Oxygen Dependence of Aluminum Air Batteries

A Major Qualifying Project Report
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Abstract

An often overlooked area of sustainable clean energy that is viable for grid power reserves is off-grid energy. Aluminum air batteries can fill this void with high energy density, sustainability, cost, and minimal emissions. This project seeks to examine the efficacy of aluminum-air batteries as a power source and the effect of pressurization on their efficacy. A theoretical and experimental investigation was performed on the Research and Development Test Cell (R&DTC) provided by AlumaPower, the corporate sponsor of the project. Experimental polarization curves were compared to those excised from literature to determine their validity. Despite issues with experimentation, the theoretical conclusion was drawn that the efficiency of the aluminum-air battery improves under pressure, and as a technology, it can be very desirable.

Contents

1 Introduction

What does the future of fuel look like? Technology in the energy sector is rapidly expanding as the world desperately looks for solutions for greenhouse gas emissions. The topic of climate change is constantly in the discussion, with recent documentary films and research on the topic having more focused attention on the potentially disastrous effects of temperatures rising even by a few degrees. There are many sources of energy, each with its own drawbacks and benefits; solar power and wind power have the benefit of generating energy without emissions after the initial manufacturing process; however, they are instantaneous. When the sun goes down, the wind stops blowing the only solar power that can be used is that which has been stored in a battery and the issue with battery storage is that there are only enough batteries to run the united states for seconds. Hydroelectric power is another option with a major limitation being location, but in Canada, the majority of the electricity comes from hydroelectric dams. Natural gas, on the other hand, can be used at any time but does give off emissions. The emissions of natural gas, however, do not rival that of fossil fuels; the energy source the United States and the rest of the world depend on the most. Lastly, there is the power source that is the focus of this paper: metal-air batteries. More specifically, this paper centers on aluminum-air batteries and their oxygen dependence. Metal air batteries have the on-demand energy nature of natural gas with the zero-emissions of wind and solar power. The only gas emission of aluminum-air batteries is hydrogen, and even that is in minuscule amounts. Aluminum air batteries are ideal for medium to large-scale applications such as home generators, cars, or trains. With the low noise output and emissions, a metal-air battery generator could be used within a home.

In 2019, wind turbines generated 24% of the United States' renewable energy, compared to 9% from solar power. The main advantage wind has over solar is the ability to function 24 hours a day.

1.1 Wind Power

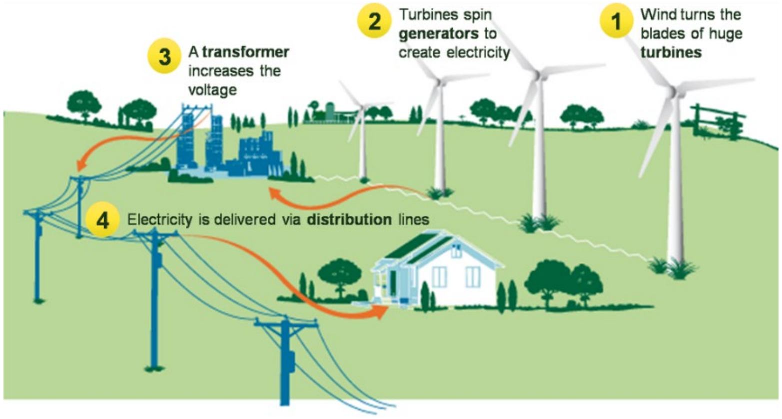


Figure 1: Electricity from Wind Turbines. Image adapted from Hartleb [1]

Energy is generated when the blades of a wind turbine are rotated by the wind, which in turn spins the generator. The electricity generated then passes through a transformer which raises the voltage before being moved to its desired location via power lines.

Wind turbines must sit above obstacles that would block airflow to maximize their efficiency. Wind turbines are suited for the tops of smooth, rounded hills, open plains and water, and mountain gaps[2]. Offshore wind farms in coastal regions harness the wind in open water. With a variety of locations suitable for wind generation, many nations can utilize this technology as it becomes more accessible and efficient. In the United States, the cost of wind power has fallen in the last decade: from $135/MWh in 2009 down to $43/MHw in 2018[3].

Solar power has a promising future as an energy source. The location of solar collectors is more flexible than that of wind. The main factors in solar energy production are latitude, climate, and weather patterns[4]. Solar thermal-electric power plants require direct solar radiation, making them more suited for arid regions with few cloudy days. Flat-plate solar thermal, as well as photovoltaic (P.V.) collectors, use global solar radiation. This allows the collection of diffused as well as direct solar radiation[4]. A rule of thumb for solar is: that its efficiency and total annual production increases closer to the equator. Seasonal variance is less at lower latitudes, leading to reliable year-round production. Similar to wind, solar energy has seen major decreases in LCOE (from \$359/MWh in 2009 to \$43/MWh in 2018), making it far more viable[3]. Solar energy works in residential areas, too. P.V. panels installed on roofs or on the ground reduce the energy homes draw from the grid. Inland Power & Light, a utility company in the northwestern U.S., installed both solar and wind technologies at their headquarters in Spokane, Washington.

1.2 Energy Storage: Batteries

Beyond the standard conventions for fuels, energy storage plays an important role in grid power. As industries continue to scale, there is a need for alternative energy storage that can allow grids to operate efficiently. Reducing the lack of proportion between energy demand and energy consumed requires a device that stores energy. These are generally referred to as batteries. There are multiple ways energy takes form, such as radiation, chemical, gravitational, heat, kinetic, and many more. Storage of energy involves conversion from forms that are difficult to store to more convenient or economically storable forms. It is important to consider that there is a wide range of capabilities for the technology that can store energy for short and long terms. Most modern energy storage is currently dominated by hydroelectric methods through dams. Hydroelectric differs from storage methods that can be provided for a grid since large-scale processes require extensive power consumption to meet the demand of regular operating conditions.

Aluminum has shown to be a viable source of energy storage since it is at the forefront of tackling the current issues that arise within grid-scale battery technology. These issues consist of battery designs with capable current density, longevity, cost, and sustainability. Through aluminum, there exists an alternative since it consists of a higher high theoretical energy density (8100 Wh kg^{-1}), which is significantly greater than that of the state-of-the-art lithium-ion batteries[5]. Using this metal also comes with sustainability advantages since it is able to operate at high capacities for an extensive amount of time. The cost also plays a role since it is expensive to extract this metal, but already existing aluminum can be recycled and repurposed for chemical energy purposes. It is imperative to consider aluminum batteries as a grid alternative for energy storage, considering the advantages the advantages they provide.

1.3 Solar Power

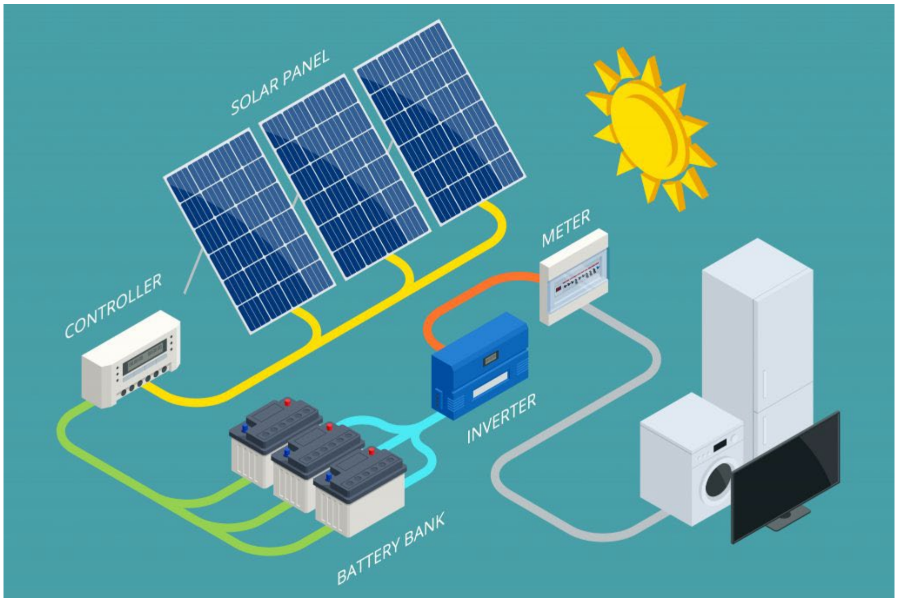
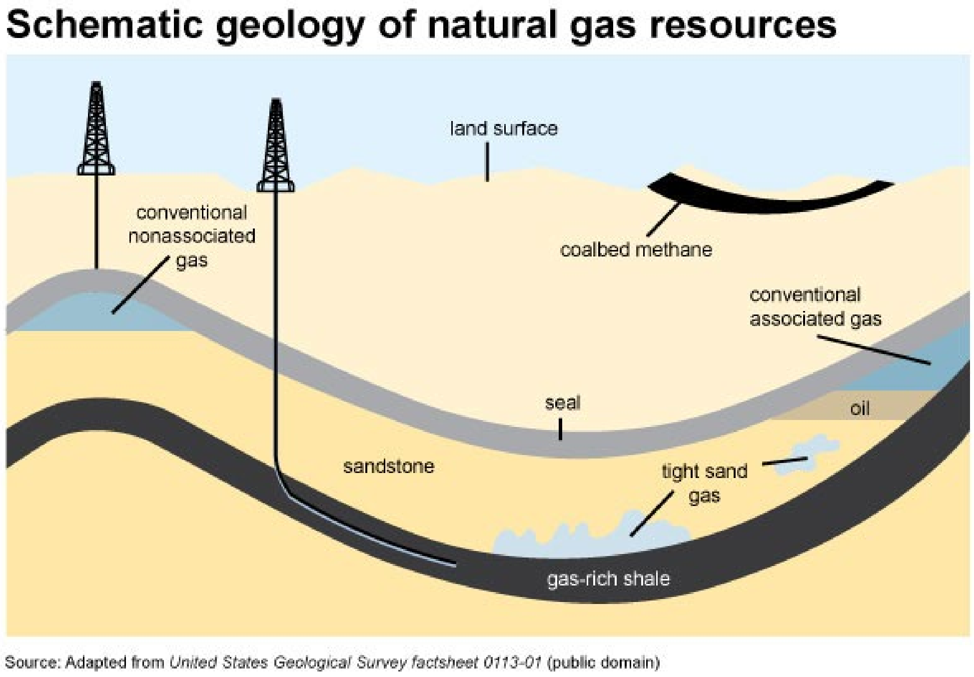


Figure 2:How solar power works Image adapted from How Does Solar Energy Work: Ultimate Guide To Solar Energy In 2022 - Sun Badger Solar [6]

The added benefit of solar power includes the implementation of technology. The process of how energy from the sun is converted to power our daily appliances is shown as a frictionless process in Figure 2. Solar panels capture solar energy in solar cells, and this energy is connected to a controller's positive and negative leads connected to a controller, which creates a charge. This charge is then stored in a battery bank; the purpose of the bank is to circumvent issues when there's no sunlight. The collected solar energy can always be used as electricity even when sunlight is not available. Although much more convenient, solar power installation is costly, which creates a high barrier to entry for most.

1.4 Natural Gas



Schematic geology of natural gas resources

Source: Adapted from *United States Geological Survey factsheet 0113-01* (public domain)

Figure 3: How Natural Gas is Collected Image adapted from Natural gas explained [7]

Here in Figure 3, the natural gas collection is depicted. The first and most essential step of natural gas production. It is crucial to keep emissions low, and natural gas is the perfect alternative to coal since it is very abundant and emits less carbon. According to the EIA, the energy needed to produce natural gas is cheaper than coal (IEA, 2015). The most efficient gas-fired plant has investment costs of $1,100 per kilowatt, compared with $3,700 for the most efficient coal-fired plant (IEA, 2015).

1.5 Focus

The main focus is to analyze what role aluminum-air batteries play in the fuels industry and how efficient they are. A fuel cell leverage the chemical energy of its fuel in order to generate electricity. These fuel cells have little to no harmful emissions, making them a great source of clean energy. Hydrogen-fueled cells have only water and heat as by-products, with electricity as the primary product[8]. It is important to know that metal-air batteries are a type of fuel cell that may be limited in their capacity to become a main source of energy. With aluminum fuel cells, the only air-born by-product is hydrogen in negligible amounts. This hydrogen could be collected if the need arises, but as long as accumulation is prevented, no threat is posed to the environment or the user. The other by-product is aluminum hydroxide; however, this is contained in the reaction vessel negating environmental risk if disposed of properly. They do not fill the same role in the energy infrastructure of society as solar, wind, and gas power. Metal air fuel cells are not a feasible method of powering the grid as the primary energy source but rather could offer a solution to off-grid power or reserve power. The cost plays a big factor because, in order to produce aluminum, it would be too expensive as an all-the-time energy source. It is ideal that aluminum-air batteries serve as a backup generator for a house or vehicle. This entertains the idea of how transportation methods can benefit greatly, such as how a train could make its entire trip on a relatively small battery and low fuel consumption, or a car could go 1000 miles with a single replacement of the aluminum. While it might not be economically or environmentally sustainable to mine aluminum for the sole purpose of energy production, this is a great use for recycled aluminum, as demonstrated in other papers[8]. This paper uses recycled aluminum to power a hydrogen fuel cell.

In this MQP, the goal will be the optimization of an Aluminum Air Battery developed by AlumaPower. This optimization centers around the variation of the air pressure levels of the gas feed. Through examining these variables, we aim to see the dependence on air and how it can have good and bad repercussions on battery operations and battery efficiency. We also will highlight how the battery will be modeled mathematically to examine its deviation from ideal behavior. A primary innovation made by Aluma Power that makes the Aluminum Air batteries is the spinning of the aluminum disc. This innovation elevates the issue of uneven wear in aluminum, which leads to decreased efficiency and unpredictable energy output. This is a common issue with metal batteries as a whole, and it will be important to get technical background information on metal batteries as a whole before understanding aluminum batteries themselves.

2 Technical Background

2.1 Overview

Aluminum-air batteries are a very promising energy technology. The aluminum is consumed and replaced, making it a primary battery. Unlike rechargeable secondary batteries, they are "recharged" in three to five minutes by replacing the aluminum. These secondary batteries function closer to an engine with the consumable aluminum fuel rather than energy from an external source being stored in the battery. Aluminum is an ideal energy source as it is naturally plentiful, inexpensive, lacks environmental impact, and has energy capacity as well as density that is quite high. In addition, aluminum-air batteries are safer than lithium batteries. Aluminum air batteries are made up of an air-breathing electrode, aluminum anode, and either ionic or liquid electrolytes[9].

2.2 *Metal-Air Battery Operation*

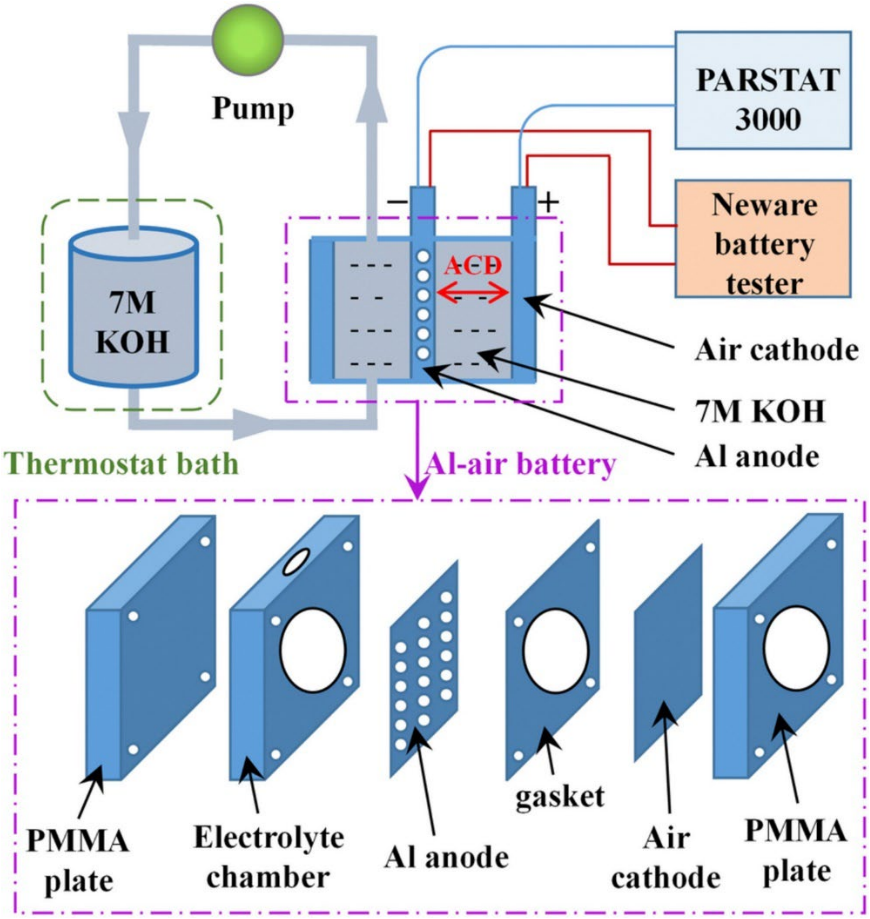


Figure 4: "Schematic diagram of the test system and composition of aluminum-air battery" image adapted from Wen et al. [10]

In Figure 4 the schematic is very similar to the one discussed in this paper, with key differences being the stationary aluminum anode and the 7 molar potassium hydroxide. The PMMA plates are the housing to the battery and are similar to the AlumaPower cell in the resin construction. The use of a motorized anode in the AlumaPower system has little impact on the construction of the cell. The potassium hydroxide electrolyte is interchangeable with the sodium hydroxide, and the higher concentration is likely to ensure the solution is basic enough. In the AlumaPower R&DTC, the three layers of the cathode assembly are the manganese dioxide catalyst, the current nickel collector, and the PTFE gas diffusion layer. The cathode assembly was later replaced with one that used nickel foam in place of the nickel mesh.

The two reactions that generate the energy within the system are the oxygen evolution reaction and the aluminum conversion to aluminum hydroxide. The electrons produced by the aluminum conversion reaction

$$Al + 3OH^- \rightarrow Al(OH)_3 + 3e^-; E^o = -2.31\mathrm{V}$$

are then consumed by the oxygen evolution reaction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-; E^0 = 0.40V$$

These reactions come together to make the overall balanced reaction

$$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3; E^0 = -2.71\ \mathrm{V}$$

There is also a non-energy producing reaction in the anode where aluminum hydroxide is converted into a different form of aluminum hydroxide, which is this double replacement reaction

$$Al(OH)_3 + NaOH \rightarrow NaAlO_2 + H_2O$$

There is also the production of aluminum oxide at the cathode, which produces a black tint in the electrolyte.

A major issue with aluminum-air batteries is their low working voltage which is limited by the electrolyte solution. This lower working voltage is also caused by. Working voltage means a lower energy density and power density. The causes for this include but are not limited to the hydrogen evolution of gas at the negative electrode, aluminum oxidation with the electrolyte, and the formation of aluminum hydroxide[10].

2.3 Electrolyte Selection

The electrolyte is the medium for electron exchange. An electrolyte is an ion or a salt that brakes apart to form ions. For Al-air batteries, the electrolyte is often aqueous and alkaline. The electrolyte limits working voltage as if there is less electrolyte in a system, then there are fewer ions[11]. The question then arises why NaOH is the ideal choice for an electrolyte. NaOH is an alkaline electrolyte, and the alternative is a neutral electrolyte which has a number of issues. The first issue is an oxide film that forms on the surface of the aluminum, which lacks solubility and impedes activation of the aluminum. The second issue is the increased build-up of Aluminum hydroxide in neutral conditions. This Al(OH)3 build-up increases electrical resistance and obstructs the conductivity of the battery. On the other hand, Alkaline electrolyte does not suffer the issues of neutral electrolyte. Potassium hydroxide is the most common of these electrolytes but is interchangeable with sodium hydroxide.

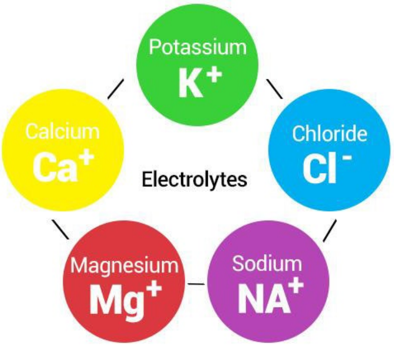


Figure 5: Common Electrolytes Image adapted from [12]

As can be seen in Figure 5 above, Na is one of the four electrolytes that could be used with the hydroxide ion (O.H.-). One drawback of alkaline electrolytes is parasitic self corrosion that can occur at the aluminum anode. Corrosion can be combatted with alloys can be used, such as

AA5052 which contains Magnesium, Manganese, Zinc, and Aluminum. The electrolyte can also be modified to help combat corrosion. And lastly, corrosion inhibitors such as zinc oxide (ZnO) can be used[13].

2.4 Metal Selection

Aluminum has a high energy density; however, the theoretical energy density is much greater than the actual. When comparing Al-air batteries to other metal-air batteries, a number of advantages can be found. First, they are quick to refuel, taking minutes rather than hours. Second, they are inexpensive due in part to their high earth abundance. Lastly, not only is aluminum transportation and storage easier than with other fuels, but it is also safer to handle than lithium-based batteries[10].

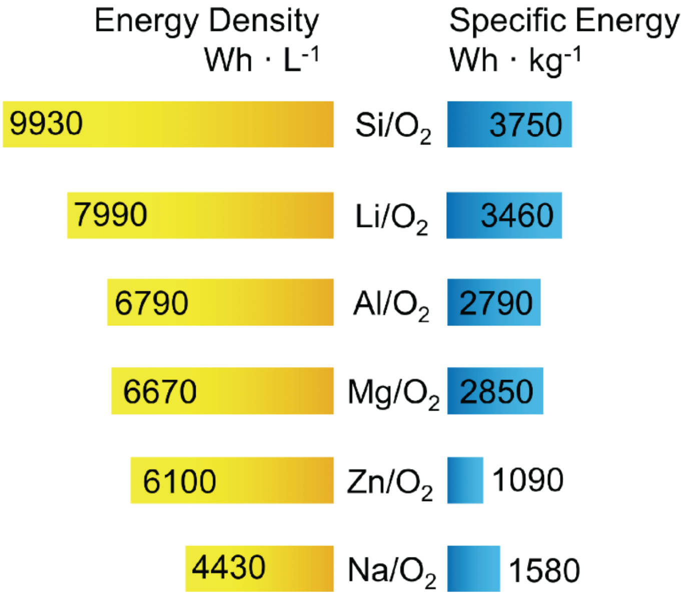


Figure 6: energy density and specific energy of common metal oxides Image adapted from Buckingham et al. [9]

As can be seen in Figure 6 above, aluminum has the third-highest energy density and fourth-highest specific energy of common metals for metal-air batteries.

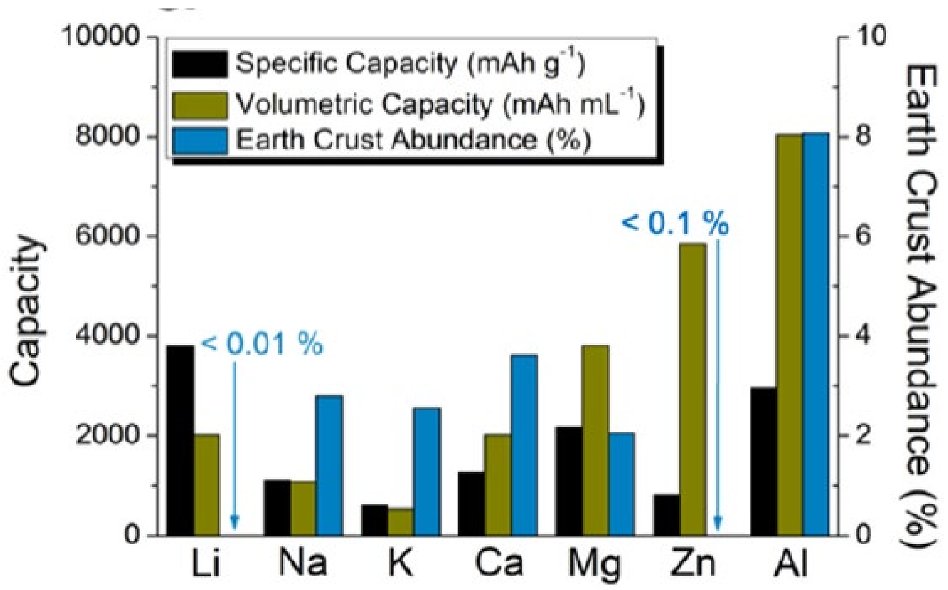


Figure 7: specific capacity, volumetric capacity, and earth abundance of common metals for batteries Image adapted from Clark et al. [14]

Aluminum has the highest earth abundance, highest volumetric capacity, and second-highest specific capacity of common battery metals, making it a great choice, as can be seen from Figure 7 above. The combination of high abundance and high energy density makes aluminum a superior choice over lithium with its inferior earth abundance.

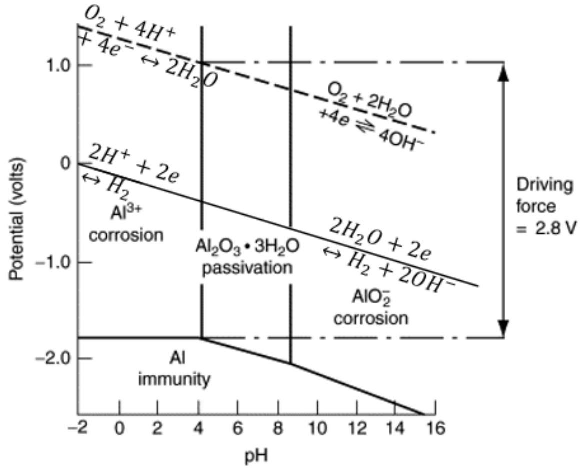


Figure 8: Aluminum Pourbaix Diagram

In order to speak to the significance of the Pourbaix diagram, it is essential to first understand how to read a Pourbaix diagram. The trapezoidal area labeled Al immunity represents the conditions at which aluminum will be solid and will not corrode. The area beneath the top dotted line and to the left of the leftmost vertical line is where aluminum is corroded to Al3+. To the right of the rightmost line, vertical, is where aluminum is corroded to AlO_2^- . The area between the two lines labeled passivation is where a layer of aluminum oxide forms on aluminum preventing corrosion which is necessary for the cell to function. This oxide film was discussed previously, and it is a primary reason for using an alkaline electrolyte over a neutral one.

3 Theory

One major potential expansion of metal-air batteries is high-pressure fuel cell operation. In this mode, we propose concentrating the oxygen feed to increase solubility, which raises the thermodynamic potential of the cell and simultaneously increases the reaction kinetics of the ORR. This theory is explored here from a fundamental thermodynamic driving force (Nernst) then kinetic (Butler-Volmer) perspectives:

Oxygen reduction half-reaction occurring at the cathode is below.

$$\mathrm{O_2 + 2H_2O + 4e^- \rightarrow 4OH^-};\, \Phi^{o}_{r,0} = 0.401(\mathrm{V});\ \Delta G^{0}_{r} = -155\left(\frac{kJ}{mol}\right)$$

In the above reaction $\Phi_{r,0}$ is the potential and ΔG^{0}_{r} is the Gibbs free energy.

3.1 Nernst equation:

The Nernst equation defines the relationship between cell potential to standard potential and to the concentration of the electrochemical reaction. It relates the effective concentrations of the components of a cell reaction to the standard cell potential. Since we are operating with a fuel cell, the Nernst equation was used. It is also an equation that can be used to calculate the cell potential at any moment during a reaction at conditions other than the standard state, which is useful for modeling. In the corrosion process occurring within the cell because of the electrochemical reaction, the equation is in the construction of Pourbaix diagrams, similarly shown in Figure 10. The first of the following equations is the Nernst equations and the subsequent equations are the derivation of the change in entropy.

$$\Phi_{r,0} = \Phi^{o}_{r,0,T^o} - \frac{\Delta S^{o}_{r}}{\nu_{re\_}F}(T - T^o) + \left(\frac{RT}{\nu_{re\_}F}\right)\ln Q_r$$

$$\Delta S_r^0 = S_{OH^-}^0 - \left(S_{O_2}^0 + S_{H_2O}^0\right) = S_{OH^-}^0 - (-205.0 - 69.9)$$

$$\Delta G_r = \Delta G_r^0 + RTln(Q_r)$$

$$\Delta G_r = \Delta H_r - T\Delta S$$

$$\Delta H_r = H_{OH^-}^0 - \left(H_{O_2}^0 + H_{H_2O}^0\right) = -230.0 - (0 - 241.8) = 11.8\left(\frac{kJ}{mol}\right)$$

Utilizing the Nernst equation and the derivations of thermodynamic properties is required to understand the effect of oxygen pressure for the cell potential. Since the cell will have an increase in pressure and the volume where the reaction occurs remains constant, it is expected that temperature should rise due to the proportional relationship it has with pressure.

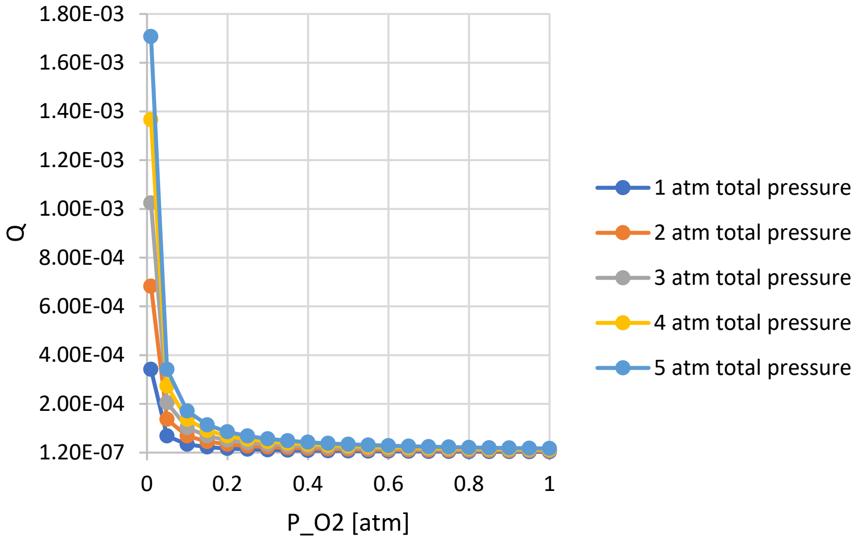


Figure 9: Reaction Quotient vs Partial Pressure of Oxygen

$$Q_r = \frac{a_{OH^-}^4}{a_{O_2} a_{H_2O}^2}$$

$$pH + pOH = 14 \rightarrow pH = 14 - pOH$$

$$[OH^-] = 10^{-pOH}$$

$$a_{O_2} = \gamma_{O_2} x_{O_2} = \gamma_{O2}\left(K_H\, y_{O_2}\right) = \gamma_{O_2} K_{O_2} \frac{P_{O_2}}{P_{total}}$$

$$a_{O_2} = H_{cc} \frac{P_{O_2}}{P_{total}}$$

$$a_{OH^-} = \frac{c_{OH}}{c}$$

$$a_{H_2O} = \frac{c_{H_2O}}{c}$$

In the above figure, the effect of partial pressure of oxygen and total pressure on the reaction quotient can be seen. Based on this model, we would expect the reaction quotient to increase with partial pressure pushing the reaction towards the products and increasing the efficacy of the reaction. So the resulting polarization curve should have a shallower, leveled slope and a later drop-off. The evaluated sample calculations for constructing this graph are in the appendix while the basic equations used are above.

3.2 Butler-Volmer equation:

$$i_r = i_{r,0}\left(1 - \frac{i_r}{i_{r,L}}\right)\left[\exp\left(\frac{\overrightarrow{a_r} F \eta_{r,\alpha}}{RT}\right) - \exp\left(-\frac{\overleftarrow{\alpha_r} F \eta_{r,\alpha}}{RT}\right)\right] (A\ cm^{-2}\ ECSA)$$

The Butler-Volmer equation states that the difference between the bulk electrolyte and electrode dictates the electrical current that passes through the electrode if the reaction is a redox reaction and unimolecular because both the anodic and cathodic reactions happen at the same electrode. Although it is not strictly true that the anodic and cathodic reactions are happening at the same electrode, the assumption must be made that this equation can be applied essential to the modeling of the cell.

4 Methodology

4.1 *Materials*

The chemicals used for this experiment were sodium hydroxide and hydrochloric acid was used for neutralizing basic waste. The use of glassware was also incorporated, and the glassware used was as follows: 250 mL vacuum flask, 2000 mL beaker. Other materials such as rubber stopper, stir bar, stir, and hot plate, 1/4” vinyl tubing, peristaltic pump, two power supplies, 12-volt motor, and an electronic load were all used as well. The primary software used was FuelCell by Scribner, while additional software includes Microsoft Excel, Microsoft Visio, and Microsoft Word.

4.2 *Cell Assembly*

In order to begin testing for a trial, there was a specific protocol we followed for assembly and disassembly. We first began by acquiring all materials that are required for both the electrochemical reaction and for the functioning of the cell itself. The following schematic shows the cell materials we used to assemble the cell.

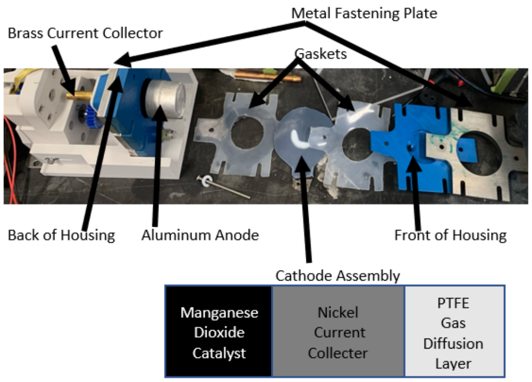


Figure 10: Exploded view of the R&DTC

As shared previously, this schematic shows the cell assembly and all its components. We began by collecting the weight of the aluminum anode to see the corrosion difference in weight once the trial was complete. This anode is placed in the back of the housing, where a motor is also attached. This motor is used to allow for the aluminum disc to spin with the help of a gear attached to the brass collector. The front of the housing consisted of multiple parts that allowed for the stability of the cell and for current collection. We proceeded to attach a plastic gasket following the anode for the purpose of creating space between the anode and the cathode. The cathode was placed after this gasket which consisted of a three-part assembly on its own. The cathode material provided included the catalyst, current collection material, and gas diffusion layer. Gaskets played an important role in the functionality of the cell as a whole because they prevented it. Short-circuiting was prevented by inserting the aluminum anode 3 mm past flush with the housing; this also provided stability for the electrochemical reaction to occur along with data accurate data collection. The components were then sealed with the front of housing materials, and we proceeded to run trials after assembly.

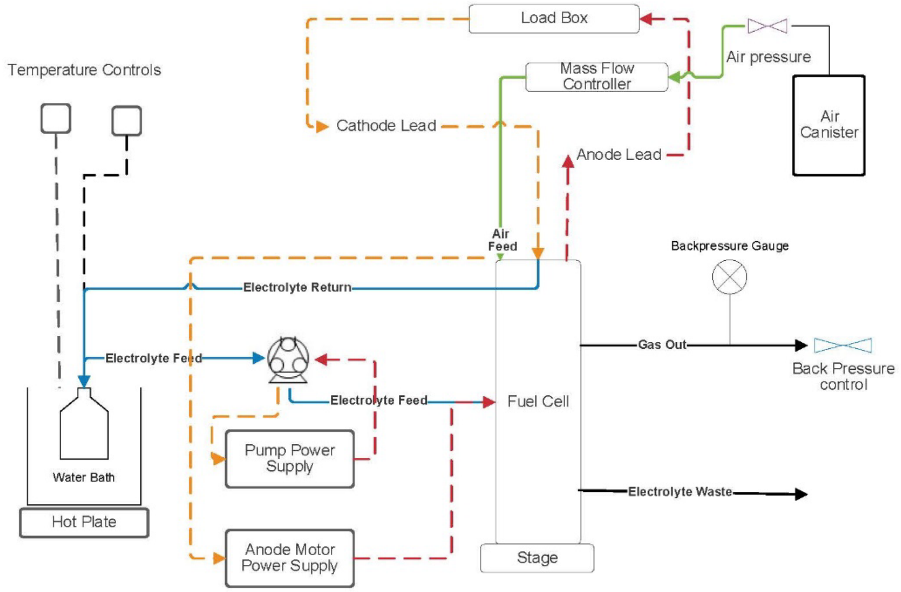


Figure 11: Schematic of test end

Figure 6 shows the schematic of the entire test set up with the cell being considered as only a single component.

4.3 Polarization Performance

A constant current is drawn, and then the resulting voltage is recorded after stabilization which takes one to two minutes to construct a polarization curve. Starting at a current of zero and going up to a current density of $200\frac{mA}{cm^2}$. The current density is obtained by dividing the current by the surface area of the aluminum anode, which is $20.25cm^2$.

The battery was first trialed at ambient air to establish. The process began by sampling the weight of the aluminum anode. We did this by removing the aluminum from the bronze rod and recording the weight after sanding the anode. In order to get accurate results and make sure the aluminum was reacting with the Sodium hydroxide solution, we proceeded to sand the aluminum anode. This anode was then adjusted back into the system, ready for our trial.

The next step was to prepare the electrolyte solution, which consisted of sodium hydroxide. The concentration of this solution was four molars to ensure the reactions occurred. For our first trial, we used 32 g with a water volume of 200 mL. This was because the molar mass of sodium hydroxide is approximately 40 g/mol, and for a 1 L solution, we would need 4 moles, but for 250 mL (1/4)L, we only need one mol. However, our was 200 mL, not 250 mL and 200 mL is 80% of 250 mL, so 80% of 40g is 32g.

Once we had set up the proper solution, it was time to prepare the system for the trials. We adjusted the motor voltage to get a constant rpm and the voltage of the pump to get a flow rate for the trial. Data was collected by entering the proper parameters were entered, and the scan button was pressed in the load equipment. The data was then found in the file the program saved it to and saved to a flash drive. The data was then plotted in excel to obtain a polarization curve.

4.4 Safety

4 Molar sodium hydroxide is alkaline and therefore highly corrosive for this reason, nitrile gloves and safety glasses were worn at all times. Once trials were finished, we disposed of the aluminum hydroxide into a waste container. The procedure following when the waste container was full consisted of neutralization for safe disposal. We needed to use a strong acid, so we decided to use highly concentrated HCl; this allowed less acid to be used in neutralization for the volume we had of the waste. pH paper was used to confirm a neutral pH safe for drain disposal. Once neutralized within the safe disposal pH range of 6.5 to 11.5, the beaker was drained into the sink and washed with water.

Through experimentation and the cleaning of equipment, a large amount of alkaline waste was produced. The problem arises with disposing of this waste. Unless there are other hazardous contaminants, an acidic or basic aqueous solution can be neutralized using a base or acid respectively. Because of the alkaline nature of the waste at a pH of 14 or higher, acid was used in this instance, 6 molar hydrochloric acid. The ratio of neutralization was found to be about 230 mL of waste to 26 mL of 6 M HCl. This was then scaled up to 1150 mL waste and 200 mL 6 M HCl. Neutral waste with a pH between 6.5 and 11.5 can be poured down the sink drain.

For electrical safety, the electrical leads were only handled when the electronic load was off, and the cell had no electrolyte. All exposed metal of the leads was wrapped in electrical tape.

5 Results

Throughout the journey with battery testing, there were multiple results encountered along the way. In the first trial, the resulting polarization curve was not desirable since the motor was operating in the wrong direction. This caused results like greater current density with lower voltage over time. The voltage drop that occurred is due to the impendence load from the current drawn. After analyzing this setback, testing was conducted by running the battery taking into account variables that were not considered before, such as external factors. With multiple trials and error testing to receive a proper polarization curve, desirable results were eventually achieved.

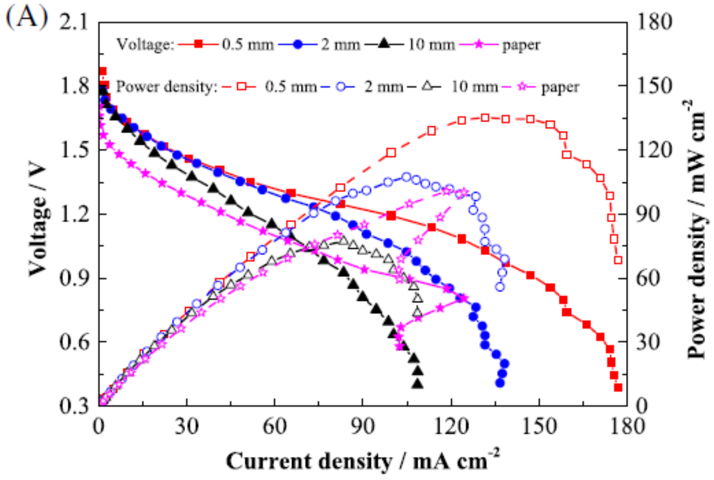


Figure 12: Aluminum air battery polarization curve image adapted from Wen et al. [10]

The Voltage range was quite similar, however. Following this trial, the focus was on ways to find what was flawed, and another ambient air trial was conducted to achieve better results. This included reevaluating how the cell is assembled, using different loads for measuring current density, and upgrading faulty equipment.

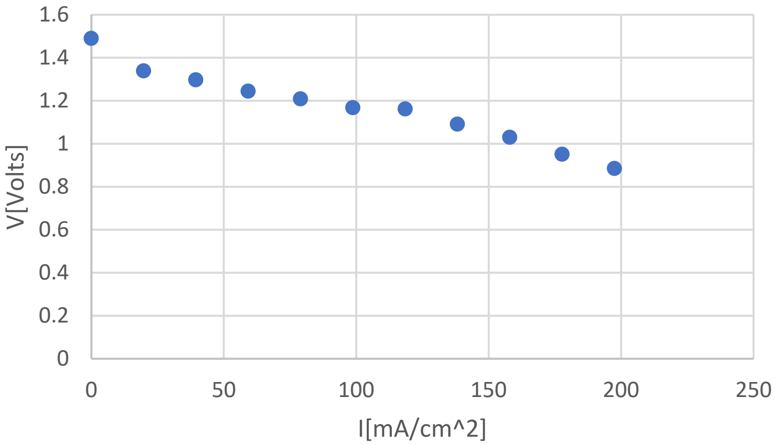


Figure 13: Polarization Curve, 32.1126 g of Sodium Hydroxide, atmospheric pressure, anode weight 178.219 g

The following trial consisted of a better polarization curve that met the standard of data that was desired. This plot shows voltage over current density, operating at a constant current of .4 A. The open-circuit voltage was measured to be 1.46 Volts, and the ohmic loss of the cell was visible through the linear drop-off. This is represented by the voltage drop-off due to resistance to the flow of ions in the electrolyte and electrons through the cell hardware and various connections. The voltage drop and the current density are proportional so that we can reference ohmic loss after this successful ambient air trial. Following this trial, testing of the cell under conditions of varied pressures was executed.

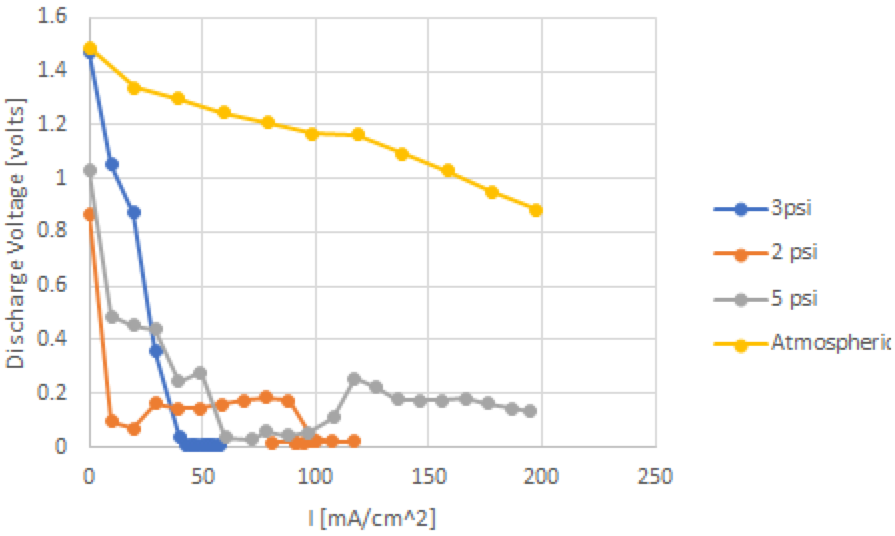


Figure 14: Polarization curve at atmospheric pressure, 2 psi, 3 psi, and 5 psi

By testing the battery with varied air pressure conditions, it was noticed that a drastic difference in results took place. Prior to testing, there were expected outcomes for the polarization curve to be less linear with a similar open-circuit voltage and longer due to how higher pressure affects solubility and other kinetic law factors. As defined in Henry's law, it is expected that solubility is to be higher, which results in a higher concentration. Higher concentration would mean the flux would be faster, as defined in Fick's law, along with faster kinetics. Instead, the data depicts that there may have been some faulty equipment within the cell or equipment management. Due to pressure increasing, it's possible that the housing of the cell may have been exposed to stress that results in unwarranted leaks in the system. Another problem could be due to the airflow from the backpressure regulator. Restricted airflow may have caused nitrogen to build up to severely limit the efficiency of the cell, resulting in polarization curve variance. The ambient air polarization curve is shown as a way of comparing the data we obtained from gas trials.

6 Discussion

The purpose of this paper is to investigate the efficacy of aluminum-air batteries and the effect of increased gas feed pressure. In theory, the increased pressure should lead to increased particle collisions and therefore increased consumption of oxygen; however, the experimental results imply a decreased oxygen consumption. If additional oxygen was available and consumed, the polarization curve would be more level and higher for longer before dropping off at the end with the same open-circuit voltage. Instead, there was an immediate drop-off in voltage as the current was drawn and a lower open-circuit voltage. A possible cause of this decreased voltage is too low of an outlet gas flowrate, causing an accumulation of nitrogen and a lack of oxygen availability. As can be seen in Figure 11, which graphs the reaction quotient against total pressure and partial pressure of oxygen, as the pressure increases, so do the reaction quotient. As the reaction quotient increases, the equilibrium is pushed towards the products of the reaction. If more time was available, the next steps would be to test the cell at the same pressures with an increased outlet flow rate to prevent nitrogen accumulation.

The best results obtained had an open-circuit voltage of 1.49 volts and a current density range of 0 to 197.53 mA/cm^2. The final voltage at 198 mA/cm^2 was 0.885 volts. The current density range is almost identical to that in the polarization curve in Figure 12.

7 Conclusion

Aluminum air batteries showed to be a functional form of energy, although there were a lot of setbacks in the way experiments were conducted. By witnessing the consumption of aluminum and the voltage output of the electrochemistry occurring, there is great benefit in further researching this technology and overcoming experimental challenges. The demand for fuel alternatives is important. When considering where these batteries will thrive most, they will be as power reserves for any homes or commercial areas. Providing a backup power alternative that is carbon neutral is a step in the right direction when it comes to reducing the output of toxic greenhouse gases as much as possible.

After experimenting with the cell, it was difficult to gauge an accurate understanding of how the cell would operate under different concentrations of air beyond altering the pressure of air. Due to limitations, it is recommended that future trials are to be conducted with a base pressure and gradually increase this pressure with close monitoring of the corresponding polarization curve. As results consisted of errors, future successful trials should be focused on proper kinetics where the polarization curve highlights them. This experimental data serves as a good source of trial and error to alter operating conditions that work best.

From a theoretical perspective, it can be predicted that the voltage should increase the slope of the polarization curve, and as a result, it should be less steep as the partial pressure of oxygen increases and the overall gas pressure increases. When conducting theoretical modeling, it is important to establish a guideline of information to refer data to. It was also required to incorporate theory as a reference to the results since it gives a better description of where issues may have come up when operating the fuel cell.

Finally, it must be considered what exactly will fuels industry look like in the future and will aluminum batteries be efficient enough to play a significant role. We can conclude that this new technology has a bright future with further testing that leads to appropriate scale-up methods. As with many new technological advancements, there come many hurdles when testing, but one thing is for certain, and that is that Aluminum air batteries are here to stay.

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Appendix 1: Sample Calculations

Reaction Quotient vs. Partial Pressure of Oxygen

$$Q_r = \frac{a_{OH^-}^4}{a_{O_2} a_{H_2O}^2} = \frac{\left(\frac{1}{55}\right)^4}{0.032\left(\frac{P_{O_2}}{P_{total}}\right)}$$

$$pH = 14 - pOH = 14 \rightarrow pOH = 0$$

$$[OH^-] = 10^{-pOH} = 1\ M$$

$$[H_2O] = 55\ M \approx c$$

$$a_{O_2} = \gamma_{O_2} x_{O_2} = \gamma_{O2}\left(K_H\, y_{O_2}\right) = \gamma_{O_2} K_{O_2} \frac{P_{O_2}}{P_{total}}$$

$$a_{O_2} = H_{cc} \frac{P_{O_2}}{P_{total}} = 0.032\left(\frac{P_{O_2}}{P_{total}}\right)$$

$$a_{OH^-} = \frac{c_{OH}}{c} = \frac{1}{55}$$

$$a_{H_2O} = \frac{c_{H_2O}}{c} = \frac{55}{55} = 1$$

Appendix 2: Figures and Tables

Polarization Curves

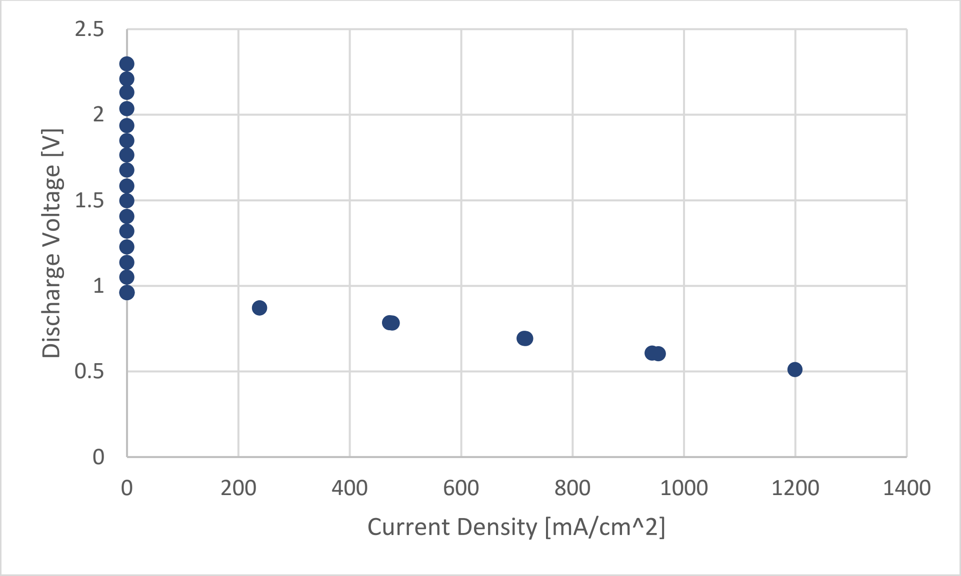

Figure 15: December 8th, 2021, full scan

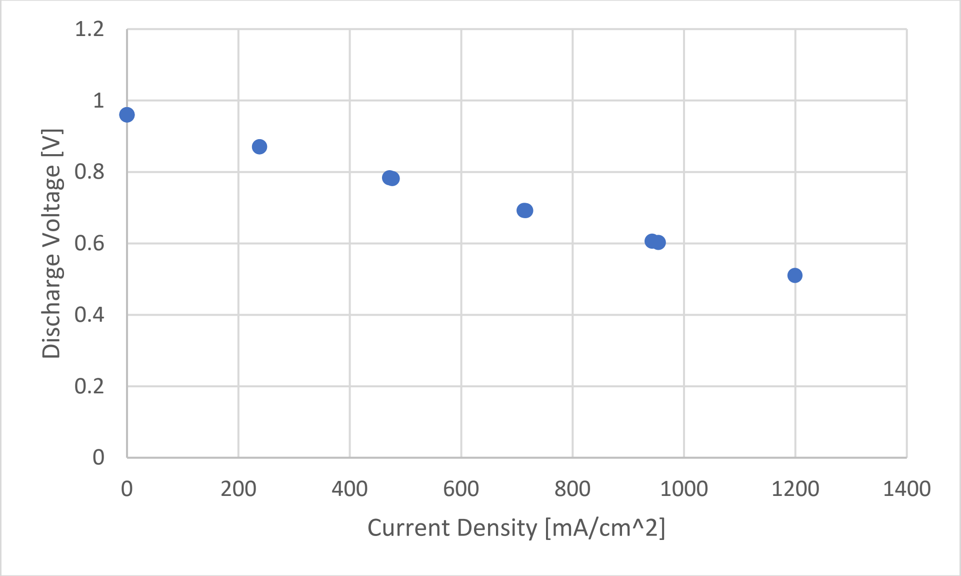

Figure 16: December 8th, 2021, modified polarization curve

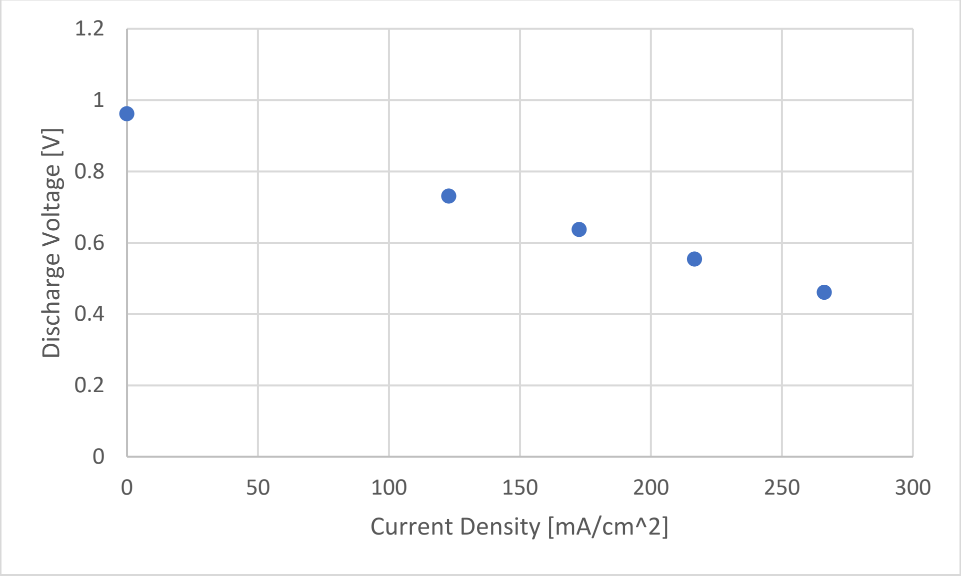

Figure 17: Potential December 17th Polarization Curve

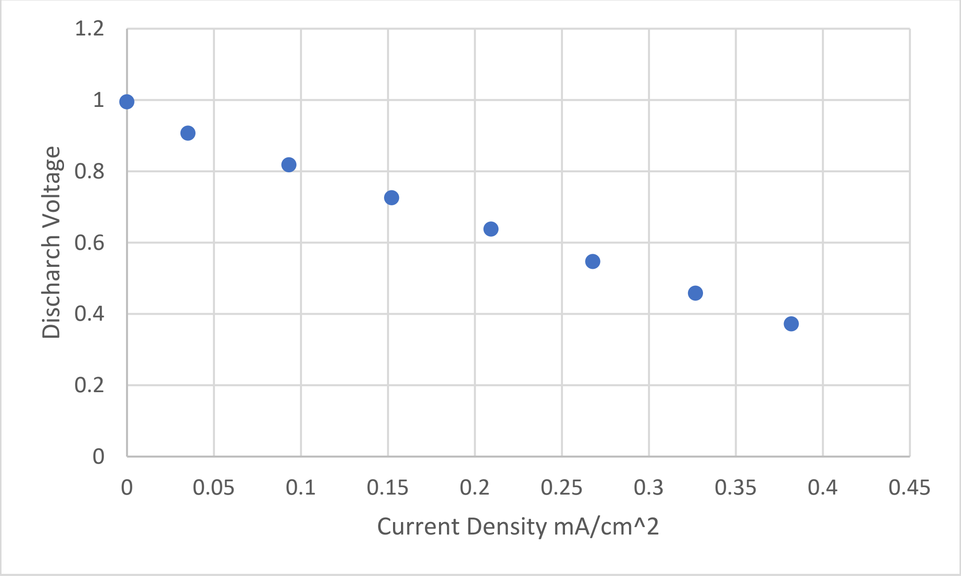

Figure 18: Third trial. 32.28038 g of NaOH were used. Once stabilized, the solution had a temperature of 45 degrees Celsius and a water bath temperature of 50 degrees Celsius. The trial duration was 1:24. An electrolyte flow rate of 1.9 mL/s and a motor speed of 263 rpm

Concentration calculations

$$m_{NaOH} = 250\,mL \times \frac{4\,mol}{1000\,mL} \times \frac{40\,g}{mol} = 32\,g\,NaOH$$

Calibration Curves

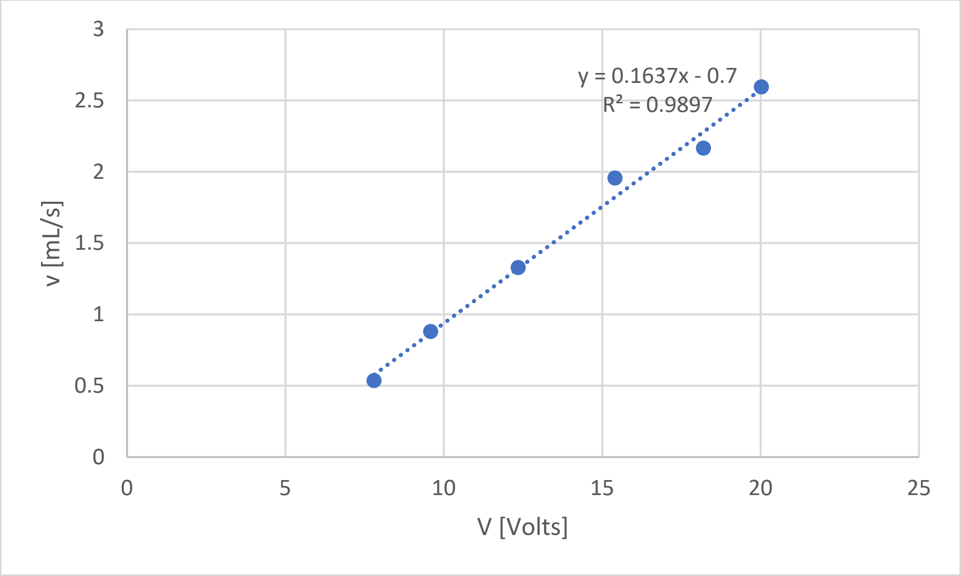

Figure 19: peristaltic pump calibration curve

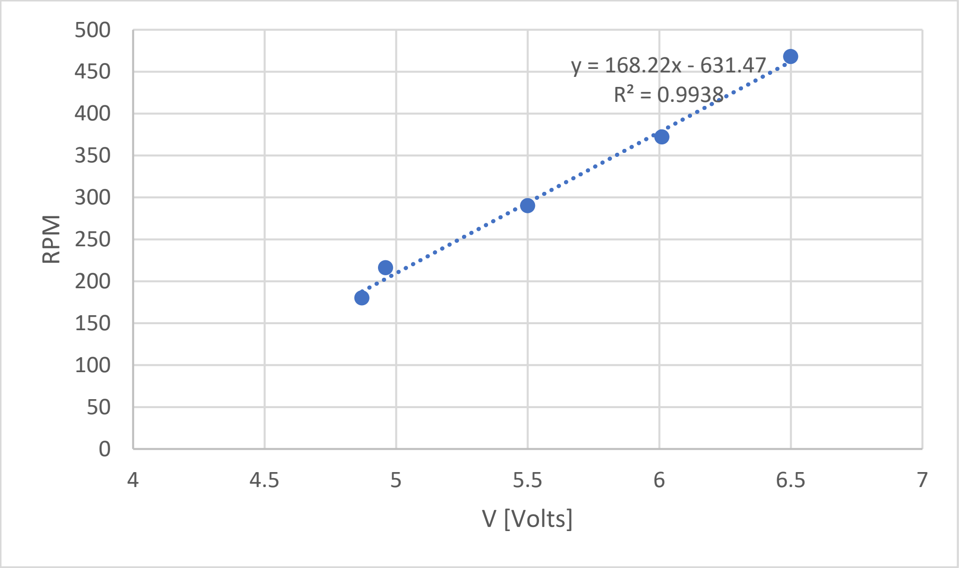

Figure 20: anode motor calibration curve