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GENE101 & CHE102

Report Four: Fuel Cell Project

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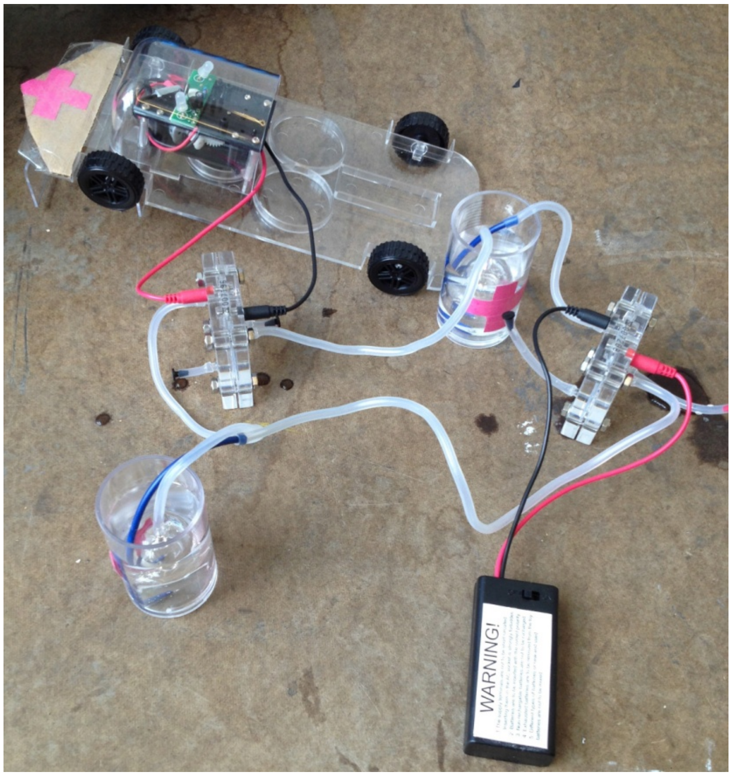

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Cover Letter

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July 20, 2014

Dr. Bill Owen, P.Eng.
Department of Engineering
University of Waterloo
Waterloo, Ontario
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Dear Dr. Owen,

We are pleased to present this report “Report Four: Fuel Cell Project” which was prepared for the GENE 101 course at the University of Waterloo. The purpose of this report is to provide a completed document for *Group 4’s* fuel cell car project.

This report documents the cumulative research, analysis and development done for *Group 4’s* fuel cell car project. It describes the safety hazards associated with the project, and gives a general overview of the chemical processes that take place within a fuel cell. It discusses the definition of the design problem and proposes hypothetical solutions. The corresponding testing, data analysis and relevant calculations are presented. The fuel cell car’s final design meets all of the project’s constraints as specified by the project outline. Further research on the applications and uses of fuel cells in society and other fuel cell related topics are also discussed.

Please contact us if you have any questions or concerns regarding this project.

This report was prepared completely and entirely by the members of *Group 4* and has not received any previous academic credit at this or any other academic institution. We would like to thank Professor Owen and Professor Chan for assisting us during this project. No additional support outside of this context was received for the authoring of this report.

Sincerely,

M Molyneaux JFernandes AHirani Samantha Ward

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Executive Summary

This document encompasses the project work behind two concurrent initiatives. The first initiative, was researching the chemistry, development and application of PEM fuel cell technology in various large and small scale contexts. The second initiative comprises of practical research, development and the application of design process techniques in order to optimize the operation of a small scale, PEM fuel cell powered, vehicle. These initiatives synergize through core concepts of the operation of the PEM fuel cell.

The team was provided with a fuel cell car kit, which contained most of the components needed to run the car as well as a manual that instructed the team on how to charge and run the vehicle. The primary goal was to maximize the run time of an engine using the fuel cell provided alone. The group was given the freedom to modify the vehicle under the gauge of administrator provided constraints. The design constraints stated: the physical dimensions of the car, that the motor's power source must be the fuel cell provided, that changes could not be irreversible and that it must run on gases contained within the collective body of the car.

Various solutions to enhance the car were proposed by the group. Firstly, the increase in water temperature in the fuel cell was predicted to increase proton conductivity across the cell and therefore increase performance. Furthermore, reducing the length of tubes connecting the fuel cell to the gas vessels was hypothesized to decrease the length of time required to charge the fuel cell due to less distance travelled by gas. On the other hand, two solutions were presented that involved modifying the vessels of gas themselves. The first of these hypothesized that replacing the current cylindrical vessels with a Ziploc bag to contain the gas would result in a larger volume of gas stored and therefore a large amount of fuel. The other solution predicted that a larger version of the currently implemented system would be effective for the same reason.

All of the solutions were considered and tested. The final modified product utilized the following solutions: decreasing length of the tubes, re-using the distilled water, removing the plugs to depressurize the fuel cell, testing and using a brand new fuel cell, changing batteries. An improved navigation system is recommended as a future modification of the fuel cell car.

The team congregated up to twice a week and collaborated on the three group reports who's content forms the bulk of this cumulative report. Meetings primarily involved planning and some work, the bulk of the work was done over a shared cloud document accessible live by the entire team at any given time. The group budgeted $15 total for potential expenses such as additional batteries, report binding costs and design resources.

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1 Introduction

This report is a culmination of aspects and information related to hydrogen fuel cell cars. In the ongoing search for scalable, high efficiency and low pollutant solutions for fuel, a new technology emerges. The first fuel cell, which produced electrical energy by combining oxygen and hydrogen, was demonstrated by a Welsh scientist in 1839 [1]. Since then, researchers have been working on scaling the technology for commercial use as an alternative to traditional fossil fuels [1].This project is being studied to further the scientific development of hydrogen fuel cells.

The structure of this report is as follows: firstly, it will discuss the proper handling, safety and precautions of experimenting with hydrogen gas and hydrogen fuel cells. Secondly, it will provide a brief background on the chemistry aspect of the PEM fuel cell. Thirdly, it will list the various restraints and observations associated with the project. Then it will discuss the problems with the group's fuel cell and its proposed solutions. Afterwards, calculations for mathematical and scientific observations for various chemical and electrical questions related to fuel cells will be provided. Finally, this report will include information on the social and environmental impacts of hydrogen as a fuel, as well as other fuel cell technology applications. Fuel cells are a very innovative technology; this report will cover a broad range of information pertaining to them.

2 Safety Hazards

Before starting to work on the fuel cell car, the group needed to ensure that safety would be taken into consideration at all times during its testing and modification. Research was conducted and the group was made aware of the safety concerns associated with working with a fuel cell. The group remained in control and were well aware of all hazards present during testing and for the duration of the project.

The use of hydrogen as a fuel presents many safety concerns, and precautions need to be taken when handling it. One of the primary concerns is its high flammability [2]. To prevent hydrogen from building up in the surrounding air and causing a fire the group worked in a well ventilated room. Additionally, it was ensured that hydrogen was handled in the absence of excess static electricity. The use of alkaline batteries posed several safety hazards that were be taken into consideration when working with the fuel cell car. The group made sure not to short circuit the battery by letting both terminals of the battery touch. This would have caused the battery to overheat leading to a fire [2]. Batteries with the proper voltage for the fuel cell were used to prevent damage to the fuel cell. When the fuel cell was no longer in use the group members disconnected the battery to mitigate the risk of a battery malfunction [3]. Despite the relatively small scale of the fuel cell car, the safety considerations of battery usage and storage, hydrogen flammability and general lab safety were still pertinent. The members who worked with the fuel cell operated carefully and were aware of potential threats associated with the chemical processes that were powering the vehicle at all times.

3 Chemistry Background of a PEM Fuel Cell

The proton exchange membrane (PEM) fuel cell essentially works by splitting hydrogen atoms into their primary constituents — protons and electrons. The proton exchange membrane allows protons to pass over it (see red arrow in Figure 1 below) while the electrons travel through an external circuit (see blue arrow in Figure 1 below), thereby providing direct electrical current to an external load. Finally, the protons and electrons reunite and combine with oxygen to form water [4]. The following paragraphs will address the chemical background as well as the importance of different components and procedures associated with the fuel cell that had to be taken into consideration throughout the design process of this project.

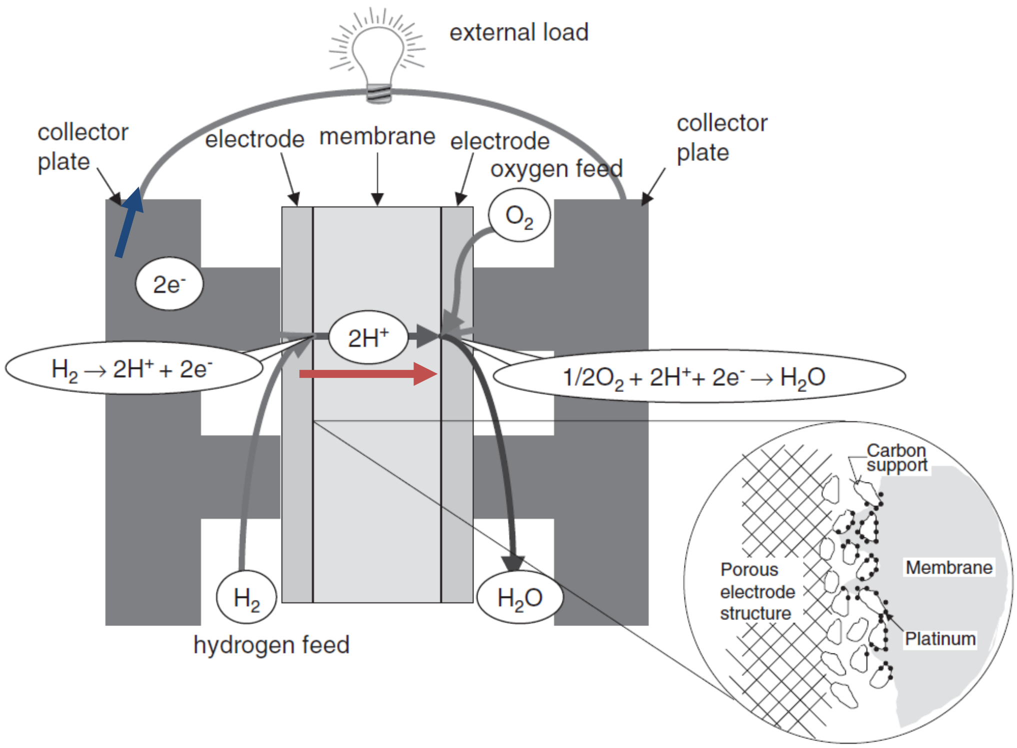

Figure 1. A visual representation of PEM fuel cell operation.

3.1 Importance of fuel cell hydration

In order to maximize the performance of the fuel cell, it is important that the proton-exchange membrane (PEM) is kept hydrated. The PEM is where protons move from the anode of the fuel cell to the cathode. During the transport of protons through the PEM the processes of electro-osmotic drag and back diffusion occur simultaneously as seen in Figure 2 [5]. The water drag occurs with the transport of the protons which carry water molecules with them from the anode to the cathode while back diffusion is the result of a concentration gradient transporting water from the cathode to the anode [6]. These two opposing processes dehydrate the anode which affects the performance of the fuel cell [5]. If the PEM is dry, the performance of the fuel cell will significantly diminish due to a high amount of ionic resistance in the cell [7]. Cell hydration is necessary because it induces a higher conductivity of protons in the PEM increasing the functionality and the overall lifespan of the fuel cell [5].

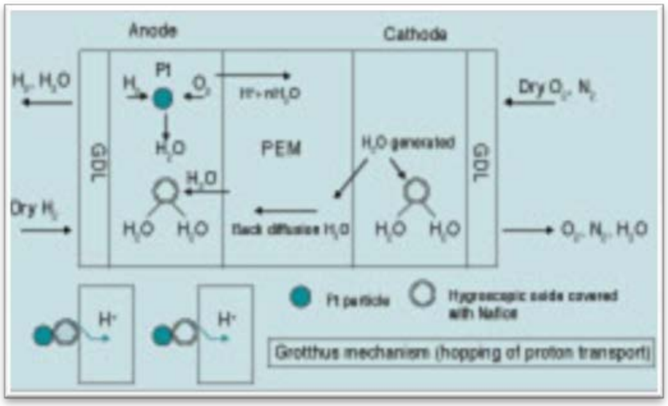

Figure 2. The transport of protons and the electro-osmotic drag and back diffusion of water through the proton-exchange membrane of a fuel cell [5]

3.2 Importance of using distilled water

When working with the fuel cell car, it is essential to only use distilled water rather than tap water. There are multiple types of minerals present in tap water such as calcium and magnesium, that can be harmful to the PEM of the fuel cell and could permanently damage the membrane [8]. Since these minerals are very small, they can easily block the fuel cell preventing it from carrying out its task [9]. If rust begins to appear on the PEM membrane [8], that is an indication that distilled water was not used.

It was important that the group only used distilled water during testing of the fuel cell or it could have permanently damaged the fuel cell. It was also important that the group was aware of the effects of hydrating the PEM fuel cell on its performance. From there the group was able to perform a needs analysis to establish a definition for the design problem and subsequently propose several solutions using their knowledge of the PEM fuel cell.

4 Problem Formulation

4.1 Needs Analysis

Multiple aspects of the fuel cell car needed adjustment in order to meet the project's requirements. The car could not run for a long enough period of time. The car originally ran for a maximum time of 1 minute 15 seconds. The car needed to run for longer than 1 minute 15 seconds. As a result, a method needed to be developed to increase the car's run time.

4.2 Definition of Design Problem

The one major problem with the fuel cell car in its original state was that the vehicle did not run for a long enough period of time.

4.3 Objectives

The original maximum run time for the car was 1 minute 15 seconds. The goal for the car was to stay powered for more than 1 minute 15 seconds because that was its original run time.

4.4 Constraints

There were several constraints associated with the fuel cell car design. The vehicle had to follow safety guidelines while in use. The vehicle also had to fit inside a box 14 cm wide x 24 cm long x 10 cm tall when completely assembled. Irreversible changes could not be made to the various provided components of the fuel cell car. The motor for the car had to be powered by the original fuel cell. The fuel cell had to run strictly on the hydrogen and oxygen gases contained within the car. Lastly, during the evaluated running tests of the fuel cell vehicle, the car could not be physically handled by the group.

5 Proposed Solutions

The group needed to increase the car's run time from a starting point of 1 minute 15 seconds. It was decided that in order to increase the car's run time, the fuel cell would need to become more efficient. The group proposed five hypothetical solutions based on research and reasoning to maximize the run time for the vehicle by increasing the efficiency of the fuel cell. The following proposed ideas were stated as a starting point in the design process.

5.1 Water Temperature Solution

The temperature of the fuel cell impacts the conductivity of the protons through the PEM; as the temperature of the cell increases, the performance of the cell also increases [7]. By adding warmer water to the vessels, the group hypothesized that more water vapour would be produced which would then flow into the PEM and hydrate it. The group planned to take advantage of this by adding hot distilled water to the fuel cell to increase the proton conductivity across the PEM making it run more efficiently and as a result increasing the speed and endurance of the car. The water temperature would be increased by keeping the bottle of distilled water immersed in a container of hot non-distilled water. Then the performance of the car would be tested under different heated water temperatures within reason to determine the temperature that would maximize the car's efficiency in terms of speed and run time.

5.2 Smaller Connecting Tubes Solution

By reducing the length of the tubes connecting the fuel cell to the vessels, the efficiency of the car would be improved along with the length of time the fuel cell could have run for. Having longer connecting tubes would result in the transfer of water taking a longer amount of time than necessary. Since the water in the fuel cell was being transported solely by the tubes, having that greater distance to travel would have affected the overall performance of the car. The drive for the gas flow in the fuel cell is based on the concept of diffusion which was related directly to having shorter connecting tubes. On the other hand, having a higher water level in each of the vessel was related directly to having shorter connecting tubes as well.

Therefore the group hypothesized that shortening the transfer pathway had the potential to reduce the amount of time it would take to charge the fuel cell.

5.3 Ziploc Solution

Another proposed solution was to replace the gas storage vessels with Ziploc bags. This would hypothetically increase the capacity of H_2 and O_2 stored due to the greater volume of the Ziploc bags. If the volume of the stored H_2 and O_2 were increased, more of the gas could be contained, thus increasing the amount of fuel being stored, allowing the car to run for a greater length of time [10]. In addition, since the Ziploc would naturally have a vacuum, the extra weight of water would not have to be added. This would result in less weight carried by the car, meaning it would consume less fuel and be able to travel faster and further. Unlike in the original setup, the Ziploc includes a natural vacuum, therefore eliminating the need for a double wall; the Ziploc bag does not start off with any gas or water in it and therefore does not require a mechanism to replace the contained water with gas.

5.4 Larger Gas Container Solution

Alternatively to the Ziploc solution, a larger version of the implemented gas storage system would be more effective. Storing more gas in bigger containers is clearly beneficial to the fuel cell's run time, since the fuel cell operates on hydrogen and oxygen and thus if more hydrogen and oxygen can be stored then it will run for a longer time. With this approach the group would have to use a taller container composed of a lighter material than the plastic cylinders provided. More specifically, a plastic water bottle. The container would have to be larger than the cylinder, but also lighter, so that once it were filled with water it would still provide a similar level of stability as the plastic cylinders did before, but it would also store more fuel. The fact that they would be lighter means that the car would have required less energy to move a certain distance due to reduced friction with the ground and so, ideally, it would run longer than it did in its original state.

5.5 Re-use Distilled Water Solution

Instead of refilling the vessels and the fuel cell with new distilled after each use, the group hypothesized that it would be more beneficial to re-use the water. The car would be able to run for a longer period of time after being run a couple of times with the same water sample. This increase in efficiency would occur due to the hydrogen being dissolved in the same water during each trial. Therefore, recycling the same saturated water would allow for the molecules to be contained within the same solution each time.

6 Proposed Solutions Testing & Results

After several potential solutions were established, the group proceeded to test them. Through testing it could be determined which solutions supported the group's hypotheses, and would improve the fuel cell's efficiency and which solutions were not effective enough to be implemented in the group's final design. The following section presents a list of the group's original proposed solutions accompanied by the testing results and data analyses for each one.

6.1 Water Temperature Solution

The testing of the "Water Temperature Solution" involved testing the efficiency of the fuel cell with distilled water at 2 different temperatures. This made it easy to observe whether or not the group's hypothesis that increasing the water temperature would better hydrate the fuel cell and increase its efficiency was correct. The distilled water was first heated in the microwave for 2 minutes to achieve the higher temperature of 65 degrees Celsius. When this hot water was used, the fuel cell ran for 1 minute 32 seconds. The second water sample was kept at room temperature around 21 degrees Celsius. When added to the fuel cell it produced a run time of 1 minute 26 seconds. The room temperature water subtracted 6 seconds from the fuel cell's run time in comparison to the hot water. The next water sample was refrigerated around 4 degrees Celsius before being added to the fuel cell. This much lower water temperature yielded a maximum run time of 1 minute 34 seconds. The results are shown in Table 6-1.

Table 6-1. Testing for the "Water Temperature Solution".

Temperature	Run Time
65 degrees Celsius	1:32
21 degrees Celsius	1:26
4 degrees Celsius	1:34

The testing for the "Water Temperature Solution" disproved the group's hypothesis because the fuel cell achieved very similar results for the high, medium and low water temperatures that were tested. Since the times were so close, the difference of 2 seconds is negligible. Therefore the water temperature did not affect the fuel cell's performance enough to use it as a way to increase the car's efficiency. The "Water Temperature Solution" was not implemented as one of the fuel cell car design solutions on Demo Day.

6.2 Smaller Connecting Tubes Solution

To test the "Small Tubes Solution", the fuel cell was run several times and the run times were recorded. The testing for the "Small Tubes Solution" supported the group's hypothesis. Provided below in Table 2, are the results from testing the fuel cell's run time with long tubes versus short tubes. The data demonstrates that in general having shorter tubes allowed the car to run for a longer period of time with an average time difference of 3 minutes. These results confirm the validity of the group's hypothesis because the reduced distance the gases and the water needed to travel increased the speed of the process which increased the fuel cell's efficiency.

Table 6-2. Run Time of Car vs. Length of Connecting Tubes.

Run #	Run Time With Long Tubes	Run Time With Short Tubes
1	1:26	1:30
2	1:30	7:25
3	1:24	3:30
4	1:16	2:53
5	1:21	6:30

6.3 Re-use Distilled Water Solution

To test the "Re-use Distilled Water Solution", the group conducted an experiment to see if the car's run time would increase after using the same water sample multiple times to run the car. The data from testing, shown in Table 6-3, supported the proposed solution and the idea was used on the Demo Day as well as throughout the rest of the design process. It was noted that the first use of water placed in the fuel cell and vessels tended to take longer to charge the car. The amount of time the car would run for increased as the water was re-used on multiple occasions. Table 3 shows the first run time with a new water sample to be 1 minute 10 seconds while the 5th time the car is charged using the same water sample, it is able to run 50 seconds longer reaching 2 minutes. Thereby, the group found that the charging process and the actual run time of the fuel cell car were impacted even if only by a few seconds to benefit the over design process of the car compared to the initial trials.

Table 6-3. Run time of car with the re-using of distilled water.

Charge Cycles	Run Time
1	1:10
2	1:40
3	1:50
4	1:50
5	2:00

6.4 Ziploc Solution

The group did not implement the "Ziploc Solution" because of several reasons including complications with the design as well as a recommendation not to pursue the method (ASME). With that in mind, the group chose to go forth with alternate design solutions that would be more effective and simpler to implement.

6.5 Larger Gas Container Solution

The group did not implement the “Larger Gas Container Solution” due to complications regarding the design of the car and the calculations associated with changing the size of the vessels (ASME). Instead of using this solution, the group implemented alternative design features to compensate for not having larger vessels to work with.

6.6 General Observations

Aside from the solutions that were finalized after data was collected and assessed, the group implemented several other contributing ideas to allow the car to run the most efficiently that were discovered through testing. After experimenting with the original car, the group discovered that the car was not functioning at its best compared to other groups from the GENE 101 class. The group received a new fuel cell and re-tested their same proposed solutions on the new fuel cell. After changing the fuel cell, the car ran for a longer period of time. Another factor that played a role in the speed of charging the fuel cell was the batteries. In combination with the changed batteries and re-using the distilled water, the car charged significantly faster than previously tested (refer to Table 3).

The group observed that through conducting tests, that when the car was about to run out of hydrogen gas to maintain a constant speed, the plugs could be removed from the smaller tubes on either side of the fuel cell, which could then be squeezed, or in other words depressurized, and the fuel cell would continue to run for a minimum of 15 more seconds. This occurred because when the small tubes were squeezed, the excess water vapour pressure that was built up within them was released and more hydrogen and oxygen was allowed to flow into the fuel cell. Lastly, the group decided to pump water into the small tubes on either side of the fuel cell after each time it was run. This, combined with re-using the distilled water, ensured that the fuel cell was well hydrated before each test run. With the fuel cell being kept well hydrated it was able to perform better by running longer and more efficiently as previously discussed, due to the increased proton conductivity over the PEM.

7 Summary of Chemistry Computations

7.1 Moles of H_2 and O_2 Produced

Assumptions and measurements:

The total pressure is assumed to be 1 atmosphere and the temperature 25 degrees Celsius (STP)
The volume of the portion of the cylinder that stores gas was measured to be 0.17 ml
The height (the displacement of the water as H_2 gas enters the vessel) was measured to be 5.1 cm

Quantity of moles in the vessels:

The number of moles of H_2 was found to be 6.87 × 10 mol
The number of moles of O_2 was found to be 3.44 × 10 mol

Refer to Appendix A for source calculations.

7.2 Quantity of Oxygen and Hydrogen Gas Lost When Stored Below Water

VH2O was measured to be 30 ml and was found by using a syringe and measuring the amountof water it takes to fill the cylinder up to the 0 mark

The percentage loss of Hydrogen when stored below water was calculated to be 3.335%
The percentage loss of Oxygen when stored below water was calculated to be 10.99%

Refer to **Appendix B** for source calculations.

8 Current and Voltage Measurements & Analysis

Fuel Cell Voltage and Current Measurements:

In this experiment, a digital Multimeter was used to measure the voltage (see Figure 3) and the current (see Figure 4) as the PEM fuel cell provided runs from a state of "full" charge to a state of depleted charge. See Appendix C for raw data.

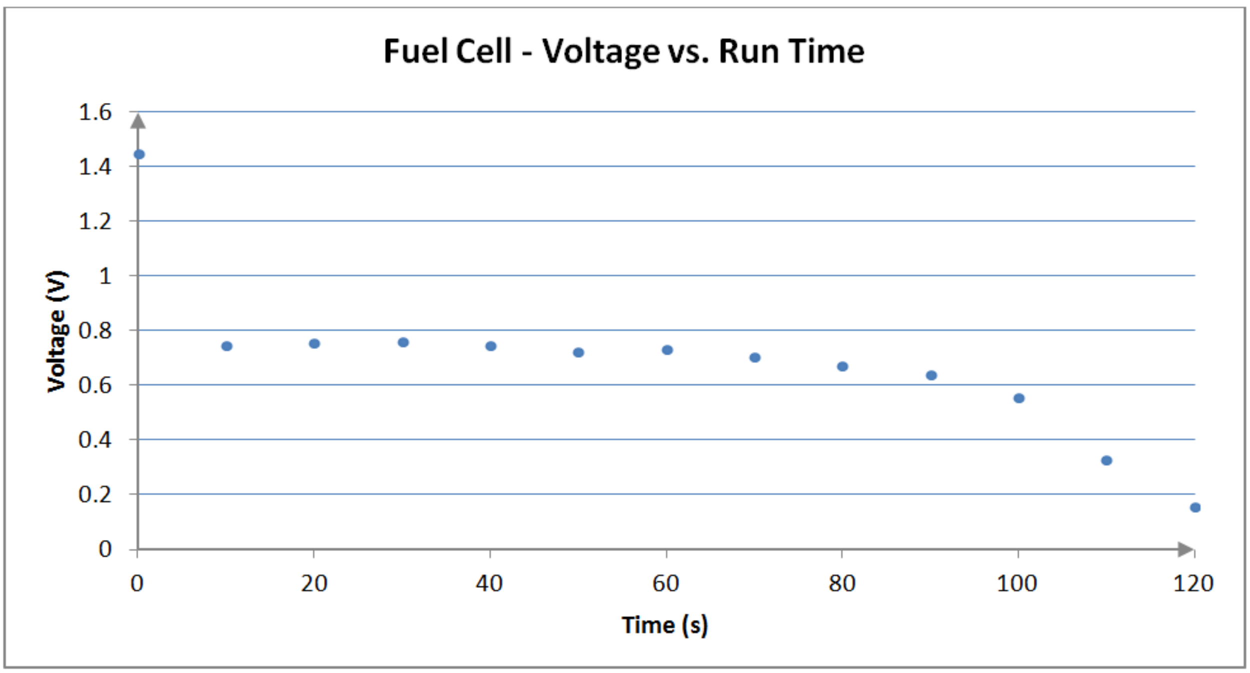

Figure 3. Graphs 12 measurements of voltage generated by a running (hydrogen) fuel cell over a 120 second period with 12 second intervals. The measurements were taken of the cell in series with a motor and by a digital Multimeter connected in parallel.

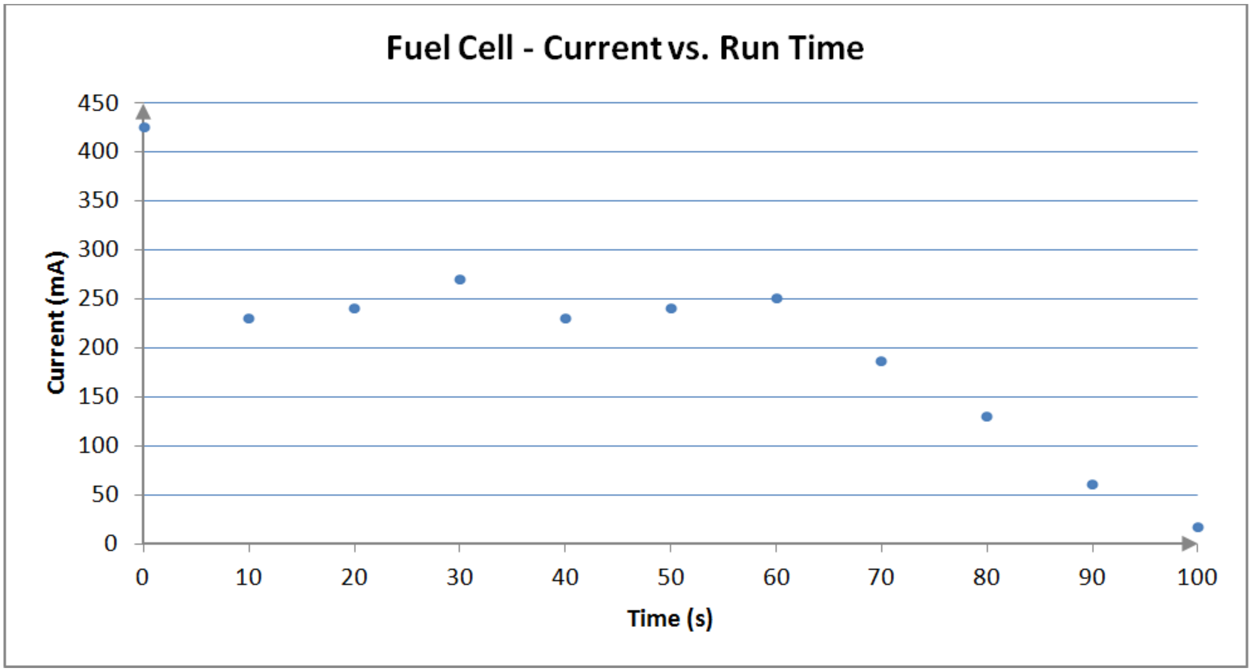

Figure 4. Graphs 10 measurements of the current going through the fuel cell over a 100 second period with 10 second intervals. The measurements were taken of the cell in series with a motor and by a digital Multimeter connected in series.

Graph Analysis:

The graphs are reasonable as they have overall negative slopes, which shows that the voltage and current is decreasing up until the fuel cell stops running. Both graphs have a proportionally massive drop in voltage or current from the initial value to the ten second mark. The voltage graph shows a consistent decrease in voltage over time. The current graph shows somewhat scattered values in the first half of the experiment, this is likely due to experimental error since the values on the Multimeter were rapidly changing making it difficult to take precise measurements.

9 Maximum Power Calculation & Discussion

The maximum power produced by the charged PEM fuel cell was calculated (shown in Figure 5) based on the values of initial voltage and initial current taken during the procedure in section 8 of this report.

Initial Voltage Value: 1.445 V
Initial Current Value: 424 mA

$$P_{max} = V \times I$$
$$P_{max} = 1.445\ V \times 424\ mA$$
$$P_{max} = 612.68\ watts$$

Figure 5. Calculation of maximum power of fuel cell based on experimental data

10 Electrochemistry Calculations & Graph Analysis

10.1 Theoretically Determination of Current Generated by Fuel Cell

The current generated by the fuel cell was calculated using the moles of O_2 (calculated in Appendix A) as well as the length of time the fuel cell ran in the experiment done in Section 8 of this report. The current was calculated to be 1.1064 Amperes. (Refer to Appendix D for source calculations).

10.2 Theoretical Determination of Voltage of Fuel Cell vs. Temperature

This graph (Figure 6) plots the theoretical relationship between temperature and voltage. The first plot is at 1.117 Volts at 287 degrees Kelvin and the last one is at 1.103 Volts at 322.5 degrees Kelvin. The negative slope illustrates that as temperature increases, voltage decreases at a linear rate. This reflects the Nernst equation (refer to Appendix E for source calculations).

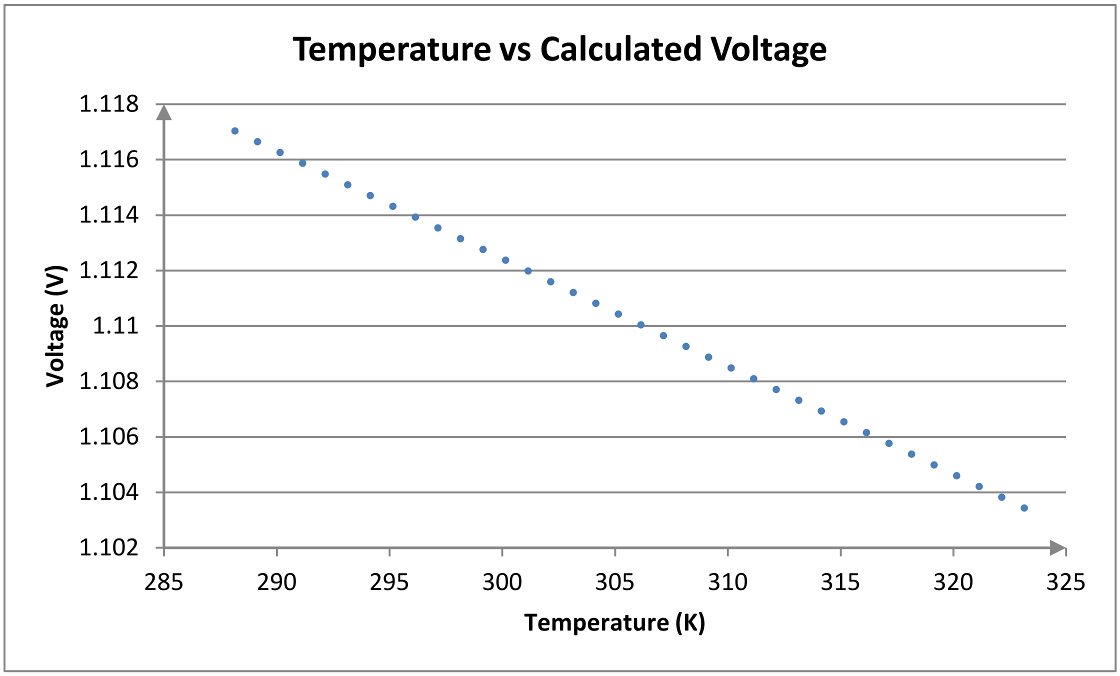

Figure 6. An estimation of the effect of temperature of environment on the voltage

10.3 Voltage and Current Efficiency

The voltage and current efficiency were calculated by dividing the measured values of voltage and current by the theoretically determined ones and finding their respective percentages. (See Appendix F for source calculations). The voltage efficiency was determined to be 117.58% and the current efficiency was determined to be 38.32%.

11 Additional Fuel Cell Research and Application

Fuel cells are still a relatively new technology. The possibilities for the future of this technology and its diverse applications are still being discovered and researched around the world today. This section will explore the following topics concerning the impacts of the fuel cell on today's society and the environment: hydrogen production as a fuel, the infeasibility of hydrogen economy, Japan's role in the future of residential fuel cell technology and the solution to predicting volcanic earthquakes.

11.1 Hydrogen Production as a Fuel

Certain hydrogen fuel production methods are currently being employed in large scale factory settings, despite hydrogen not being adopted as mainstream fuel. Hydrogen fuel is not mainstream and its production methods are still in development and subject to evolution and refinement. Based on the current statistics, the most prominent methods of production are fossil fuel based [11]. While these methods are considered the most economical methods at this moment in time; the question of long term sustainability needs to be asked. Alternative methods need to be further researched in terms of their scalability. Once these methods are shown to be economically sound in larger scale scenarios they can begin to garner widespread use.

There are several processes in place for the production of Hydrogen that involve fossil fuels as well as the capturing of emitted CO_2 in order to maintain a zero-emission, and therefore sustainable, process. [12] The first and most popular of these, accounting for 95% of Hydrogen fuel produced in the US today, is known as steam methane reforming, or SMR for short. This process involves the conversion of methane and water vapour into hydrogen and carbon monoxide according to the endothermic reaction below. [12]

$$\mathrm{CH_4 + H_2O + heat \rightarrow CO + 3H_2} \text{ [12]}$$

Water Electrolysis, an alternative to the fossil fuel methods, is quite promising in terms of its environmental impact. The process can be very renewable but this depends largely on the source of electricity used for the process. The process involves the splitting of water into hydrogen and oxygen through the application of electrical energy according to the reaction below. [12]

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2 + heat} \text{ [12]}$$

11.2 The Infeasibility of Hydrogen Economy

A hydrogen economy is often praised to be the future of the automotive world, but closer inspection shows that is not feasible. Firstly, the process that is used to transfer hydrogen from its raw resource to useable electricity is very inefficient. Secondly, hydrogen fuel cells require platinum which is a scarce resource. The reason why hydrogen economy is not feasible is its energy inefficient process and costly resources which will be discussed in this report.

The first reason why a hydrogen economy is unfeasible is because the supply chain from raw material to user is much too inefficient. One way of acquiring hydrogen is to mine natural gas out of the ground. The hydrogen then must be isolated from the natural gas which uses energy

[13]. Another way to acquire hydrogen is to use electrolysis and separate it from water [13][14]. Both these methods introduce an extra step which makes the use of hydrogen as a fuel less energy intensive. Hydrogen then must be compressed into a liquid in order to be transported. To compress hydrogen to 20 MPa, it takes about 7.2% of its HHV(this unit is a type of energy efficiency) [13]. After it has been isolated and compressed, the hydrogen must be transferred by truck to the fuelling station which also uses energy depending on the distance to the fuelling stations. The conversion of hydrogen to electricity using a fuel cell is another step where energy is lost. When the hydrogen is finally in the car, at most only 50% of the energy in hydrogen is converted into energy which gives motion to the vehicle [14]. Taking these four factors into account, only 25% of energy is left for practical use. This value is too low to run a sustainable energy economy. To better imagine this, four power plants must be constructed in which three are used to cover the energy lost and one to produce useable energy [14]. Figure 7 illustrates a visual of the four factors discussed. It is easy to see the efficient process of electric batteries over hydrogen which has many more wasteful steps.

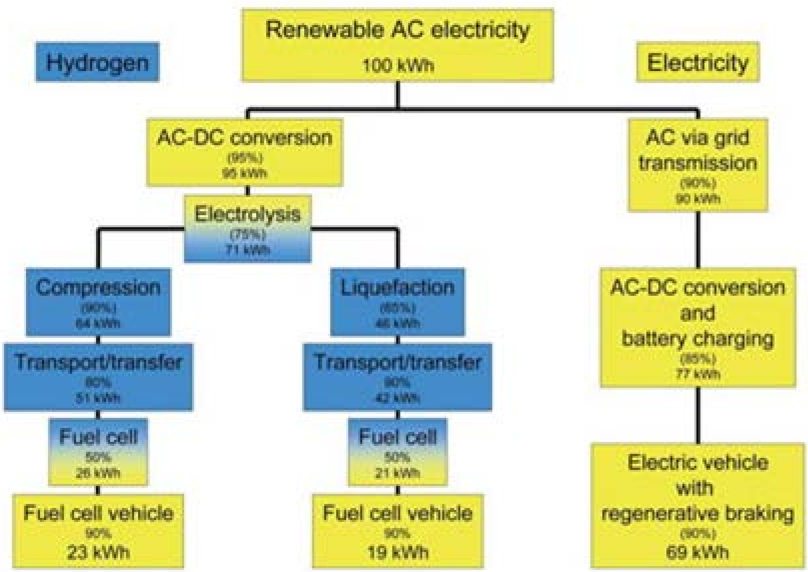

Figure 7. Useful transport energy derived from renewable electricity [13].

Platinum is a crucial element in the design of a hydrogen fuel cell. Platinum acts as a catalyst in the proton exchange membrane. This means that large quantities of platinum must be mined to keep up with the new demand for it if hydrogen economy becomes a reality. According to an estimate, 500 million fuel cell vehicles would exhaust earth's platinum supply within 15 years [15]. Platinum is also an extremely expensive metal, the price of platinum has sometimes reached $70/g [15]. This fact will drive up the cost of a hydrogen fuel cell car which would naturally reduce its demand.

Although hydrogen might seem like the resource to replace gasoline, it is simply not energy intensive and cheap enough to compete with its competitors. Firstly, the inefficient process wastes too much energy on the way in the form of mining, compressing, transporting and converting it to usable electricity. Secondly, it uses platinum, a resource that is expensive and scarce especially in a hypothetical hydrogen economy. In conclusion, hydrogen will probably never become mainstream because it is much too infeasible.

11.3 Japan's Role in the Future of Residential Fuel Cell Technology

While some claim there is no future for fuel cell technology in our society, Japan seems to think otherwise. The government began subsidizing ENE-FARM fuel cell systems for residential use when they first became available in 2009 [16]. By 2010 10,000 units had been distributed and were actively powering and heating homes [17]. Leading up to 2011, nuclear generated power contributed 30% of Japan's energy [18]. The disaster of the Fukushima-Daiichi power plant, caused a lot of fear surrounding nuclear energy resulting in public protests and the subsequent shut-down of 89% of Japan's operating nuclear plants in 2012 and eventually 100% in September of 2013 [18]. The consequent search for alternate energy sources ensued.

The 2011 tsunami proved to be pivotal in the trajectory of fuel cell technology's popularity as a mainstream residential energy source. At the end of the year 2012, 34,000 fuel cell units had been subsidized and installed across Japan [16]. Another benefit to the use of fuel cell technology is that each house is supplied with its own fuel cell unit, meaning there is no grid system [18]. This especially appeals to a country like Japan that is prone to natural disasters; with each home being supplied energy, independent of a grid, the risk of city wide power outages no longer exists.

Japan has been leading the fuel cell revolution up until now, supporting the technology from its initiation and later turning to it as a substitute for nuclear energy (its main energy source). In a society that tends to resist change, the recent revolution indicates that the future of the fuel cell technology's success depends on its continued success and evolution in Japan.

11.4 The Solution to Predicting Volcanic Earthquakes

Volcanic eruptions, combined with earthquakes, could be defined as one of the most breathtaking, vigorous, yet hazardous natural disasters on Earth [19]. Trying to anticipate the event of an earthquake, or worse a volcano erupting, was not an easy task to accomplish. If the prediction is made incorrectly, the price can be fatal and unforgivable to those responsible. Scientist had studied past eruptions, but the data did not evidently give proof to a true solution [20]. Foreseeing such high-risk outbreaks, had always challenged researchers to discover new methods for predicting earthquakes related to volcanic eruptions.

<u>Hydrogen Detectors</u>

An innovative technique was created to anticipate the earthquakes and eruptions several days before hand. This method was created by American and Japanese geologists who used automatic hydrogen detectors to help warn scientists when the disasters would occur [21]. The procedure made use of monitoring the hydrogen gas that escaped from the soil, fault lines and fume vents within the volcanic grounds [21]. The hydrogen gas that was found in these regions was originally formed underground by chemical reactions within the rock bed which experienced high impact stress related to the shock followed by the eruption [21]. Their information was monitored and then sent by satellite to be studied and assessed by scientists at the United States Geological Survey (USGS) within the Volcano Observatory in Vancouver, Washington [21]. The procedure took on the same concept as a fuel cell, but does not have a built-in reference of hydrogen fuel [22]. When the gas flowed into the collection chambers, electricity was generated to show signs that rocks were being fractured below ground [22]. With having approximately 15 network sensors, the results were more accurately measured when the voltage was generated, which caused the electrodes to contact more of the hydrogen molecules [24]. Therefore, since the sensors were placed near the Earth's surface and there was minimal amount of hydrogen gas present in normal air at that location, the sensors were extremely responsive to small samples of gas escaping [22]. After collecting data from different active volcanoes, it was shown that the release of hydrogen gas before an earthquake also provided evidence to the technique of seismic activity [23].

<u>The Impacts on Society</u>

In conclusion, Scientists had noted that the eruptions generally followed within days of the detected hydrogen gas [22]. With a combined effort of the detectors showing a signal far enough in advance and the movement picked up from the seismometer, the public was able to act on a higher-level warming system [21]. Evacuation procedures were also implemented once the data was collected and the authorities were informed [24]. In addition, the risk assessment was related to past eruptions coinciding with the possibility of future occurrences [25]. Therefore, the task of determining when the next eruption might occur relies on the hydrogen detectors, the probability of statistics and proof of evidence.

12 Conclusion & Recommendations

The final design of the fuel cell car was successful in solving the design problem and achieving the objective of running for longer than 1 minutes 15 seconds with a new maximum run time of 8 minutes 4 seconds. It also met all of the project constraints. Several major modifications were implemented in the final design of the car. These modifications included changing the fuel cell, depressurizing the small tubes, using new batteries, the "Smaller Connecting Tubes Solution" and the "Re-used Distilled Water Solution". With these implementations in place, the fuel cell consistently achieved longer run times. This report has an overview of the calculations to various scientific and mathematical questions that support the findings. In addition, many aspects of the hydrogen fuel cell relating to society and the environment were discussed. This gave multiple perspectives on the social and environmental impacts of hydrogen as a fuel. Recommendations for future modifications of the fuel cell car include the implementation of a remote control system to improve the navigation of the car through an obstacle course. In conclusion, this report has given extensive information of hydrogen fuel cells which can be used to further their development in the scientific community.

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Appendix A: Calculation for moles of H_2 and O_2

The ideal gas formula can be used to estimate the moles of H_2 gas formed.

$$PV = nRT$$

$$n = \frac{PV}{RT}$$

Where P is the total pressure in atm

$$P_{total} = P_{H_2} + P_{H_2O}^{Vap} - \rho \cdot g \cdot h$$

Where V is volume of the portion of the cylinder that stores gas in L
Where n is the number of moles of $H_2(g)$
Where R is the gas constant in $\frac{L \cdot atm}{K \cdot mol}$
Where T is assumed to be room temperature in K
Where ρ is density
Where g is the acceleration due to gravity
Where h is height of the displacement of the water as H_2 gas enters the vessel

P_{total} is assumed to be 1 atm
$P_{H_2O}^{Vap}$ is 18.65 $torr$ at 21 °C [26]
V is measured to be 0.17 ml
R is 0.08205746 $\frac{L \cdot atm}{K \cdot mol}$ [27]
T is assumed 21 °C
ρ_{water} is 1000 kg/m^3 [26]
g is 9.81 m/s^2
h was measured to be 0.051 m

$$n_{H_2} = \frac{P_{H_2} V_{cylinder}}{RT}$$

$$n_{H_2} = \frac{(P_{total} - P_{H_2O}^{Vap} + \rho \cdot g \cdot h) \cdot V_{cylinder}}{RT}$$

$$n_{H_2} = \frac{[(1\ atm) - (18.65\ torr \cdot \frac{1\ atm}{760\ torr}) + ((\frac{1\ kg}{m^3})(\frac{9.81\ m}{s^2})(0.051 m))\frac{1\ atm}{101325\ Pa}](17\ ml \cdot \frac{1\ L}{1000\ ml})}{(21 + 273.15)K \cdot (0.08205746 \frac{L \cdot atm}{K \cdot mol})}$$

$$n_{H_2} = 6.87 \times 10^{-4}\ mol$$

$\therefore$ 6.87×10^{-4} $moles$ of H_2 (g) will be produced.

For every 2 $moles$ of H_2 (g) produced, one mole of O_2 (g) is produced
based on the chemical formula of water: H_2O

$$n_{O_2} = 6.87 \times 10^{-4}\ mol\ H_2 \cdot \frac{1\ mol\ O_2}{2\ mol\ H_2}$$

$$n_{O_2} = 3.44 \times 10^{-4}\ mol\ O_2$$

$\therefore$ 3.44×10^{-4} $moles$ of O_2 (g) will be produced

Appendix B: Calculation of Percentage loss and H_2 and O_2

Henry's Law is used to determine the mole fraction of O_2 and H_2

$$K_H = \frac{p_i}{x_i}$$
$$x_i = \frac{p_i}{k_H}$$

Where K_H = Henry's law constant in atm
Where p_i = partial pressure of gas in atm
Where x_i = mole fraction of gas

V_{H_2O} was measured to be 30 ml and was found by using a syringe and measuring the amount of water it takes to fill the cylinder up to the 0 mark

Determining percent hydrogen lost:

$K_H^{H_2} = 7.099 \times 10^4$ [28]
$P_{H_2} = 0.98$ atm
Calculated in Appendix A by: $P_{H_2} = P_{total} - [P_{H_2O}^{Vap} - \rho \cdot g \cdot h]$
$n_{H_2} = 6.87 \times 10^{-4}$

Find mole fraction of H_2 in water:

$$x_{H_2} = \frac{P_i}{k_H}$$
$$x_{H_2} = \frac{0.98 \text{ atm}}{7.099 \times 10^4 \text{ atm}}$$
$$x_{H_2} = 0.000013804$$

Find the moles of H_2O

$$n_{H_2O} = \frac{m_{H_2O}}{M_{H_2O}}$$
$$n_{H_2O} = \frac{30 \text{ mL} * \frac{1\, g_{H_2O}}{mL_{H_2O}}}{\frac{18\, g_{H_2O}}{1\, mol_{H_2O}}}$$
$$n_{H_2O} = 1.66 \text{ mol}$$

Find moles of H_2

$$n_{H_2} = \frac{n_{H_2O}}{x_{H_2O}} \times x_{H_2}$$
$$n_{H_2} = \frac{n_{H_2O}}{1 - x_{H_2}} \times x_{H_2}$$
$$n_{H_2} = \frac{1.66\, mol}{1 - 0.000013804} \times 0.000013804$$
$$n_{H_2} = 2.2914 \times 10^{-5} \text{ mol}$$

Find percentage loss of H_2

$$\% \, loss_{H_2} = \frac{n_{H_2 \, dissolved}}{n_{H_2 \, original}} \times 100\%$$
$$\% \, loss_{H_2} = \frac{2.2914 \times 10^{-5}}{6.87 \times 10^{-4}} \times 100\%$$
$$\% \, loss_{H_2} = 3.335\%$$

Determining percent oxygen lost:

$K_H^{O_2} = 4.259 \times 10^4$ [27]
$P_{O_2} = 0.97$ atm
Calculated in Appendix A by: $P_{O_2} = P_{total} - [P_{H_2O}^{Vap} - \rho \cdot g \cdot h]$
$n_{O_2} = 3.44 \times 10^{-4}$

Find mole fraction of O_2 in water:

$$x_{O_2} = \frac{P_i}{k_H}$$
$$x_{O_2} = \frac{0.97 \text{ atm}}{4.259 \times 10^4 \text{ atm}}$$
$$x_{O_2} = 0.000022775$$

Moles of H_2O calculated previously to be 1.66 mol

Find moles of O_2 dissolved:

$$n_{O_2} = \frac{n_{H_2O}}{x_{H_2O}} \times x_{O_2}$$
$$n_{O_2} = \frac{n_{H_2O}}{1 - x_{O_2}} \times x_{O_2}$$
$$n_{O_2} = \frac{1.66 \, mol}{1 - 0.000022775} \times 0.000022775$$
$$n_{O_2} = 3.7807 \times 10^{-5} \text{ mol}$$

Find percentage loss of O_2

$$\% \, loss_{O_2} = \frac{n_{O_2 \, dissolved}}{n_{O_2 \, original}} \times 100\%$$
$$\% \, loss_{O_2} = \frac{3.7807 \times 10^{-5}}{3.44 \times 10^{-4}} \times 100\%$$
$$\% \, loss_{O_2} = 10.99\%$$

Appendix C: Voltage and Current Raw Data

Names: Group 4 (Morgan, Ali, Sam and John)

Table 1: Decoding and Measuring Resistance

+-5% M

Band 1 colour	Band 2 colour	Band 3 colour	Tolerance colour	Expected Value	Measured Value	Percent Error	Meets Spec?
red	black	orange	gold	20×10^3	0.021	5%	yes
brown	black	blue	gold	10×10^6	10.198 k	+1.94%	yes
grey	red	red	gold	82×10^2	8.184 K	0.195%	yes
green	brown	red	gold	51×10^2	5.002 K	1.92%	yes

Table 2: Fuel Cell Voltage and Current Measurements

	Cell	
voltage current	Voltage (V)	Current (mA)
	1.445	424
Max Power ($P = V \times I$) (W)	612.68	

Table 3: Voltage vs Time for Fuel Cell

Time (s)	Voltage (V)	Current (mA)
0	1.445 1.45	424 425
~~30~~ 10	0.6 0.749	216 230
~~60~~ 20	0.76 0.7555	264 240
~~90~~ 30	0.73 0.76	299 270
~~120~~ 40	0.7212 0.7483	234 230
~~150~~ 50	0.7009 0.724	33 240
180 60	0.642 0.736	250
210 70	0.13 0.7086	186
240 80	0.6757	130
270 90	0.6404	60
300 100	0.557	17

0.331
0.1600

Runtime
New water: 1:50
(0 recharges)

(recharged 5 times)

(recharged 4 times)

(recharged 2 times)

(recharged 3 times)

Appendix D: Theoretically Determination of Current Generated by Fuel Cell

The following equation is used to solve for the charge in coulombs:

$$Q = Fn$$

Current is then solved by using:

$$I = \frac{Q}{t}$$

Where Q represents charge in coulombs
Where F represents Faraday's constant
Where n represents number of moles of electrons
Where I represents current in *amperes*
Where t represents time in seconds

The value of Faraday's constant is $96,485.31 \frac{C}{mol}$ [Cite ppt]
The value of t used is 120 s based on the total run time while voltage and current measurements were taken.
The moles of electrons generated depends on O_2

$n_{O_2} = 3.44 \cdot 10^{-4}$

Based on the following equation: $4e^- + 2O_2 + 4H^+ \rightarrow 2H_2O_{(l)} \varepsilon^\circ = 1.229V$

$n = n_{O_2} \cdot \frac{4\ mol\ e^-}{1\ mol\ O_2}$
$n = 1.376 \cdot 10^{-3}\ mol$

Then Q can be calculated by:

$Q = \frac{96{,}485.31\ C}{mol} \cdot 1.376 \cdot 10^{-3}\ mol$
$Q = 132.764\ C$

Finally the current in Amperes is computed by:

$$I = \frac{Q}{t}$$
$$I = \frac{132.764\ C}{120\ s}$$
$$I = 1.1064A$$

Appendix E: Theoretical Determination of Voltage of Fuel Cell vs. Temperature

The following equation was used to determine the theoretical voltages at various temperatures

$$E_{cell} = E^{\circ}_{cell} - \frac{RT}{nF} \cdot lnQ[29]$$

Where E_{cell} represents the half-cell reduction potential at a given temperature in volts.
Where E°_{cell} represents the standard half-cell reduction potential in volts.
Where R is the universal gas constant in $\frac{J}{K \cdot mol}$
Where T is temperature in degrees Kelvin.
Where n is moles of electrons.
Where F is Faraday's constant.
Where Q is the reaction quotient.

E°_{cell} is provided as 1.229 V [29].
R has the value $8.314 \frac{J}{K \cdot mol}$ [29].
n was determined in Appendix 4 to be $1.376 \cdot 10^{-3}\ mol$
F is $96,485.31 \frac{C}{mol}$ [29]
The equation was evaluated at T ranging from 291.15 K to 323.15 K at 1 K intervals.

$$Q \approx \frac{1}{(P_{H_2})^2 (P_{O_2})}[29]$$

$$Q \approx \frac{1}{(0.98\ atm)^2 (0.97\ atm)}$$

$$Q \approx 1.073$$

Sample Calculation at $T = 288.15$ K

$$E_{cell} = E^{\circ}_{cell} - \frac{RT}{nF} \cdot lnQ$$

$$E_{cell} = 1.229\ V - \frac{(8.314 \frac{J}{K \cdot mol})(288.15\ K)}{(4\ mol)(96485\ C)} \cdot ln(1.073)$$

$$E_{cell} = 1.117\ V$$

Appendix F : Voltage and Current Efficiency

Theoretical current was calculated to be 1.1064 Amperes (see Appendix D).
Theoretical voltage is provided as 1.229 V.

The value of current was experimentally determined to be 0.424 Amperes (see Appendix C).
The value of voltage was experimentally determined to be 1.445 V (see Appendix C).

$$\text{Efficiency}_{Voltage} = \frac{Measured\ Value}{TheoreticalValue} \times 100\%$$
$$\text{Efficiency}_{Voltage} = \frac{1.445\ V}{1.229\ V} \times 100\%$$
$$\text{Efficiency}_{Voltage} = 117.58\%$$

$$\text{Efficiency}_{Current} = \frac{MeasuredValue}{TheoreticalValue} \times 100\%$$
$$\text{Efficiency}_{Current} = \frac{0.424\ A}{1.1064\ A} \times 100\%$$
$$\text{Efficiency}_{Current} = 38.32\%$$