# Optimization of a Chem-E-Car

New Jersey Governor's School of Engineering and Technology 2014

Michael Amoako
*michael.amoako2015@gmail.com*
Teaneck High School

David Fan
*davidfan2005@yahoo.com*
Montgomery High School

Wendy Ide
*wenfen10@gmail.com*
High Technology HS

Nina Lin
*missninalin@gmail.com*
Lenape High School

Marcus Loo
*slayer71432@gmail.com*
Park Ridge High School

## Abstract

In light of the recent movement towards reducing fossil fuel consumption, the need for a suitable alternative energy source is greater than ever. To explore the utility of household products as unconventional yet efficient energy sources, a car powered entirely by chemical reactions was built. Fuel cell batteries of varying salinity, pH, and designs were built and tested while a stopping mechanism was calibrated. A shoebox-sized car was then built with both the battery and stopping mechanism implemented and tested at various distances and loads. It was found that increasing salinity increased battery current but did not affect the voltage, while increasing and decreasing pH both increased current and voltage. The iodine clock reaction was also found to follow a first-order law, with a reaction time linearly proportional to the concentration of iodine. Ultimately, the car was able to stop at each intended distance through the iodine clock reaction. Although the aluminum batteries and iodine clock were implemented to power only a shoebox sized car, the scale-up of similar, widely available materials could possibly mean a future of globally accessible transportation.

.

## Introduction

The need for affordable and efficient alternative energy sources is a defining issue of the twenty-first century that is receiving growing attention from both the scientific community and the public alike. While hydrocarbons have driven a majority of the world's energy consumption for over a century, such sources are both unsustainable and environmentally detrimental. If the world's energy needs continue to grow at their current rate, fossil fuel reserves are estimated to deplete by 2052, followed by natural gas by 2060 and coal by 2088.[1] The consequences of using these energy sources to the end will be unprecedented, both for the environment and the global economy. Thus, it is clear that the world needs to find a feasible alternative.

While substantial advances in alternative energy have recently been made in the automobile industry, current alternative energy sources for powering vehicles are either expensive or not widely accessible to all. Ethanol fuels, for example, are not practical because they provide low mileage per gallon and require a large amount of organic material and land to produce, land that is increasingly difficult to provide.[2] Currently, hydrogen fuel cars are very expensive and often require high

1

running temperatures, reducing their longevity and efficacy. In addition, hydrogen fuel is difficult to safely transport for mass distribution because it needs to be compressed and purified.[2] Because of the public's inaccessibility to many "green" technologies, the future depends on developing a less demanding way to encourage the use of alternative energy in vehicles.

The objective of this project is to investigate and employ common household products as nonconventional energy sources in a car powered entirely by chemical reactions. The car must also be able to travel variable distances and carry variable loads with no additional user input. In addition, the goal is to gain a better understanding of how chemical reactions can be calibrated to automate processes and how engineers optimize what is available to achieve the intended goal. The project began by conceptualizing, building, and optimizing a battery system and stopping mechanism before finally building the actual car and testing it.

## 2. Background

### 2.1 Basic Electrochemistry

Electrochemical processes employ both oxidation and reduction, which are the loss and gain of electrons, respectively. When paired together in a redox reaction, electrons flow from the *reducing agent* (substance that is oxidized—loses electrons) to the *oxidizing agent* (substance that is reduced—gains electrons), generating electrical potential energy that can be harnessed to perform work, i.e., on a motor.

Galvanic cells can harness this energy by separating the oxidation and reduction processes and diverting the electrons produced through an external circuit.[3] The anode half-cell is the site of oxidation while the cathode half-cell is the site of reduction, and both are connected by a salt bridge. The salt bridge contains an electrolyte or aqueous solution of ions, which flow freely between the anode and cathode to maintain charge neutrality in each. Without the salt bridge, the cathode would become progressively more negative as it gains electrons, while the anode would become progressively more positive.[4] Since electrons always flow from the substance being oxidized to the substance being reduced, this buildup of charge would render the cell nonfunctional.

Cell potential, the difference in ability of electrons to flow from one place to another or the difference between the anode and cathode potential to become oxidized, can be quantified in volts (V) as voltage. Cell potential can also be thought of as the potential energy that drives redox reactions.[4,5] In this sense, electrons fall from the anode, which has a *higher* potential to become oxidized, to the cathode which has a *lower* potential to become oxidized. Cell potential is calculated by subtracting the reduction potentials of the anode half-reaction from that of the cathode half-reaction ($E^0_{cell} = E^0_{cathode} - E^0_{anode}$), or adding the oxidation potential of the anode half-reaction to the reduction potential of the cathode half-reaction ($E^0_{cell} = E^0_{anode} + E^0_{cathode}$). Oxidation potential is the negative of reduction potential since both are opposite processes.

### 2.2 Circuits

Circuit configuration is essential to maximizing voltage and current output as differently designed circuits have various electrical properties. Series circuits allow electrons to flow in only one direction, while parallel circuits allow electrons to flow in multiple directions.[6] Electron flow is severed when one component of a series circuit fails. Because the car photoreceptor,

motor, and power source are wired in series, the circuit is broken when the photoreceptor no longer receives light (see Diagram 1). However, in a parallel circuit, if one component fails, the rest of the components still receive electron flow.[7]
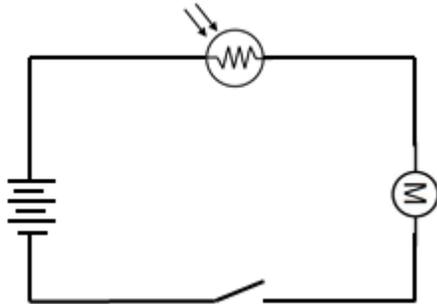


*Diagram 1*

Three definitions that require an understanding of basic circuitry are as follow:

1. Voltage (V) is the measure of potential difference between two points, in volts (V)

2. Current (I) accounts for the amount of electrons that flow in the wire, in amperes (A)

3. Resistance (R) measures any hindrance of movement for the electrons, in ohms (Ω)

Mathematically, voltage, current, and resistance are related by Ohm's Law: $V = IR$.[5] Power (Watts) is defined as $P = IV$ for ohmic circuits.

In a series circuit, the total resistance equals the sum of the individual resistances of the components. Current is uniform throughout a series circuit and voltage drops split proportionally. Note that since current (I) is constant through a series circuit for resistors, V and R are directly proportional. Therefore, higher resistors experience greater voltage drops than lower resistors.

In a parallel circuit, total resistance is the reciprocal of the sum of the reciprocals of each individual resistance. When wired in parallel, the components experience equivalent voltage drops and split current proportionally. Since voltage is constant over resistors in parallel, I and R are inversely proportional to each other. This means that higher resistors let less current pass through them than lower resistors when in parallel.

When batteries are wired in series, their voltages add. On the other hand, when batteries are wired in parallel, the total voltage equals the voltage of a single cell. The advantage to wiring batteries in parallel is that the overall current capacity increases. In order to generate enough current to power the car, three different wiring methods can be followed—series, parallel or a hybrid configuration.
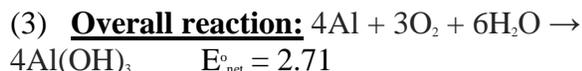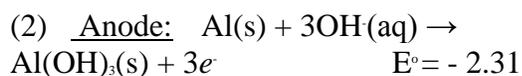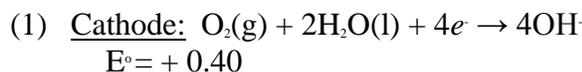
## 2.3 Aluminum-Air Batteries

Aluminum and oxygen act as the anode and cathode, respectively, in the car. While oxygen itself is reduced in the battery, activated carbon is used as an adsorbent to capture oxygen upon contact with the air. Because activated carbon is very porous, its large surface area allows it to capture oxygen on its surface, facilitating the reaction of oxygen with water to form hydroxide ion, which then reacts with aluminum itself. Paper towels drenched in saline solution serve as the salt-bridge that preserves charge neutrality in each half-cell, while copper wires transfer electron flow to the DC motor.

The consistency of carbon directly affects oxygen's rate of diffusion through the salt solution and into the aluminum anode. According to Fick's Law, the rate of diffusion is directly proportional to surface area and concentration difference, but inversely proportional to the distance over which diffusion occurs.[7] The size of the activated carbon particles gives perspective

into the manner in which mass transport occurs in a reaction chamber. In this case, oxygen from the air diffuses into the porous medium with the help of activated carbon. The surface of the carbon between particles act as a 'oxygen carrier' and eventually initiates the reduction process with the electrolyte solution. Larger particles will not be able to carry out the adsorption process due to their limited surface area, while smaller particles will impede the diffusion of oxygen. Therefore, coarse, fine, and semi-coarse consistencies were tested.

The following half-reactions take place in the aluminum-air batteries, as shown in Equation 1 and 2. The standard cell potential of the cell is calculated using Equation three. [6]

(1)  Cathode: $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-$
        $E° = + 0.40$

(2)  Anode:  $Al(s) + 3OH^-(aq) \rightarrow$
$Al(OH)_3(s) + 3e^-$          $E° = - 2.31$

(3)  **Overall reaction:** $4Al + 3O_2 + 6H_2O \rightarrow$
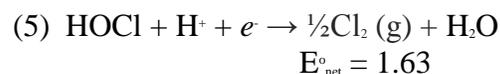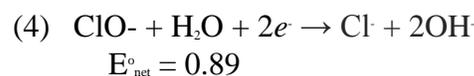$4Al(OH)_3$       $E°_{net} = 2.71$


When vinegar is added to the cell, cell potential is expected to increase because of specific chemical changes. Normally aluminum reacts with OH- to create aluminum oxide, however by adding vinegar (5% acetic acid), the dissociated $H^+$ ions react with oxygen to form water and prevent aluminum from coming in contact with oxygen. But since the aluminum comes in contact with water, it is oxidized into aluminum ion, $Al^{+3}$. This results in a higher cell potential.

**Overall reaction:**     $Al + 3H^+ + ¾O_2 \rightarrow$
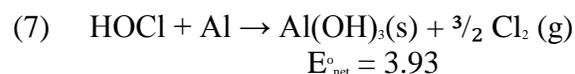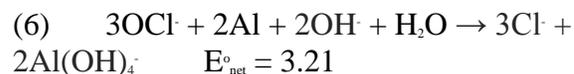$Al^{3+} + \frac{3}{2} H_2O$  $E°_{net} = 2.91$
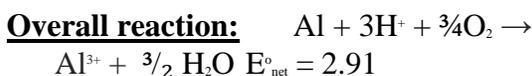
When bleach is added to the cell, the cell potential is higher because HOCl, which has a higher reduction potential, is reduced instead of oxygen. Thus, both increasing and decreasing pH are hypothesized to increase cell voltage and current.[8] This can be seen in Equations 4 and 5.

(4)  $ClO- + H_2O + 2e^- \rightarrow Cl^- + 2OH^-$
        $E°_{net} = 0.89$

(5)  $HOCl + H^+ + e^- \rightarrow ½Cl_2 (g) + H_2O$
            $E°_{net} = 1.63$

By adding Aluminum to this, two more possible reactions can take place, in equations 6 and 7.

(6)     $3OCl^- + 2Al + 2OH^- + H_2O \rightarrow 3Cl^- +$
$2Al(OH)_4^-$       $E°_{net} = 3.21$

(7)    $HOCl + Al \rightarrow Al(OH)_3(s) + \frac{3}{2} Cl_2 (g)$
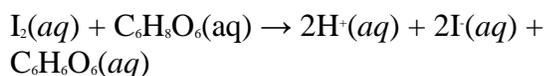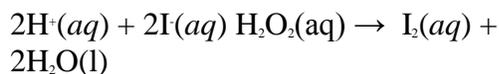            $E°_{net} = 3.93$


### 2.4 Iodine Clock Reaction

The iodine clock reaction is a classic example of a chemical clock; a mixture of reactants in which sudden property changes occur when concentration rises past a certain threshold.[8] Clock reactions are often used by educators to help students visualize reaction kinetics, as changes in temperature and concentration (and thus reaction rate) are directly seen as color change.

Because this project utilized only household products, the iodine clock used in the car differed slightly from the traditional clock reaction which uses ACS grade chemicals. This variant involves two main solutions. The first solution is composed of Vitamin C and iodine while the second solution is composed of hydrogen peroxide and starch. Vitamin C and iodine undergo a redox reaction in which Vitamin C acts an electron donor, preventing the iodine from forming a complex with starch. Once all the Vitamin C reacts, the iodine is then free to form a complex with starch, which induces

the solution to change from clear to dark-blue. Because iodine is the limiting reactant that dictates when color change is induced, iodine concentration can be manipulated to change the reaction rate. All solutions were kept at room temperature to ensure consistency between results. The two simultaneous reactions involved in the iodine clock are shown below in equations 5 and 6.

$$2H^+(aq) + 2I^-(aq)\ H_2O_2(aq) \rightarrow\ I_2(aq) + 2H_2O(l)$$

$$I_2(aq) + C_6H_8O_6(aq) \rightarrow 2H^+(aq) + 2I^-(aq) + C_6H_6O_6(aq)$$

where:  $I^-$ = iodide ion
$H_2O_2$ = Hydrogen peroxide
$I_2(aq)$ or $I_3^-$ = Iodine (aq.) or triiodide ion
$C_6H_8O_6$ = Ascorbic acid
$C_6H_6O_6$ = Dehydroascorbic acid

## 2.5 Role of Iodine Clock in Stopping Mechanism

The car circuit contains a motor, photoreceptor and batteries. When the car first starts, a flashlight shines through a glass beaker containing the iodine clock onto the photoreceptor, switching it "on" and keeping the circuit closed. At this point, the beaker is clear as the iodine clock reaction has not reached completion. As the iodine clock reaction progresses, the car continues to move until the glass beaker suddenly turns dark, preventing light from reaching the photoreceptor and breaking the circuit. Because reaction time is a function of iodine concentration and can be easily measured, the iodine clock can be effectively calibrated to control the time and distance that the car travels for.

## 3. Implementing the Car Design

### 3.1 Starting Mechanism

All batteries were made using cheap and easily accessible household products. While parameters such as battery dimension, carbon mass and consistency, and circuitry were modified between design iterations, the following describes the final "CD case design" that proved to be the most successful.

Each CD case contained four cells which were made simultaneously. See Figures 1 and 2 for schematics of one cell. Two 9-10 cm long pieces of copper wire were then cut with one being taped onto the CD case (-).

Next, a 11 x11 cm piece of aluminum foil and paper towel were cut out and each folded into 5.5 x 11 cm pieces, and placed on top of the first copper wire (-). The folded paper towel was then soaked with 5 ml of salt water solution (concentration varied by trial) and placed on top of the aluminum foil again.

The second copper wire (+) was placed on the wetted paper towel and covered with the pre-prepared carbon. The carbon was only spread on either the right or left half of the paper towel, leaving the other side blank. Depending on whether pH was manipulated, 2 ml of vinegar or bleach were then sprinkled on top of the carbon to decrease and increase pH respectively. Finally, the entire cell was folded in half to 5.5 x 5.5 cm and secured in the CD case with binder clips.

After each cell's voltage and current was measured, the cells were then wired in varied combinations of series and parallel circuits to maximize voltage and current respectively. The cells were connected in series by connecting the positive wires (inside paper towel and graphite) to the

negative wires (touching aluminum foil). The cells were connected in parallel by connecting positive to positive and negative to negative wires (see Figures 3 and 4).

It was important to ensure that the crushed carbon was uniformly moist because the salt solution proactively balances charge.[9] Whenever the crushed carbon dried out, the cell had to be wetted in order to sustain voltage production. It was also important to ensure that the copper wires spanned the width of the battery so that surface area for conducting electron flow was maximized.
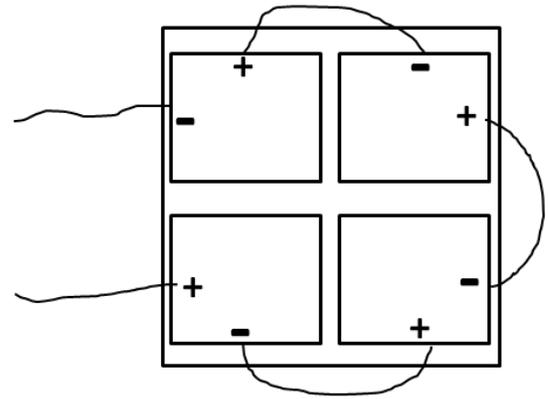
Previous designs were similar to the one described above, but used plastic sheets and clamps instead of binder clips, making them much heavier and impractical for implementation in the car.
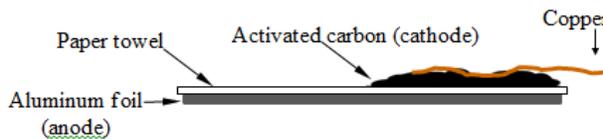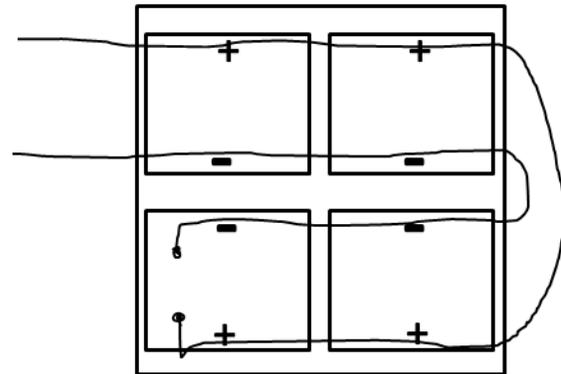


Figure 1
(side view diagram of open cell)
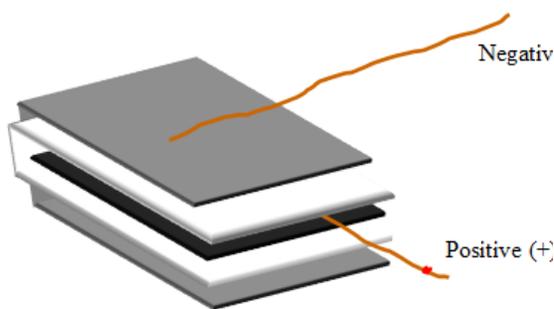


Figure 2
(layered diagram of folded cell)



Figure 3
(CD case of four cells in series)



Figure 4
(CD case of four cells in parallel)

Table 1. Material costs for Aluminum-Air Battery

| PRODUCT | COST |
|---|---|
| Heavy Duty Aluminum Foil | $5.08 |
| Copper Wires (18 gauge, x5) | $16.20 |
| Slim CD and DVD Storage Cases (50/pk.) | $11.54 |
| White Vinegar Distilled | $8.99 |
| Clorox Bleach | $7.28 |
| Morton Iodized Salt (x2) | $5.44 |

| | |
|---|---|
| Bounty Paper Towels | $5.97 |
| ACCO Binder Clips | $4.36 |
| NSI PVC Tape | $2.15 |
| Black Diamond Premium Activated Carbon | $13.59 |
| **TOTAL (incl. taxes):** | **$86.24** |

## 3.2 Stopping Mechanism

A well-mixed solution of extremely fine crushed Vitamin C tablet and 60 ml of warm water was first prepared. 5 ml of this solution was then transferred to a second beaker (labeled Beaker B) containing 60 ml of warm water and 4-6 ml of iodine (increments of 0.1 ml were tested in each successive trial). The solution turned clear upon adding the Vitamin C and was also allowed to cool to room temperature. Finally, 60 ml of warm water, 15 ml of hydrogen-peroxide and 2.5 ml of liquid starch were added to a third beaker (labeled Beaker C), well stirred and allowed to cool to room temperature. Beaker B was added to Beaker C and the time required for color change was recorded. Trials were conducted in this fashion for varied amounts of iodine in order to observe the resultant changes in reaction rate.[8]

**Table 2. Material costs for Stopping Mechanism**

| PRODUCT | COST |
|---|---|
| Hydrogen Peroxide (3%) | $5.30 |
| Rite Aid Antiseptic Solution (x2) | $23.98 |
| Sta-Flo Liquid Starch | $7.00 |
| Ester-C Vitamin C tablets | $10.08 |
| **Total (incl. taxes):** | **$49.61** |

## 3.3 Building the Car and Performing the Load Tests

A 30 x 23 x 0.50 cm plexiglass car base containing four 5.0 cm radius wheels from a previous Rutgers AIChe car was removed and modified for our car. A 1.5 V, 7600 RPM motor was first wired in series to the battery setup. A photoreceptor switch was then wired to the battery and placed inside a covered cardboard roll. Next, a hole was cut in the cardboard and a flashlight was inserted and allowed to shine inside the roll. Finally, an empty beaker for the iodine clock reaction was placed in between the photoreceptor switch and the flashlight.

Load tests were performed to analyze the car's performance while traveling at various distances, voltages and loads. Loads of up to 500 ml of water were tested in 50 ml increments for 3, 4.5 and 6 V batteries. At the start of each trial, the pre-prepared iodine clock solutions were added to the empty beaker and the cardboard container was covered to block out light. The amount of time required to travel 10 feet was recorded for each variation in load and voltage. Upon conducting these trials, average velocity were calculated using kinematic equations. Acceleration was not taken into consideration as the car traveled at a constant speed and came to an abrupt stop after the stopping mechanism had taken place. The velocity at each load and voltage was then used to predict the amount of time it would to take to travel at 20, 30, 40 and 50 feet with those same parameters. Because acceleration was negligible, these calculations are representative of the car's motion at those distances.

**Table 3. Material costs for Modeled Car**

| PRODUCT | COST |
|---|---|
| Acrylic Plexiglass Sheet (x2) | $17.94 |

| | |
|---|---|
| Morphibians Rover | $21.99 |
| Energizer 9V Alkaline Battery (x2) | $7.65 |
| Mini Cree LED Flashlight | $2.45 |
| Duracell AA Battery | $4.39 |
| **Total (incl. taxes):** | **$58.23** |

## 4. Results and Discussion

### 4.1 Aluminum-Air Batteries

#### 4.1.1 Individual Cell vs. Battery Voltages

When the original 7 cm x 12 cm paper towel, unfolded, and 5% saltwater cells were tested, each yielded an average voltage of 0.6-0.8 V and current of 0.01 A. Multiple plastic sheets and metal clamps were used to bind the cells together in a series battery; however, this setup was excessively heavy and difficult to work with. The aluminum rusted easily and saltwater often leaked out, drying out the cells prematurely. Due to these difficulties, it was decided to implement the aforementioned CD case design, the design in which each case or battery contained four 5.5 cm x 5.5 cm folded cells. Surprisingly, batteries built to these specs also yielded 0.6-0.8 V despite being much smaller in surface area. This can be attributed to cell potential's intensive property, which makes cell potential independent of the number of electrons transferred or amount of material present.[1] Consistently, adding more carbon did not change the amount of voltage produced either, since the density of carbon remained the same; 5.5 cm x 5.5 cm cells with 1.5 g, 2.0 g and 2.5 g of carbon respectively also yielded 0.6-0.8 V. However cells with more carbon seemed to maintain their voltage longer, probably because more reactants were available to react, thus lengthening the duration of reaction. Because each CD case battery could easily hold four cells while being significantly lighter and more durable than the plastic clamp design, the CD case design was implemented into the car.

Although each four-cell battery alone produced about 2.2 V on average, the total voltage produced by wiring multiple cells together in series was significantly lower than expected. Three separate series-circuits each composed of four batteries (16 cells) were built, and each circuit averaged only 5 V - about 56.8% of the expected 8.8 V yield. This voltage drop could be due to the lengthy period of time spent wiring the batteries together. During this time, oxygen levels likely plummeted while aluminum hydroxide (non-electrically conductive) likely accumulated on the aluminum foil as a byproduct of redox reactions, which would reduce the amount of oxygen available to react and also increase resistance, thus reducing voltage. Despite the significant loss in voltage, each circuit should have been able to run the motor because one commercial AA battery (1.5 V total) sufficed previously, however, none of the three circuits succeeded. This was due to the circuits' low current of 0.01 A, which is significantly less than the commercial batteries' combined current of around 3 A.

Because the previous three circuits were wired in series, each had the combined voltages of all cells involved but the current of only one cell. Thus to increase current, cells were wired in a series/parallel hybrid configuration instead. Four batteries were wired in series, and four of these series packs were wired in parallel. This setup produced around 2 V and 0.18 A, but still failed to power the motor. Because each individual cell contained only 0.01 A, it was not surprising that the series/parallel setup did not experience a significant enough increase in current. When making the cells, the pH and salinity were manipulated in order to try to maximize current and voltage.

The data collected from changing either the pH or salinity of the cells were compared with each other." See Figures 5 and 6.

### 4.1.2 Effect of Salinity on Voltage and Current

The previously mentioned battery cells were all made with 5% salt solution. Because saltwater served as the ion bridge for the battery, it was hypothesized that an increase in salinity would increase voltage and current due to the battery's larger capacity for neutralizing charge in the anode and cathode. Interestingly, raising the salinity to 10%, 12%, 15% and 20% by mass respectively did not significantly impact voltage. While 12% salt solution exhibited slightly higher average voltages than 5% and 15%, both 10% and 20% were higher than 12%. In addition, voltage difference between the five concentrations never exceeded 0.07 V, which is an unexpectedly marginal difference for such large differences in salt content. Any differences in voltage were likely due to minor variations between cells or limitations in device accuracy. However as expected, raising salinity did increase current, with 20% salinity exhibiting the highest average starting current of 0.22 A for a single cell. 12% salinity has been cited as having the highest electrical conductance[6]; however, the data collected suggests maximum conductivity at 20% for pure salt solutions.

When four cells with 20% salt solution were wired together in series and three in parallel, the circuit yielded 5 V total (each cell produced on average 2.2 V and 0.2 A) and 0.25 A. Again there was a significant drop in voltage and current, likely for the same reasons mentioned above. 0.25 A was still not enough current to run the car, so pH was next tested.

### 4.1.3 Effect of pH on Voltage and Current

It was previously hypothesized by the group that both an increase and decrease in pH would increase voltage and current output, with higher pH experiencing greater increases due to the bleach reactions' higher cell potential of 3.93 V. As expected, increasing pH through adding bleach did increase the cell voltage; by 0.045 V on average. Decreasing pH through adding vinegar increased the average cell voltage by 0.092 V on average. This was surprising as the bleach reaction's cell potential is much higher than that of the vinegar reaction, and thus adding bleach should have resulted in significantly higher average voltages. Interestingly, vinegar cells were more stable on average while bleach cells experienced sharper drops in voltage. Because the vinegar cell wires remained shiny instead of turning red, the acetate in vinegar could have prevented copper oxide from accumulating on the copper wires, thus reducing resistance and maintaining contact with the solution.

Both increasing and decreasing pH resulted in higher starting currents, with bleach exhibiting the highest average starting current for most salt concentrations. Because of the discrepancy between bleach and vinegar's performance in voltage output and current respectively, other factors such as electrolyte solubility might affect the voltage.

When four 20% saltwater w/ bleach cells were wired in series with three in parallel, a maximum of 6.7 V and 0.4 A was produced, although each cell had an average voltage of 0.8 V and current of 0.25 A. 0.4 A still was not sufficient to run the motor, and ultimately, no battery configuration succeeded at doing so. Because of this, commercial AA batteries were used in the load tests instead of the aluminum foil batteries.

### 4.1.4 Proposed Solutions to Challenges and Additional Findings

Ideally, the car batteries should have produced higher voltages and currents than what was observed. As mentioned above, when cells were wired in series and parallel, the total voltage and current output dropped sharply, at times to only 50% of the expected starting output. This is probably a limitation incurred by the use of only household products, which contain many impurities and only a small percentage of the active ingredient. If pure ingredients were to be used, perhaps the batteries would produce more voltage and current. The prolonged period of time spent wiring the cells together also contributed to decreased voltage and current output. Because it was difficult to maintain wire contact with the wet graphite, at times individual cells short circuited and had to be fixed individually, which was difficult as the CD case could not be reopened without unwiring neighboring cells. The process of opening the CD cases at times inadvertently damaged previously functional cells, creating additional problems. Thus the inaccessibility of individual cells was a major flaw of the CD case design that unnecessarily prolonged the wiring period. Additionally, there were a limited number of functional multimeters available in the lab, which impeded the rate at which batteries could be tested.

The use of alligator clips to connect the wires is one improvement that could be implemented. This would potentially increase accessibility to each cell and tighten wire contact, decreasing possibilities for failure. Another improvement could be to use larger CD cases, increasing the amount of oxygen available to react and thus lengthening the runtime of each cell.

Towards the end of the program, aluminum reactor shape was experimented in an attempt to further optimize current output, however, these trials were never completed. Yet the trials conducted indicate that modifications in shape are highly promising in optimizing battery performance. The most promising shape tested was that of a log. The log shaped cells were largely the same as the previous rectangular cells, except the aluminum foil was wrapped around a paper towel roll instead of a flat surface. Each of these cells produced a surprisingly high average current of 0.80 A but ordinary voltage of 0.722 V. This is a significant gain in current, as a single log cell yielded more current that almost four rectangular battery cases wired in parallel. Although the ten log cells produced were not wired into a circuit, the individual cell values indicate that a high current would have been obtained. These preliminary results are highly promising with regards to producing high current aluminum air cells from household products. Future investigation into this design is highly suggested.

### 4.2 Iodine Clock

(see Figure 7)

When iodine was added in 0.1 ml increments from 4 to 6 ml, the reaction time was found to follow a linear relationship with a coefficient of determination ($r^2$) of 0.93. This linear relationship is expected, as iodine is the rate determining step and the rate law is cited in references as being first order. [11] At first, the group did not obtain a strictly linear relationship because the solutions were not all cooled to the same temperature, and thus all subsequent trials were conducted at room temperature. At times Vitamin C fell out of solution, causing variations in reaction rate. Thus the Vitamin C had to be remixed prior to each trial.

### 4.3 Load Tests

(see Figures 8-14)

When tests were performed with various voltages (3, 4.5 and 6 V) and loads up to 500 ml of water over a distance of 10 feet, it was found that load did not significantly impact runtime. At higher voltages, load had an even lesser impact on the car's runtime, as indicated by the best fit line's smaller slope. All three graphs showed a near-linear relationship between load and time, indicating that acceleration and friction were both negligible. This linear relationship is further corroborated by $r^2$ values that were all greater than 90%. The time required to travel 10 feet at each load and voltage were used to calculate the time required to travel at 20, 30, 40 and 50 feet.

## 4.4 Design Economics/Cost Analysis

### 4.4.1 Battery

The components of the starting mechanism cost a total of $86.24. While the starting mechanism was affordable, the aluminum airfoil battery lacked longevity and overall performance meaning it would have to be replaced frequently. The battery maintained its voltage above 80% (the standard shelf life mark) for only 10 minutes at most; barely enough time to run a series of load tests. Commercial-scale energy sources require much longer run times. Furthermore, the aluminum battery's inconsistency is a drawback to its affordability. If better materials had been used, perhaps a more consistent voltage could have been obtained, however, cost might have increased as well. The balance between cost and quality is delicate.

### 4.4.2 Stopping Mechanism

Like the starting mechanism, the components of the stopping mechanism were relatively cheap. With a total cost of only $36.78, the stopping mechanism was not only cost-effective, but efficient. By controlling the temperature in the reaction,

the group successfully attained both consistent and reproducible results. Evidently, the Iodine clock reaction is practical in that it is affordable, reliable, and easily prepared. The intended goal for the stopping mechanism was achieved in the clock reaction's ability to stop the car at its intended distance. In this case, household chemicals provided to be a viable alternative to pure ACS grade chemicals.

### 4.4.3 Car Platform and Components

Similar to the starting and stopping mechanism, the car platform was fairly inexpensive. The total cost was $58.23, again less than the 2012 GSET team's $110.10. It should be noted however that the car base and photoreceptor for this year's car were already provided by the project mentors, which reduced this year's costs.

### 4.4.4 Overall Cost

Because a primary goal of the project was to design a *cost-effective*, working car using readily accessible materials, achieving a suitable price was paramount to maintaining design feasibility. The project mentors designated a desired cost of between $400 and $600, however the end cost of $194.08 was much lower, making the car very cheap in comparison. Despite this low cost, the aforementioned performance flaws detracted from the car's price advantage. Because household products were used instead of pure chemicals, the aluminum batteries did not sustain their expected voltage and current, even though the iodine clock reaction was successful with household products. The group saved money by reusing a previous group's car base, however the base was heavy and difficult to move, which further increased the base current needed to power the car. In all, the car was somewhat cost-efficient in that it was able to achieve the project

objectives despite possessing several drawbacks.

## 5. Conclusion

When four 20% saltwater and bleach aluminum-air batteries were wired in series, the maximum voltage obtained was 6.7 V with insignificant current. When four cells were wired in series, and four of these series packs were wired in parallel, around 2.0 Volts were produced with 0.18 Amps of current. None of these configurations could produce enough current to run the motor, despite having a high enough voltage. Even four batteries in just parallel could only produce 0.30 Amps at most.

It was found that increasing salinity increased current but left voltage unaffected, while both increasing and decreasing pH increased current and voltage, with lower pH experiencing the greatest increases. The iodine clock reaction was successfully calibrated to the nearest 0.1 ml and implemented into the car stopping mechanism. Reaction time was found to be linearly dependent on iodine amount with a high coefficient of determination of 93%, corroborating its first order rate law and indicating consistent data values. Although none of the battery configurations succeeded in running the car, load tests were performed with AA batteries containing the same voltage as our batteries, thus accurately reflecting our car's kinematic properties.

### 5.1 Future Work

The research presented in this project has raised some questions that can be answered by future studies in this area. Firstly, using half-reactions with higher stability and reduction potential might provide more voltage and current to power the car, reducing the number of batteries needed and potentially improving car speed.

Hydrogen fuel cells are used regularly to power AIChE cars and would be a viable option to use for similar Chem-E-Car projects. In addition, studies should be done on battery longevity; as mentioned in the cost analysis, the batteries in this project did not maintain their voltage for very long. Because there is a strong need for batteries with longer shelf life, these research findings would be beneficial for both manufacturers and consumers. Besides finding alternatives that maintain high voltage, a possible line of research would be testing the current versus time. Since voltage is not the only factor needed to keep the car moving, it is important that in the future, current could be taken into account of as well. The car itself could also be improved upon and even rebuilt as it was heavy and difficult to move. Finally, perhaps alternative chemicals such as sodium thiosulfate and hydrogen chloride could be investigated for use in the stopping mechanism instead of iodine, for their potential accuracy and ease of implementation.

Though the objective of this research was to design a shoe sized car, it is possible that in the future, a vehicle can possibly be powered entirely by chemical reactions. Cars today cost an average of $20,000. Though this car is smaller, the cost was only $194.08 and much of the costs attributed to the actual chemicals themselves. Also, since the products used were household products, a greater production of either the starting or stopping mechanism to complement a bigger car would not be detrimental as these products are readily accessible to the consumers.

engineering and for organizing an amazing Governor's Shool Program that pushed us to expand and challenge our critical thinking skills. We give our gratitude to our RTA, Laura Gunderson, for her patience and continuous guidance. We would also like to thank our mentors Joanne Horng, Nicholas Ngai, Ingrid J. Paredes, Shriram Sundarraj, Christian Tabedzki, and Mercedes Wu for dedicating their free time to supervise and guide us in the lab. We'd especially like to thank Shriram Sundarraj who dedicated numerous weekends and worked unremittingly to help us gain a deep understanding of our project and finish on time. We'd also like to thank Morgan Stanley, Lockheed Martin, Silverline Windows, Jersey South Industries Inc., the Provident Bank Foundation, and Novo Nordisk for sponsoring the program. Lastly but most importantly, we would like to thank Rutgers University the Governor School faculty, and the State of New Jersey for funding and granting us this unparalleled opportunity to learn at such a prestigious program.

## References

[1]"The End Of Fossil Fuels." - Our Green Energy. https://www.ecotricity.co.uk/our-green-energy/energy-independence/the-end-of-fossil-fuels (July 17, 2014).

[2]"Alternative Energy Vehicles – Pros and Cons." Field Service Management Tools Tech Mobile Software SmartVan RSS. http://thesmartvan.com/blog/2011/07/08/12864/alternative-energy-vehicles-pros-and-cons/ (July 23, 2014).

[3]"Index of /CHM130FieldLab/Lab8." Index of /CHM130FieldLab/Lab8. http://www.chemistryland.com/CHM130FieldLab/Lab8 (July 24, 2014).

[4]"Voltaic Cells." - Chemwiki. http://chemwiki.ucdavis.edu/Analytical_Chemistry/Electrochemistry/Voltaic_Cells (July 19, 2014).

[5]"Electrochemistry." Electrochemical Reactions. http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch20/electro.php#voltaic (July 19, 2014).

[6]"Electrical4u." Electrical4u. http://www.electrical4u.com/aluminum-air-battery (July 19, 2014).

[7]"Movement." A-level Biology Cells and Organelles Revision -. http://www.s-cool.co.uk/a-level/biology/cells-and-organelles/revise-it/movement (July 23, 2014).

[8]"The Salty Science of an Aluminum Air Battery." TPT Salty Science. http://sciencegeekgirl.com/documents/TPT_Salty_Science.pdf (July 19, 2014).

[7]"Journal of Mathematical Chemistry." Chemical Clock Reactions: The Effect of Precursor Consumption. https://www.maths.nottingham.ac.uk/personal/jb/clock.pdf (July 23, 2014).

[8]Brown, T. L., LeMay, H. E., Bursten, B. E., & Brown, T. L. (2006). *Chemistry, the Central Science*. Upper Saddle River, NJ: Prentice Hall.

[9]"Design and analysis of aluminum/air battery system for electric vehicles." Design and analysis of aluminum/air battery system for electric vehicles. http://www.sciencedirect.com/science/article/pii/S0378775302003701 (July 19, 2014).

[10]"Redox flow batteries: a review." J Appl Electrochem. http://ecpower.utk.edu/Publications/do

cs/Redox%20flow%20batteries%20a %20review.pdf (July 19, 2014).

[11]"The Rate Law of an Iodine Clock Reaction." The Rate Law of an Iodine Clock Reaction. http://faculty.ccbcmd.edu/~cyau/124 %2006%20Iodine%20Clock%20Kinet ics%20JAN%202014.pdf (July 19, 2014).

[12]Spencer, James N., George M. Bodner, and Lyman H. Rickard. *Chemistry: structure and dynamics*. New York: John Wiley, 2010.

[13]"An Open-Ended Project: Building a High Performance, yet Simple, Household Battery." - Journal of Chemical Education (ACS Publications and Division of Chemical Education). http://pubs.acs.org/doi/abs/10.1021/ed 4000603 (July 24, 2014).
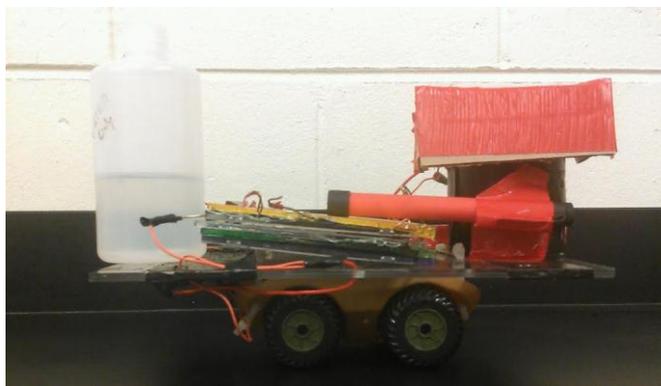
*Picture 1: Side view of car with load*
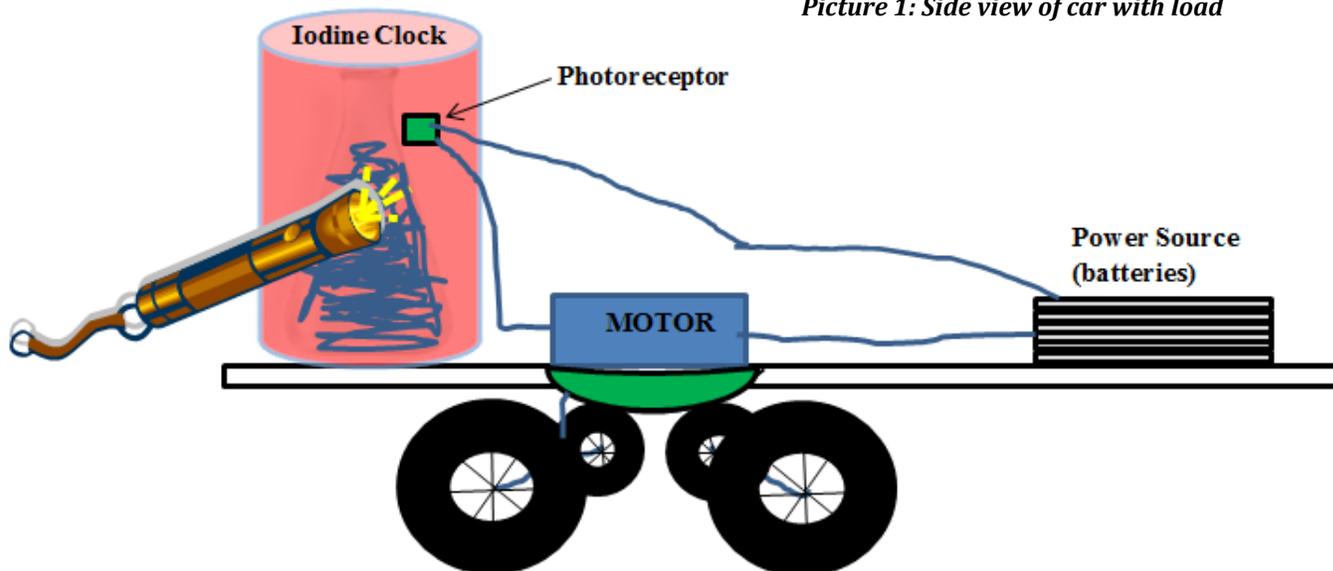


*Diagram 2*
*(Diagram of car setup)*
*Iodine clock is dark blue in diagram, light cannot hit the photoreceptor, the car is stopped*
Actual picture above.
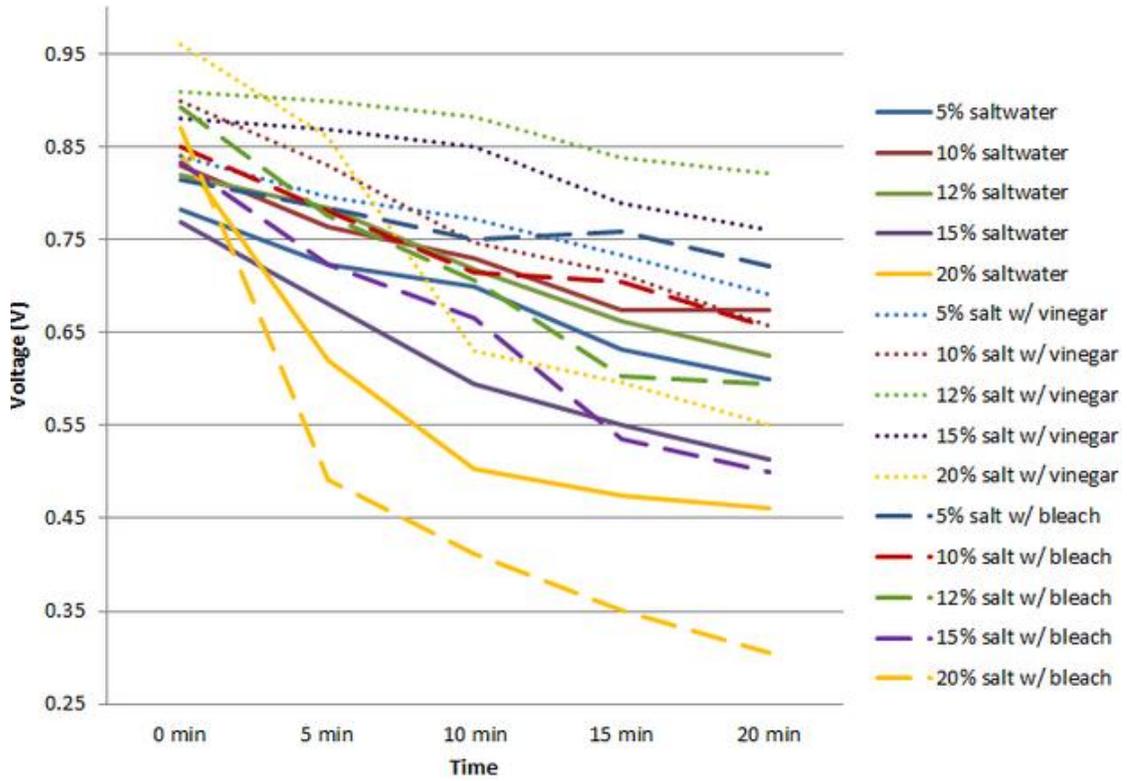
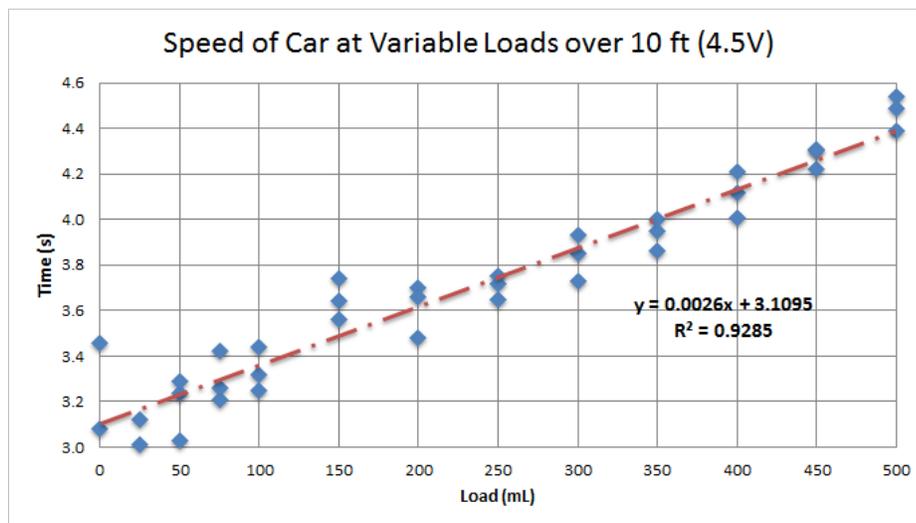*Figure 5 : Voltage drop per cell for different salinity and pH levels.*
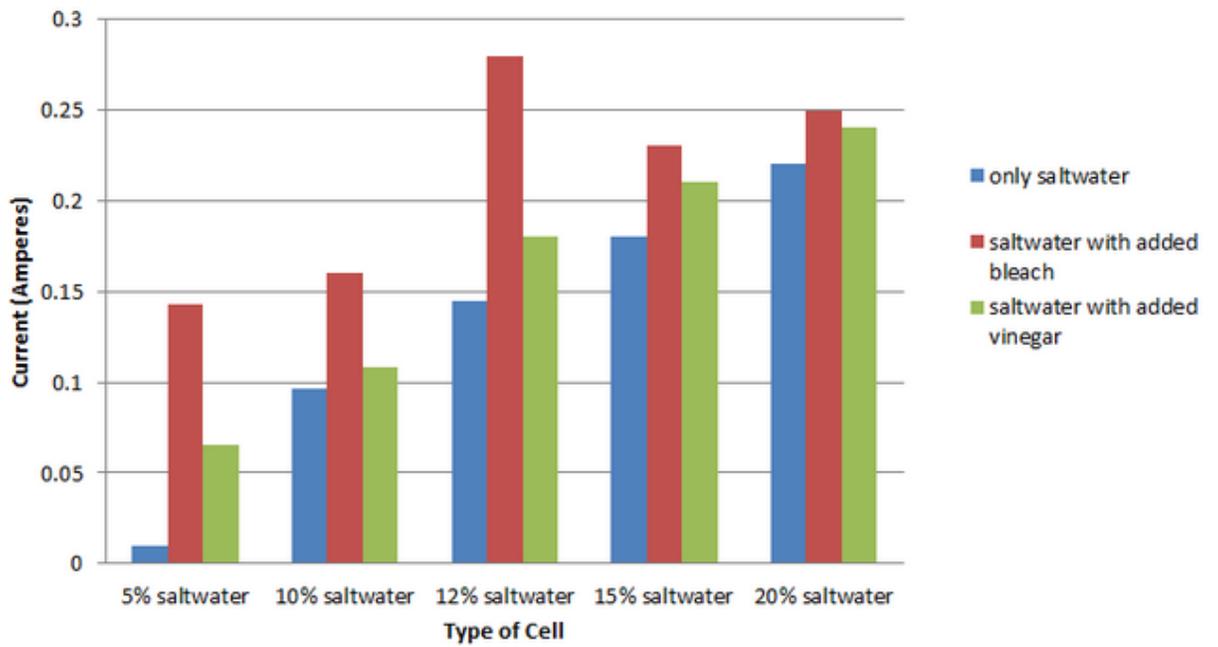


*Figure 6: Current as function of salinity and pH concentration changes*
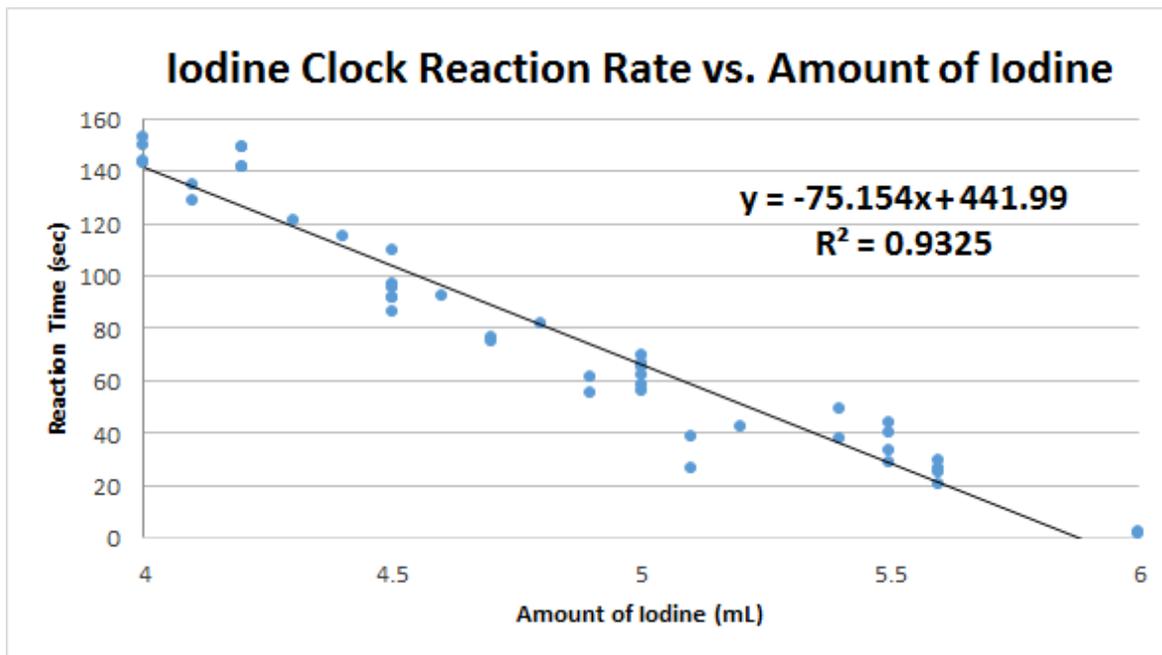
**Figure 7: Iodine Clock reaction rate with household products**
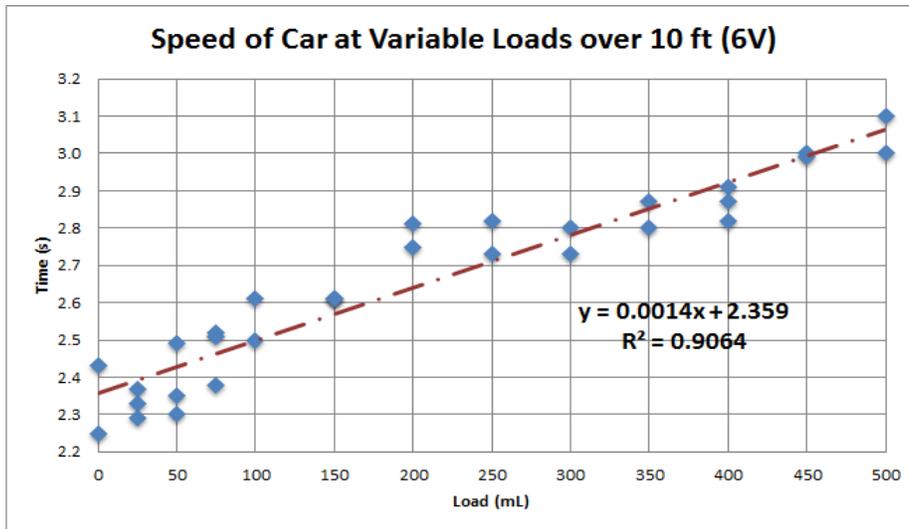


**Figure 8**



**Figure 9**
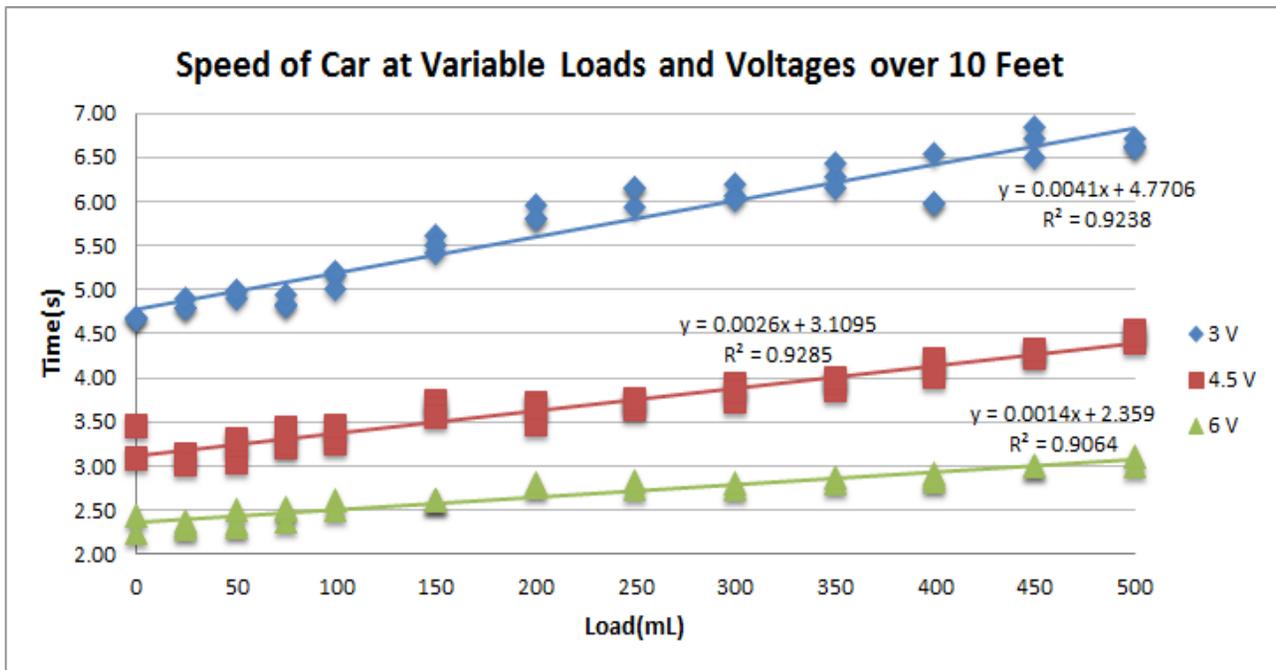
16
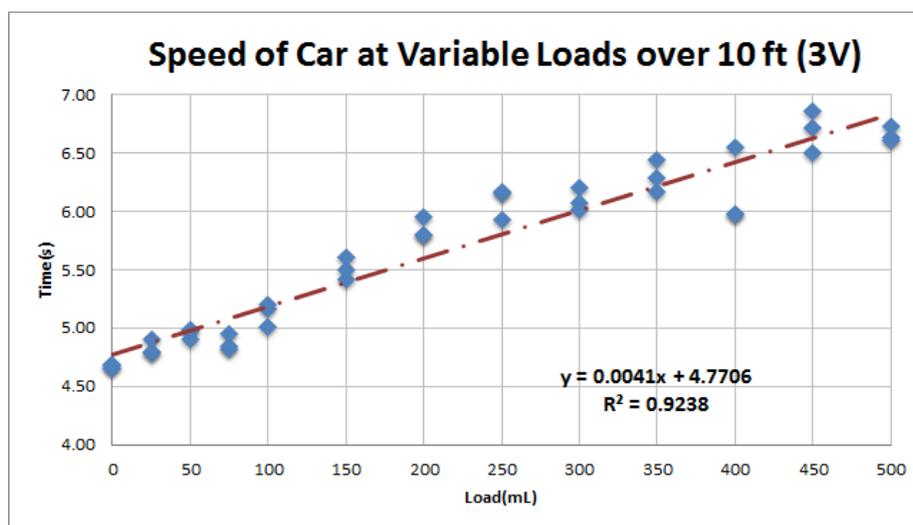
*Figure 10*



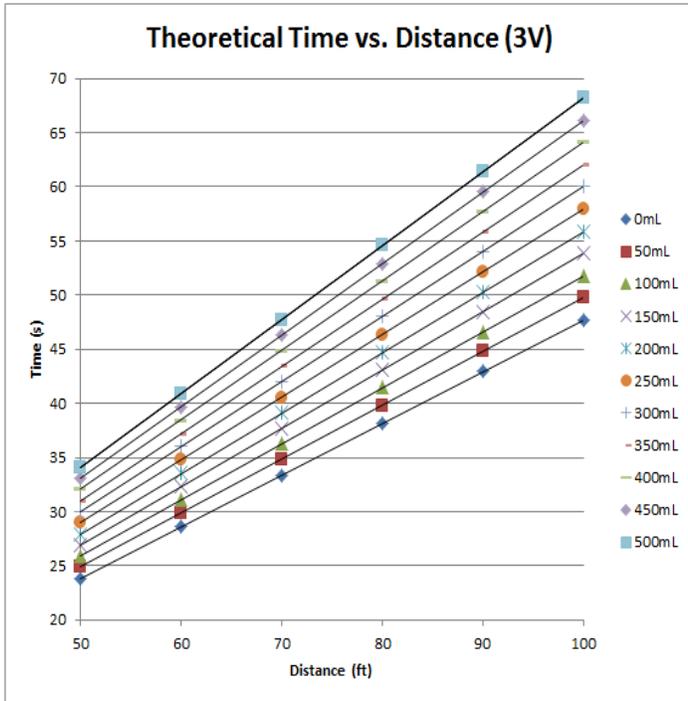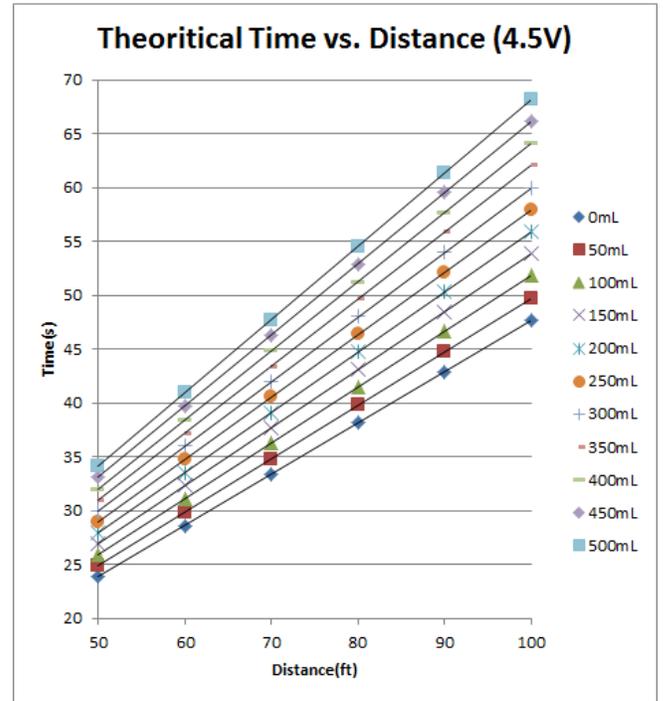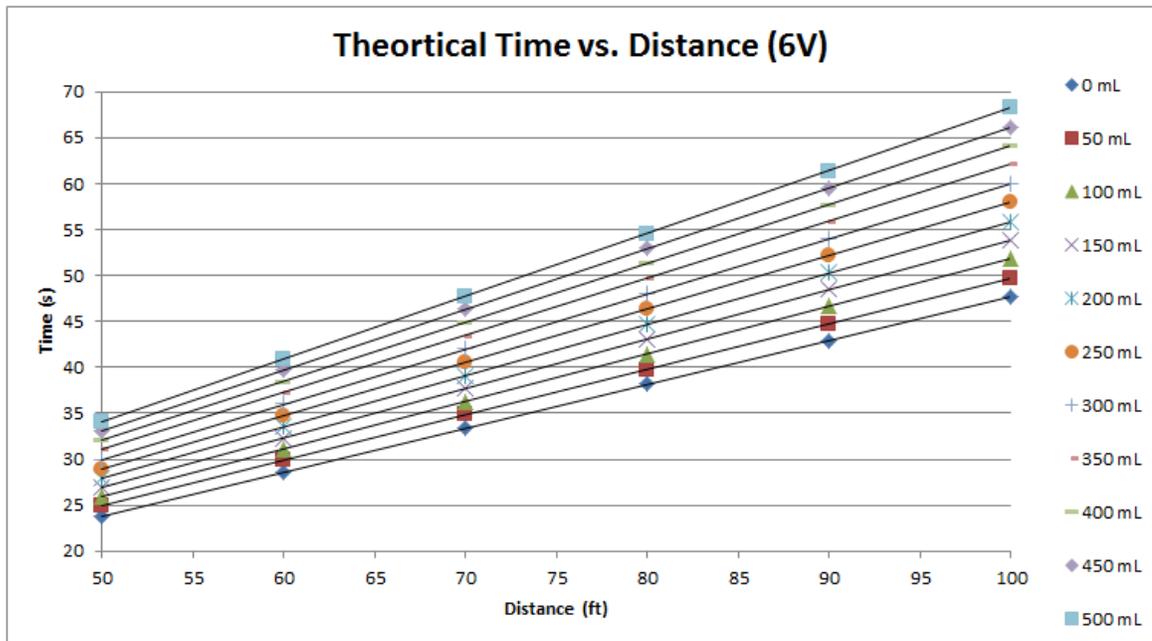*Figure 11: Speed of Car at Variable Loads over 10 ft*

17

*Figure 12*



*Figure 13*



*Figure 14*

18