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Article

Developing a portable, reusable, and inexpensive magnesium-air fuel cell

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SUMMARY

Global warming is becoming an increasingly bigger problem, and it is important that we work to find alternative sources of electricity. The goal of this project was to determine what metal is best for use in a portable and reusable metal-air fuel cell. The three metals tested for use in a metal-air fuel cell were aluminum, zinc, and magnesium. These metals were selected due to their high theoretical voltage, faradic capacity, and widespread usage as sacrificial anodes in the naval shipbuilding industry. We created a design for a portable and reusable fuel cell frame in Google Sketchup and then 3D-printed. For each of the three types of metal, we tested the fuel cell three times over a total span of six hours. Every hour, we recorded the voltage and current produced by the fuel cell. After the three trials, we averaged the data at every measurement point. Our data shows that magnesium produced the greatest voltage and current. On average, magnesium produced 197% more voltage and 740% more current than zinc. Additionally, magnesium produced a voltage 280% greater and a current 1593% greater than aluminum during the six hours of testing. This project indicates that magnesium produces the greatest voltage and current in a metal-air fuel cell, as well as the viability of magnesium-air fuel cells. Due to their long shelf life and self-sufficiency, they can be used by emergency response teams and in developing areas.

INTRODUCTION

A metal-air fuel cell generates power through a redox reaction. Like all fuel cells, a metal-air fuel cell possesses a positive electrode, the anode, a negative electrode, called the cathode, and an electrolytic substance separating the two electrodes (1). The redox reaction oxidizes the metal, and reduces oxygen and water vapor in the atmosphere. The freed electrons from the metal then generate an electrical current and can be used to power an appliance. The metal is the anode, while the surrounding air acts as the cathode (5). In this project, carbon electrode fabric is used to enable the diffusion of oxygen and water vapor into the fuel cell (6). The reduced hydroxides and metal then react to form a metal oxide byproduct. The voltage produced by a metal-air fuel cell is primarily dependent on its reactivity. More reactive metals tend to produce greater voltages.

The metals most commonly used in metal-air batteries are aluminum and zinc. These metals are popular because they are relatively reactive yet remain stable when not in use (5). Magnesium is another metal that displays these qualities. Further research shows that magnesium possesses a variety of desirable traits that make it suitable for use in a metal-air fuel cell, such as a high theoretical voltage and faradic capacity (**Table 1**). Magnesium is the least dense of the three metals and also produces the greatest theoretical voltage. The faradic capacity of magnesium comes close to that of aluminum; however; aluminum's low voltage makes it less viable to use compared to magnesium. The primary barrier that prevents magnesium's use as an anode material in batteries is a difficulty in identifying a long-lasting electrolytic substance to use in conjunction with it. However, in a fuel cell, which is replenishable, magnesium becomes a viable option because both the electrolyte and metal can be replaced.

Additionally, the naval shipbuilding industry uses sacrificial anodes to protect metal parts that are submerged underwater. Sacrificial anodes function by being more reactive than the metal that they are protecting. When the part is submerged, the saltwater acts as an electrolyte, and the more reactive sacrificial anode is corroded away, protecting the part itself. The three most commonly used metals for sacrificial anodes are aluminum, zinc, and magnesium. This is due to their relatively high reactivity compared to the metal they are protecting (**Figure 1, Table 1**) (4). As a result, we expected these metals would produce the greatest voltage in a metal-air fuel cell.

The goal of this project, therefore, was to determine which type of metal produces the greatest voltage and current in a metal-air fuel cell. Based on the theoretical voltage and highest reactivity of magnesium out of the three metals, we hypothesized that magnesium would produce the greatest voltage and current in a metal-air fuel cell.

RESULTS

Given that the goal of this project was to determine which metal is the most viable for use in a metal-air fuel cell, we first tested the voltage and current the fuel cell generated for each candidate metal. The metal-air fuel cell consisted of a fuel cell frame, a saltwater electrolyte, a carbon fabric cathode and a metal anode. All three metals were tested over a period of six hours, with three trials per metal. All three trials were conducted in the same environment with the same setup. We

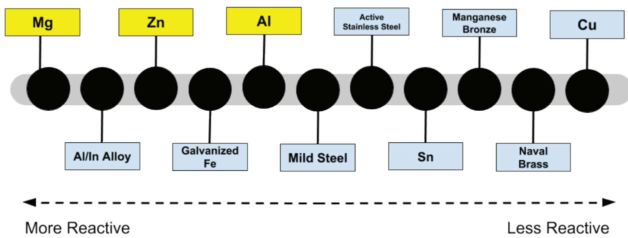

Figure 1: Reactivity series of various metals.

	Mg	Al	Zn
Density (g/cm^3)	1.74	2.70	7.14
Faradic capacity (Ah/g)	2.21	2.98	0.82
Theoretical voltage (V)	2.93	1.20	1.65

Table 1: Comparison between the density, faradic capacity, and theoretical voltage of magnesium, aluminum, and zinc (5).

visualized the recorded data with a line graph for each trial (**Figure 2A-C, 3A-C**). Then, we averaged the voltage and current output at each measurement for each metal, and we plotted each average on another line graph (**Figures 2D, 3D**).

The results of the experiment show that magnesium consistently produced a far greater voltage and current than both zinc and aluminum. In terms of voltage, magnesium produced an average of 4.04 volts after 6 hours, compared to 2.16 volts for zinc and 1.5 volts for aluminum (**Figure 2D**). This equates to a 197% difference in voltage between zinc and magnesium, and a 280% difference between aluminum and magnesium. Magnesium also produced far more current than zinc and aluminum, averaging 646.67 mA at the 6-hour mark, compared to 105.37 mA for zinc and 53.03 mA for aluminum (**Figure 3D**). Magnesium consistently outperformed both zinc and aluminum by a wide margin.

The average standard deviation of the voltage produced by magnesium was 0.05, which is lower than that of both zinc and aluminum (0.15 and 0.19, respectively) (**Table 2**). This result shows that magnesium is also able to produce a more consistent voltage. The average standard deviation of the current produced by the magnesium was 24.89, compared with 1.94 and 1.83 for zinc and aluminum, respectively (**Table 2**).

We also tested the magnesium-air fuel cell's ability to charge a smartphone using an Adafruit PowerBoost. We connected the fuel cell to the PowerBoost using alligator wires, then plugged in a standard USB charging cable into the PowerBoost and a phone. We found that we were successfully able to charge the smartphone.

DISCUSSION

The results of this experiment show that magnesium is the best metal for use in a metal-air fuel cell. Averaging 4.04 V and 646.67 mA over the six hours of testing across three trials, not only can magnesium-air fuel cells produce electricity, they produce enough to be a viable energy source. The difference in the average current standard deviation of magnesium can be attributed to the fact that magnesium produced far more current than the other two test metals. If the current produced by the zinc and aluminum were to increase by using more metal, we predict that the standard deviation would also scale up to a value comparable to that of magnesium. In our testing, the magnesium-air fuel cell produced enough electricity to charge a smartphone as well. Additionally, metal-air fuel cells possess a very long shelf life and simply require saltwater

	Mg	Al	Zn
Avg voltage at 6 hours (V)	4.04	1.50	2.16
Avg current at 6 hours (mA)	646.67	53.03	105.37
Avg voltage std deviation (V)	0.05	0.19	0.15
Avg current std deviation (mA)	24.89	1.94	1.83

Table 2: Average voltage and current produced over six hours for all three metals. Values are reflective of three trials.

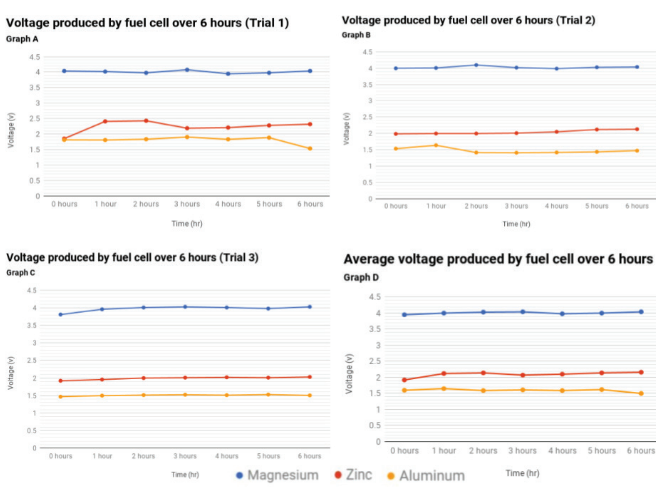

Figure 2: Voltage produced by the three metals over the first 6 hours of the first (A), second (B), and third (C) trials, as well as the average voltage produced by each metal at each measurement (D).

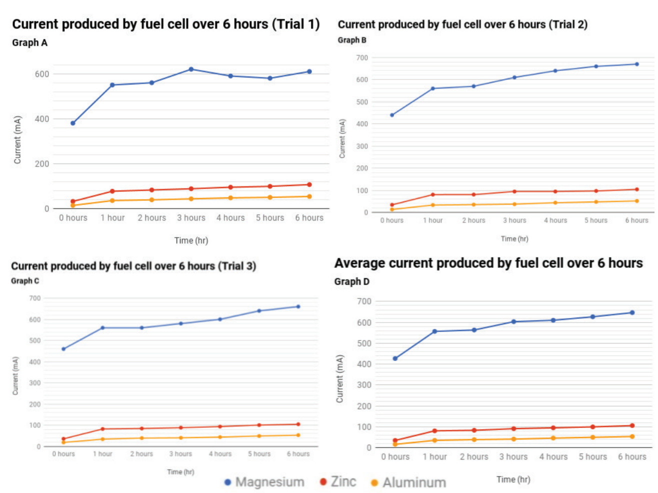

Figure 3: Current produced by the three metals over the first 6 hours of the first (A), second (B), and third (C) trials, as well as the average current produced by each metal at each measurement (D).

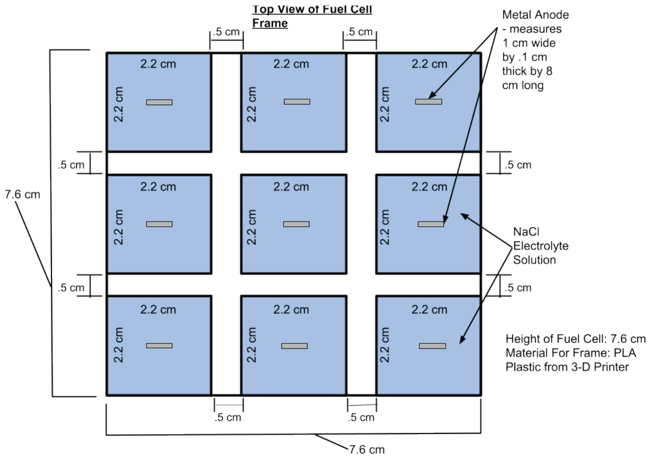

Figure 4: Top view of the design of the metal-air fuel cell frame used in the experiment.

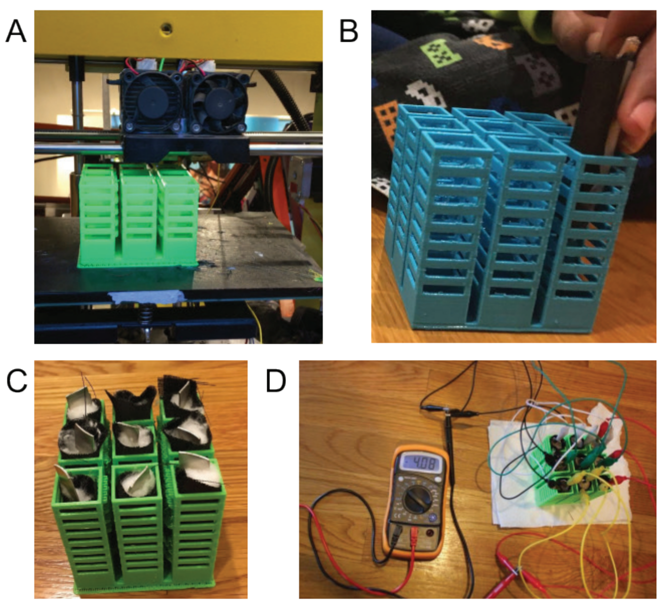

Figure 5: Assembly and testing of a reusable fuel cell. A: A fuel cell frame being 3D-printed. B: A completed set (magnesium anode wrapped with cotton and carbon fabric) being inserted into a subcell of a fuel cell frame. C: A fuel cell frame with all subcells filled but not yet wired. D: A running fuel cell whose voltage output is being measured. The fuel cell is fully wired, and the alligator clips at the end of each "row" of subcells are connected to the multimeter's leads.

	Mg	Al	Zn
9 anode metal strips	$3.15	$1.16	$3.41
9 carbon cathode pieces	$34.47	$34.47	$34.47
3D-printed fuel cell frame	$10.00	$10.00	$10.00
Total	**$47.62**	**$45.63**	**$47.88**

Table 3: Component cost of the magnesium, aluminum, and zinc fuel cells. The total cost is the sum of each individual part of the fuel cell – the anode, cathode, and frame. Cost of water and salt was marginal and is therefore not represented in the table.

to begin the reaction to produce electricity. We attribute the results of this experiment to magnesium's highest reactivity and theoretical voltage out of the three metals tested (**Figure 1, Table 1**).

A breakdown of the costs of the fuel cell used in this project shows that a complete fuel cell was constructed for under $50 (**Table 3**). We calculated the cost of each material in the fuel cell based on the amount of the material that was actually used in the fuel cell. However, since the materials were purchased in small amounts for the purpose of experimentation, costs can be reduced if they are purchased in greater quantity. If cost-cutting factors are taken into account, we estimate that these fuel cells can be constructed for less than $15, with anodes able to be replaced for less than $2 every time.

The applications of a portable, reusable, and inexpensive fuel cell such as the one tested in this experiment are far-reaching. For example, remote areas that are not connected to a power grid could power essential appliances using these fuel cells. Emergency responses teams who require quick access to electricity can also use this fuel cell to generate power. Magnesium-air and other metal-air fuel cells can even be implemented in suburban and urban environments as large units for powering individual houses or apartment complexes. For future research, this project could be further advanced from either an engineering or scientific standpoint. The fuel cell frame currently uses bulky alligator wires for the purpose of testing. In the future, we can design a more streamlined frame with a lid that encases all wiring, such that closing the lid over the fuel cell frame will automatically close the circuit. Additionally, companies such as MagPower are developing magnesium-air fuel cell technology with hydrogen inhibitors added to their fuel cells (2). In magnesium-air fuel cells, a variation of the normal reaction causes hydrogen evolution, which leads to the faster corrosion of the anode. By determining effective additives that inhibit hydrogen evolution, the longevity of the fuel cell can be increased.

MATERIALS AND METHODS

Design and construction of a reusable fuel cell frame

In order to be portable, the fuel cell was designed as a cube with side lengths of 7.6 centimeters. Within this cube were 9 subcells, each containing its own anode, cathode, and electrolyte (**Figure 4**). A mockup of the frame was created in Google Sketchup and then 3D-printed (**Figure 5A**).

In order to construct the fuel cells, we cut ELAT carbon electrode fabric (NuVant Systems) into 7.5 centimeter square swatches (nine per fuel cell frame, one per subcell). Then, we cut zinc, aluminum, and magnesium sheet metal into thirty 8 cm by 1 cm pieces. We wrapped one standard cotton ball (CVS brand) around each piece of metal, leaving about 1 cm of room at the top for wiring. We then tightly wrapped the carbon fabric swatch around the cotton and metal piece, forming the internals of one full subcell. We then inserted that set into one of the subcells in the fuel cell frame (Figure 5B). The same was done for all nine subcells (Figure 5C). We then mixed iodized salt (Morton Salt, Inc.) and distilled, bottled water at room temperature until the salt crystals would no longer dissolve in order to create a fully saturated saltwater solution. Using a pipette, we pipetted 15 mL of the saltwater solution onto the cotton of each of the subcells, which then acted as an electrolyte (2, 3). Next, we used alligator clips to wire the fuel cell. We wired three subcells in series, forming three rows of three series-wired subcells. We then wired these rows in parallel to form the fully constructed fuel cell. At this point, the oxidation reaction began, enabling the fuel cell to produce electricity. We took an initial measurement of voltage and current using a multimeter (Figure 5D).

Voltage and current testing

We tested the voltage and current output of the fuel cell using a multimeter for six hours once every hour, at which point the fuel cell was disassembled and set up once again for the next metal. After determining that magnesium was the best metal to use in a metal-air fuel cell, further experimentation was conducted with a PowerBoost (Adafruit) to test whether the fuel cell could produce enough electricity to charge a smartphone. The alligator clips from the fuel cell were wired to the PowerBoost, directly supplying power to the USB port on the PowerBoost unit. A smartphone was attached to the USB port to test whether the fuel cell supplied enough electricity to successfully charge it.

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