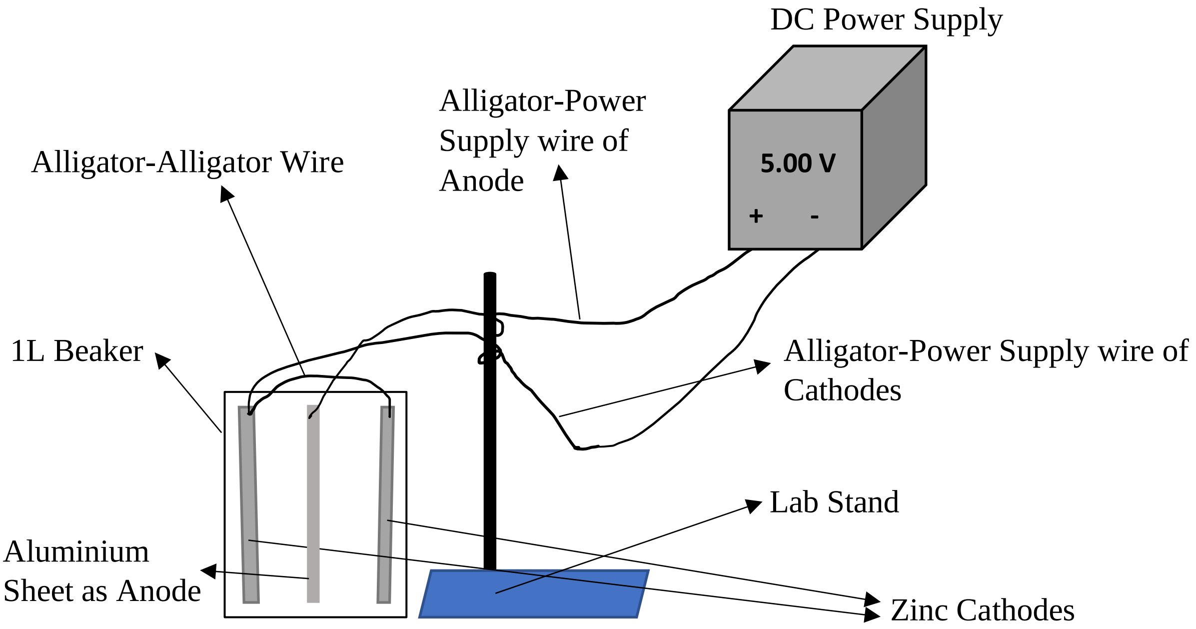


Figure 4: Simplified Anodization Set-Up with Labels

5.2.3 Citric Acid Bath Process

1. Pour distilled water into the water bath until it can coat the half of a 25mL beaker

2. Turn on the water bath and set it to the desired temperature. Wait until it reaches set temperature which can be seen in the external screen of the water bath.

3. Pour 25mL of 1M Citric Acid into a 50mL beaker. Put the aluminium sheet in the beaker and close it uses a glass dish to prevent evaporating citric acid escaping the beaker at high temperatures.

4. Place the beaker into the hot water bath carefully and shut the lid of the water bath.

5. After an hour, carefully take beaker out and the aluminium sheet out using tweezers.

6. After taking the aluminium out, rinse it using distilled water and acetone and gently pat dry using paper towels. After the aluminium is completely dried, weigh it using the digital scale and record the value.

5.2.4 Safety

Chemical	Possible Threats	Safety Precautions
≥99.5% Sulfuric(IV) Acid (H_2SO_4)	**CORROSIVE.** Causes severe eye and skin damage on contact. Reacts very violently with water, producing heat. Its fumes	Should be handled with utmost care. The handler must use appropriate gloves and long-sleeved coats to cover any exposed skin.

	can cause permanent airway damage. Ingestion can cause severe damage or death [7].	Safety glasses must be used to protect against any eye contact. Must be used only in a fume hood in order to be protected from the fumes.
5M Sodium Hydroxide Solution (NaOH)	**CORROSIVE, HARMFUL.** Causes severe eye and skin damage on contact. Inhalation can cause pulmonary edema, build-up of fluids in the lungs. Ingestion can cause severe damage or death [7] [8].	Should be handled with utmost care. The handler should use appropriate gloves and long-sleeved coats to cover any exposed skin. Safety glasses must be used to protect against any eye contact. Must be used only in a fume hood in order to be protected from the fumes.
Technical Grade Acetone (CH_3COCH_3)	**HIGLY FLAMMABLE, IRRITANT.** Highly flammable vapor and liquid. Can cause drowsiness or dizziness if inhaled. Can cause airway irritations. It has a distinct smell. Causes serious eye irritation [7].	Appropriate gloves should be used. Should be kept away from direct heat or any fire source since it is highly flammable.
1M Citric Acid ($HOC(COOH)(CH_2COOH)_2$)	**IRRITANT.** Can cause eye, skin, and respiratory irritation [7].	Appropriate gloves should be used.

Table 3: Table of possible threats and safety precautions of used chemicals.

All these chemicals mentioned must be disposed of properly. They must be put in non-reactive bottles and kept away from the sunlight and deposited to chemical waste deposits. If they are not taken care of properly, they can damage the environment since they are all harmful to living beings.

Analysis

6.1 Raw Data Tables

Due to the large amount of total data collected, in order to make the data a little tidier, anodized, and non-anodized data will be in separate tables.

6.1.2 Non-Anodized Aluminium Raw Data Table

Trial #	1	2	3	4	5	1	2	3	4	5
	Initial Weight (±0.001g)					Weight After Acid Bath (±0.001g)				
60.0±0.1°C	3.317	3.165	3.240	3.375	3.351	3.312	3.158	3.235	3.369	3.347
70.0±0.1°C	3.145	3.276	3.315	3.125	3.261	3.139	3.270	3.308	3.119	3.253
80.0±0.1°C	2.974	3.019	3.312	3.187	3.029	2.964	3.010	3.303	3.181	3.022
90.0±0.1°C	2.794	3.256	2.985	3.152	3.098	2.784	3.245	2.974	3.140	3.086
100.0±0.1°C	2.983	3.093	3.187	3.042	2.843	2.970	3.079	3.178	3.028	2.831

Table 4: Raw data table of non-anodized aluminium specimens.

6.1.3 Initial and Anodized Weight Raw Data Table

Trial #	1	2	3	4	5	1	2	3	4	5
	Initial Weight (±0.001g)					Weight After Anodizing (±0.001g)				
	3.272	3.049	3.317	3.368	3.277	3.307	3.083	3.351	3.401	3.309
	3.188	3.128	3.325	2.900	3.189	3.221	3.150	3.363	2.941	3.231
	2.906	3.002	3.362	3.049	3.161	2.944	3.041	3.401	3.100	3.206
	3.013	2.881	3.298	3.012	2.984	3.051	2.930	3.332	3.050	3.019
	2.945	3.326	3.421	3.210	2.799	2.987	3.378	3.464	3.249	2.832

Table 5: Raw data table of anodized aluminium specimens’ initial weight and anodized weight.

6.1.4 Anodized Weight and Final Weight Raw Data Table

Trial #	1	2	3	4	5	1	2	3	4	5
	Anodized Weight (±0.001g)					Weight After Acid Bath (±0.001g)				
60.0±0.1°C	3.307	3.083	3.351	3.401	3.309	3.273	3.054	3.315	3.362	3.275
70.0±0.1°C	3.221	3.150	3.363	2.941	3.231	3.179	3.111	3.321	2.898	3.191
80.0±0.1°C	2.944	3.041	3.401	3.100	3.206	2.898	2.993	3.351	3.056	3.159
90.0±0.1°C	3.051	2.930	3.332	3.050	3.019	3.002	2.878	3.282	2.998	2.965
100.0±0.1°C	2.987	3.378	3.464	3.249	2.832	2.929	3.322	3.403	3.194	2.780

Table 6: Raw Data table of the anodized aluminium specimens’ anodized weight and final weight.

6.2 Qualitative Observations

During the physical removal of the outer layer, the colour of the aluminium changed from a blackish colour to a more metallic grey. After that, in the chemical cleansing/etching process, at the instant the aluminium was dropped into the sodium hydroxide, the solution's colour changed to a white from colourless, bubbles could be seen rising towards the surface from the aluminium, sizzling could be heard. During the anodization process, bubbles could be seen from both the cathodes and the anode as well. After the anodization, the part of the aluminium which was soaked in sulfuric acid had a darker colour than the rest of it.

6.3 Processed Data

To find the amount of mass lost in terms of grams for the non-anodized aluminium, the final weight of the aluminium was subtracted from the initial weight. For the anodized aluminium, the final weight was subtracted from the anodized weight.

Example calculation:

$$3.317 \pm 0.001 - 3.312 \pm 0.001 = 0.005 \pm 0.002\text{g}$$

To find the average mass lost in grams, the mass loss values for a data set were added together and then divided by 5.

Example calculation:

$$\frac{0.005 + 0.007 + 0.005 + 0.006 + 0.004}{5} = 0.005\text{g}$$

To find the percentage uncertainty value of the average mass loss values, the formula below was utilized:

$$\frac{\text{Max Data-Min Data}}{2 \times \sqrt{Number\ of\ Data}}$$

Example calculation:

$$\frac{0.007 - 0.004}{2 \times \sqrt{5}} = 6.71 \times 10^{-4}$$

Then the uncertainty was turned to percentage uncertainty:

$$\frac{6.71 \times 10^{-4}}{0.005} \times 100 = 13.4\%$$

To find the percentage weight loss, the weight loss values were multiplied by 100 and divided by the weight of the aluminium.

Example calculation:

$$\frac{0.005 \times 100}{3.317} = 0.15$$

Then, to find the average percentage weight loss, the percentage weight loss values within a group were added together and divided by 5.

Example calculation:

$$\frac{0.150 + 0.227 + 0.150 + 0.176 + 0.180}{5} = 0.177$$

The same percentage uncertainty equation was utilized here as well:

$$\frac{0.227 - 0.150}{2 \times \sqrt{5}} = 0.017$$

$$\frac{0.017}{0.177} \times 100 = 9.60\%$$

To calculate the theoretical mass loss of the aluminium anode, the average weight gained from anodizing was subtracted from the average mass lost from the acid bath:

$$3.44 \times 10^{-2} \pm 0.20\% - 3.36 \times 10^{-2} \pm 6.50\% = 8.00 \times 10^{-3} mg \pm 6.70\%$$

6.4 Processed Data Tables

6.4.1 Non-Anodized Aluminium Processed Data Table

		Average Weight Loss (mg)	Average Percentage Weight Loss
Temperature (±0.1°C)	60.0±0.1°C	$5.00 \times 10^{-3} \pm 13.4\%$	$0.18\% \pm 9.40\%$
	70.0±0.1°C	$6.00 \times 10^{-3} \pm 7.45\%$	$0.20\% \pm 1.39\%$
	80.0±0.1°C	$8.00 \times 10^{-3} \pm 11.2\%$	$0.26\% \pm 12.7\%$
	90.0±0.1°C	$1.10 \times 10^{-2} \pm 4.06\%$	$0.37\% \pm 1.11\%$
	100.0±0.1°C	$1.20 \times 10^{-2} \pm 9.32\%$	$0.41\% \pm 9.82\%$

Table 7: Processed data table of non-anodized aluminium including average weight loss and average percentage weight loss.

6.4.2 Anodized Aluminium Processed Data Table

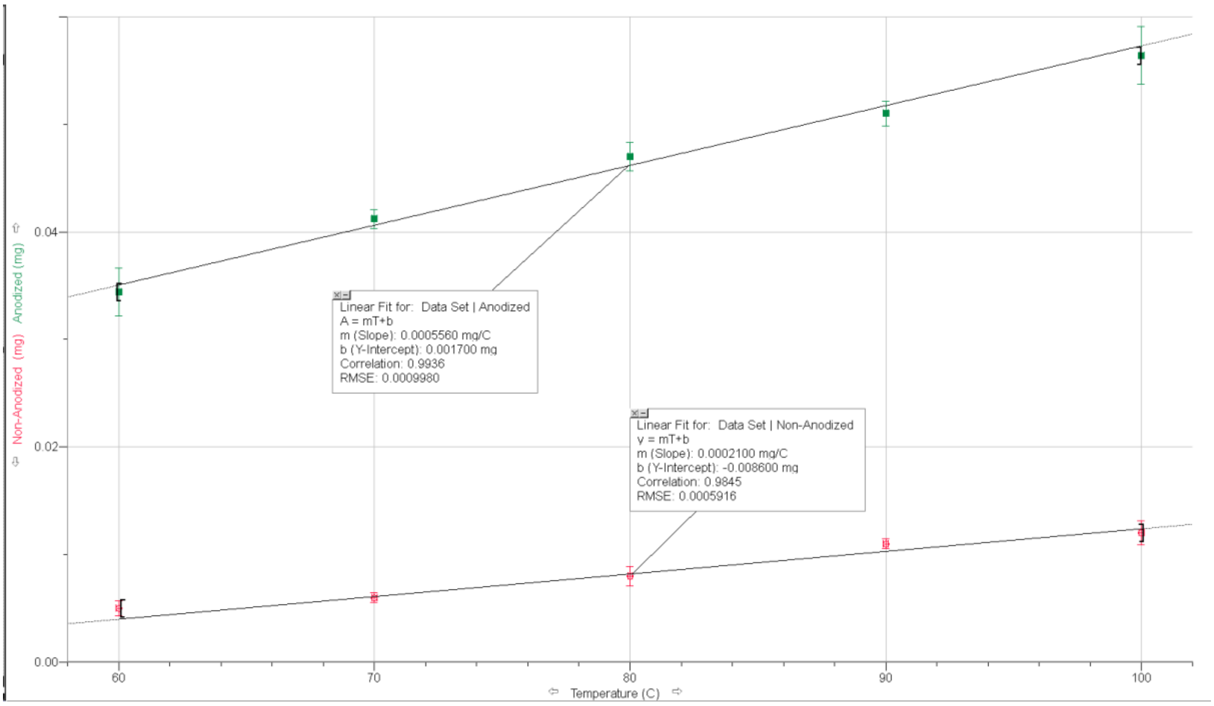
	Average Weight Gain from Anodization(mg)	Average Percentage Weight Gain	Average Weight Loss(mg)	Average Percentage Weight Loss	Theoretical Aluminium Weight Loss (mg)
60.0±0.1°C	3.36×10^{-2} ±0.20%	1.02% ± 2.98%	3.44×10^{-2} ±6.50%	1.04% ±4.43%	8.00×10^{-3} ±6.70%

70.0±0.1°C	3.52×10^{-2} ±12.70%	1.12% ±14.18%	4.12×10^{-2} ±2.17%	1.28% ±3.91%	6.00×10^{-3} ±14.87%
80.0.±0.1°C	4.24×10^{-2} ±6.85%	1.35% ±8.49%	4.70×10^{-2} ±2.85%	1.50% ±2.37%	4.60×10^{-3} ±9.7%
90.0±0.1°C	3.88×10^{-2} ±8.64%	1.27% ±11.79%	5.10×10^{-2} ±2.19%	1.67% ±3.86%	1.22×10^{-2} ±10.83%
100.0±0.1°C	4.18×10^{-2} ±10.16%	1.31% ±6.56%	5.64×10^{-2} ±4.76%	1.78% ±2.40%	1.46×10^{-2} ±14.92%

Table 8: Processed data table of anodized aluminium including average weight gained from anodization, average percentage weight gain from anodization, average weight loss and average percentage weight loss ±0.1°C

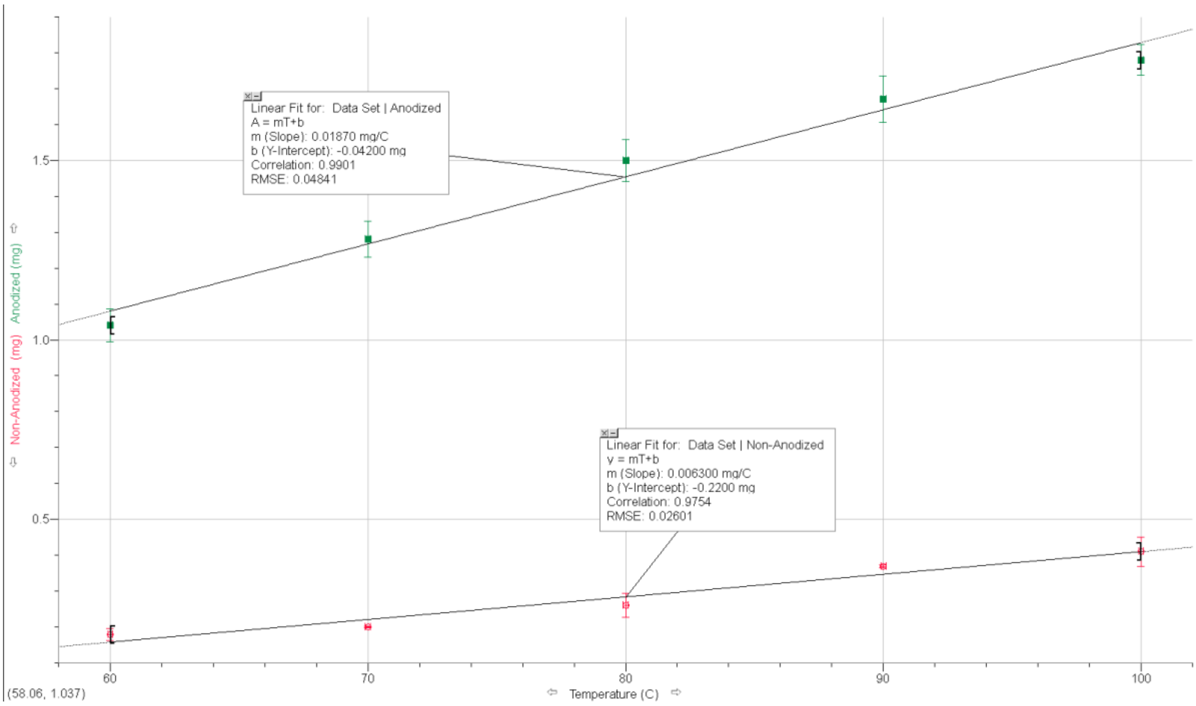
6.4.3 Processed Data Graphs

Graph 1: Non-anodized and anodized aluminium specimens with best fit lines and error bars.



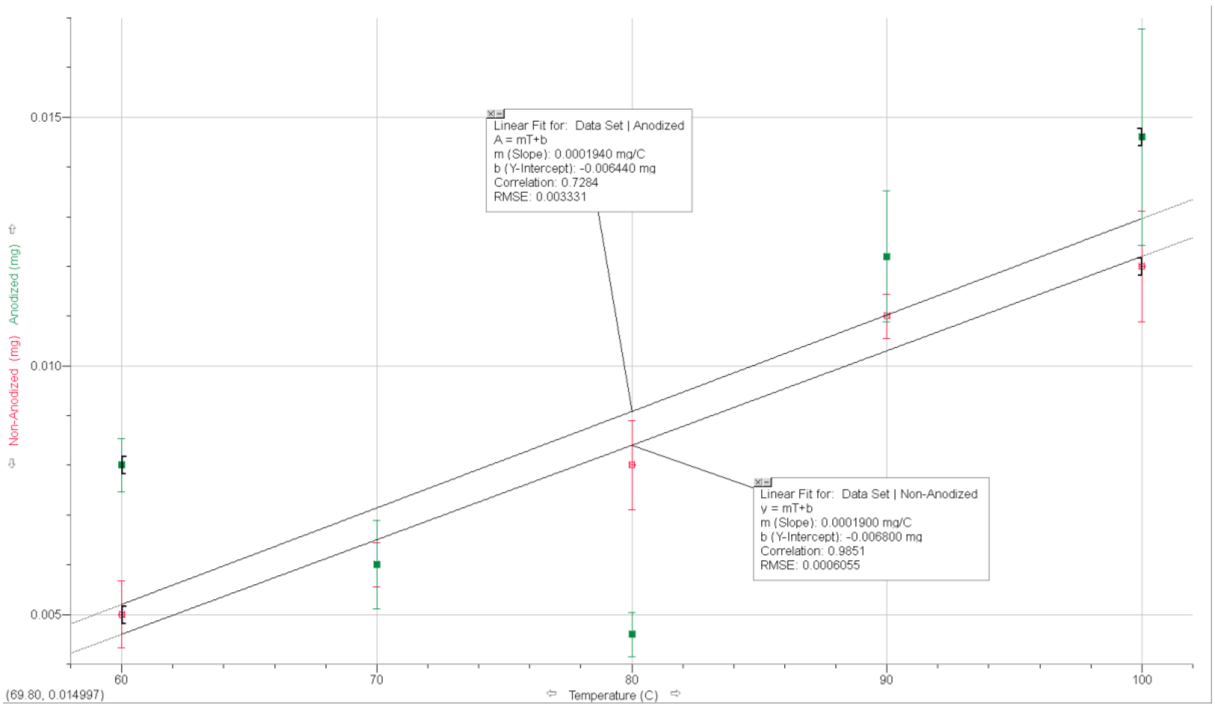
Graph 1: Processed data graph of both non-anodized and anodized aluminium specimens with best fit lines and error bars. Average weight loss plotted against temperature.

Graph 2: Processed data graph of both non-anodized and anodized aluminium specimens with best fit lines and error bars.



Graph 2: Processed data graph of both non-anodized and anodized aluminium specimens with best fit lines and error bars. Average percentage weight loss plotted against temperature.

Graph 3: Average weight loss of non-anodized aluminium plotted with theoretical weight loss of anodized aluminium against temperature.



Graph 3: Processed data graph of both non-anodized and anodized aluminium specimens with best fit lines and

error bars. Average weight loss of non-anodized aluminium plotted with theoretical weight loss of anodized aluminium against temperature.

Evaluation and Conclusion

This study was conducted to see the effect that anodizing an aluminium sheet has on its leaching in citric acid.

Anodization is a process used in widely in our daily life with its purpose ranging from simple dyeing of aluminium to corrosion proofing underwater pipelines. It's the process of forcing an oxide layer on top of the aluminium by the electrolysis of water in acidic electrolyte solutions. The water gets electrolysed forming O^{2-} and OH^{-} ions then, the O^{2-} ions react with the aluminium ions present in the environment to form anodic aluminium oxides. That is how the oxide layer is forced upon the aluminium. Since it is a simple electrochemical reaction, factors such as temperature and the molarity of the electrolyte solution affect how much aluminium oxide is formed, so they were kept constant during the process.

Aluminium getting corroded and getting involved in our food products during the cooking process is called leaching. Leaching occurs under acidic and high temperature environments because the irritation on the surface of the aluminium. Leaching causes excess intake of aluminium which can have serious adverse health effects such as dementia.

While anodizing procedures are mostly used for corrosion proofing materials such as aluminium, the study showed that anodizing cookware in a laboratory setting doesn't help the leaching of it into various foods. The experiment was conducted several times for each data set to reduce the random error that could have been caused by the equipment, the lab setting and the overall procedure. The correlation coefficient of the R^2 value of all the graphs plotted are above 0.94 which means they have a strong correlation which shows that the relation between temperature of the acid bath and the leaching/corrosion of the aluminium are closely related.

As it can be seen from **Graph1** and **Graph 2**, the anodized aluminium had a significantly higher average weight loss than non-anodized aluminium. The reason for this is the oxide layer forced upon the aluminium reacting with the H^{+} ions found in the acidic medium and forming $Al^{3+} and\ H_2O$ The balanced equation for the reaction is

$Al_2O_3 + 6H^{+} \rightarrow 2Al^{3+} + 3H_2O$ [6], but these values are not representative of the whole situation.

Most of the mass gained from anodization is oxidation and is not entirely aluminium. Since the aim of the experiment was to see if anodization effects the mass loss of aluminium, a theoretical aluminium mass lost was found by subtracting the mass lost after acid bath from the mass gained from anodization. While the value found does not include the whole of the aluminium leached, it is a closer representation of the mass of aluminium lost. Referring to **Graph 3**, we can see that the theoretical mass loss value is closer to expected values from literature. While my theory does not explain the sudden drop of theoretical mass loss at the 80.0°C mark, it is fair to assume that it was caused by the random error caused by various uncontrollable effects. That being said, as it can be seen from **Graph 3**¸ the theoretical mass loss of the aluminium is still related to the temperature of the acid bath since its correlation coefficient is 0.7284.

An extension to the experiment could have been to investigate the effect of different voltage values while anodizing on the amount of aluminium leached, it could give an insight on to how the aluminium should be treated before usage. Another extension could have been to investigate the effect of pH on the leaching of aluminium. This could give an insight on to how different cooking mediums effect the leaching of aluminium.

While the experiment done has various strengths, it also has clear weaknesses. One of those weaknesses is that the sheer amount of chemicals used, and waste produced is very large, but this can be solved by using smaller scale aluminium sheets and smaller beakers.

Another weakness is that the experiment consumes a lot of time since there is a high amount of raw data to be collected. The experiment took around 4 months to complete from the start including the preliminary testing process. During this time, I had to travel to the school and back every day during summer consuming more fuel than needed, and also the lab had to be occupied.

A limitation of the experiment is something that could be expanded upon. There are a lot of variables which effect the leaching of aluminium in a cooking medium, but because of multiple limitations, those could not be investigated. Some of the strengths of the experiment is it is easy to replicate for other individuals since the procedure is not too complex, it uses materials which can be substituted with ones easier to find and use, such as replacing the water bath with an oven.

References:

1. Caṅkaranārāyaṇaṉ S. Surface Modification of Magnesium and Its Alloys for Biomedical Applications. Elsevier, Woodhead Publ., 2015.

2. Klotz, Katrin, et al. "The Health Effects of Aluminum Exposure." Deutsches Arzteblatt International, U.S. National Library of Medicine, 29 Sept. 2017, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5651828/.

3. G. D. Fasman, C. D. Moore, Proceeding of the National Academy of Sciences of the United States of America, 9 (1994) 11232.

4. Sulka, Grzegorz D. "Highly Ordered Anodic Porous Alumina Formation by Self-Organized Anodizing." Nanostructured Materials in Electrochemistry, pp. 1–116., https://doi.org/10.1002/9783527621507.ch1.

5. Aerts, Tim. Study of the Influence of Temperature and Heat Transfer during Anodic Oxide Growth on Aluminum. Diss. Vrije Universiteit Brussel, 2009.

6. Effect of Ph, Salinity and Temperature on Aluminum Cookware Leaching ... https://www.researchgate.net/publication/221971675_Effect_of_pH_Salinity_and_Temperature_on_Aluminum_Cookware_Leaching_During_Food_Preparation.

7. CLEAPSS Science Home, https://science.cleapss.org.uk/.

8. "Healthy New Jersey." Department of Health for the State of New Jersey | Homepage, https://nj.gov/health/.

9. Fermo, Paola, et al. "Quantification of the Aluminum Content Leached into Foods Baked Using Aluminum Foil." *International Journal of Environmental Research and Public Health*, vol. 17, no. 22, 2020, p. 8357., https://doi.org/10.3390/ijerph17228357.

10. Al Juhaiman, Layla A. "Estimating Aluminum Leaching from Aluminum Cook Wares in Different Meat Extracts and Milk." *Journal of Saudi Chemical Society*, vol. 14, no. 1, 2010, pp. 131–137., https://doi.org/10.1016/j.jscs.2009.12.020.

11. Dordevic, Dani, et al. "Aluminum Contamination of Food during Culinary Preparation: Case Study with Aluminum Foil and Consumers' Preferences." *Food Science & Nutrition*, vol. 7, no. 10, 2019, pp. 3349–3360., https://doi.org/10.1002/fsn3.1204.

12. Li, Jingui, et al. "Effect of Anodizing Temperature and Organic Acid Addition on the Structure and Corrosion Resistance of Anodic Aluminum Oxide Films." *Thin Solid Films*, vol. 713, 2020, p. 138359., https://doi.org/10.1016/j.tsf.2020.138359.

13. Bouchama, L., et al. "Enhancing Aluminum Corrosion Resistance by Two-Step Anodizing Process." *Surface and Coatings Technology*, vol. 235, 2013, pp. 676–684., https://doi.org/10.1016/j.surfcoat.2013.08.046.