The Design of a Power System Using Treated Aluminum Fuel

By

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2015

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Submitted to the Department of Mechanical Engineering
on May 8th, 2015 in Partial Fulfillment of the
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ABSTRACT

Aluminum is the most abundant metal in the Earth’s crust and a highly sought after fuel source due to its extreme energy density. It has the ability to produce large quantities of hydrogen and heat when reacted with water making it an attractive fuel for underwater vehicles and ocean sensor platforms. The biggest challenge in using aluminum as a fuel has been overcoming the rapidly-forming oxide layer that gives aluminum its excellent corrosion resistance. Recently, a safe, controllable, and inexpensive treatment process was developed which bypasses this layer and allows aluminum to efficiently react with water. The fuel made using this process generates an average hydrogen yield of 94 percent. This fuel has been successfully tested in a power system, in which a fuel cell generated 30 watts for 90 minutes using only hydrogen. Firstly, an introduction and background is given on the benefits and challenges of using hydrogen as a fuel. The basic chemistry and background behind using aluminum as a fuel provides the motivation behind this thesis. Secondly, the materials science of using aluminum fuels is examined as well as prior aluminum fuels which have been attempted. The treatment process is then analyzed using the physics previously discussed as well as the overall efficiency and practicality of the treated aluminum fuel. Thirdly, a working power system design is then presented which runs entirely off hydrogen gas generated by specially treated aluminum fuel. This system was run for 90 minutes at 30 watts, showing that aluminum can be used as a safe and environmentally friendly fuel source.

Thesis Supervisor: Douglas P. Hart
Title: Professor of Mechanical Engineering
ACKNOWLEDGEMENTS

This project is the result of a team effort on behalf of many people as well as the unbelievable support from my friends, family, and colleagues. I would like to recognize and thank these people and organizations for their help.

I would first like to thank my family for their love, heated discussions, hugs, long runs, lifting sessions, therapeutic tractor/bobcat/sawmill work sessions, and fun barbecues which allowed me to put my mind at rest and appreciate how blessed I am to have such a cool project.

Colleen, you have been there for me every step of the way. Even at my lowest points you helped hold me up and keep me focused. You made me dinner when I was too busy to cook, packed me lunch when I forgot, and most of all gave me hugs when I needed them. I love you.

To my mother and father: I would not be the person I am today without your love and incessant drive to make me a better person. Your guidance and advice for me has been invaluable and memorable.

My advisor, friend, and mentor: Doug Hart. Thank you for believing in this project even when my morale was low after many failures. I cannot wait to start my PhD and push this thing forward. Here’s to many more fun memories and experiences soon to come!

To Professor Eagar and Dr. Richard Taylor: your insight and generosity to help me understand the potential physics how this treatment process works is unparalleled. I also cannot thank you enough for your generosity in everything you have done for me.

Dr. Nick Pulsone, Dr. Andrew Siegel, and the rest of those involved from Lincoln Laboratory. This project would not be possible without you, as well as the insight and help provided throughout this project.
My lab-mates Mark and Thanasi. Thank you for supporting me through this and helping me throughout the whole process. We need to fix Doug’s rocking couch at some point.

John Vivilecchia, who runs the MIT Lincoln Laboratory Beaverworks Center. Without the use of this space, I would not have been able to complete my testing and build my system. It has been an invaluable resource to me, thank you. John, I’m look forward to doing my PhD and spending many more hours in the Beaverworks Center.

To my roommates Clark and Josh: I cannot thank you guys enough for an awesome year. I had a blast doing man meat nights, having a few cold brews, and going out to enjoy life. You helped me relax when I needed to and pushed me when I needed to work.

Rob Mazzarese; you are the man. Your insight and help with the IP has helped me shape and focus my project in a unique manner. Thank you for your input and incredible generosity. I hope to work with you more in the future.
## CONTENTS

**ABSTRACT** .......................................................................................................................... 1  
**ACKNOWLEDGEMENTS** ........................................................................................................ 2  
**CONTENTS** .......................................................................................................................... 5  
**LIST OF FIGURES** .................................................................................................................. 7  
**LIST OF TABLES** .................................................................................................................... 11  

### CHAPTER 1  ................................................................................................................................ 13  
1.1  **HYDROGEN AS A FUEL SOURCE** .................................................................................. 14  
   1.1.1  **Hydrogen Production** ............................................................................................. 15  
   1.1.2  **Hydrogen Storage** .................................................................................................... 15  
1.2  **HYDRIDES AND OTHER HYDROGEN SOURCES** ............................................................ 16  
1.3  **A USABLE ALUMINUM FUEL** ....................................................................................... 18  
1.4  **HYDROGEN STORAGE IN ALUMINUM** ......................................................................... 20  
1.5  **DECOMPOSITION OF ALUMINUM** .................................................................................. 21  
1.6  **CONCLUSION** .................................................................................................................. 22  

### CHAPTER 2  ................................................................................................................................ 23  
2.1  **THE HISTORY OF ALUMINUM** ..................................................................................... 24  
2.2  **DISRUPTING THE OXIDE LAYER** ................................................................................... 25  
2.3  **INTERACTION OF ALUMINUM WITH LIQUID METALS** ............................................. 27  
2.4  **TYPES OF ALUMINUM FUELS** ...................................................................................... 30  
2.5  **CHEMISTRY OF THE ALUMINUM-WATER REACTION** ...................................................... 31  
2.6  **CONCLUSION** .................................................................................................................. 32  

### CHAPTER 3  ................................................................................................................................ 35  
3.1  **METALLIC REACTION DURING TREATMENT** ................................................................. 35  
3.2  **REACTION WITH WATER** .............................................................................................. 46  
3.3  **REACTION DATA** ............................................................................................................. 50  
3.4  **EUTECTIC CONCENTRATION IN THE FUEL** .................................................................... 50  

### CHAPTER 4  ................................................................................................................................ 53  
4.1  **FUNCTIONAL REQUIREMENTS AND DESIGN CONSIDERATIONS** ............................. 54  
   4.1.1  **Fuel Cell Selection** ..................................................................................................... 55  
   4.1.2  **Aluminum Requirements** ........................................................................................... 57  
4.2  **REACTOR DESIGN** ........................................................................................................... 57  
   4.2.1  **Hydrogen Leakage** ....................................................................................................... 58  
   4.2.2  **Observing the Reaction** .............................................................................................. 60  
   4.2.3  **Finding the cause of low reaction completion** ............................................................. 67  
4.3  **FINAL REACTOR DESIGN** .............................................................................................. 71  
4.4  **RESULTS AND DISCUSSION OF REACTOR** ................................................................. 74  

### CHAPTER 5  ................................................................................................................................ 77
5.1 ADVANCING THE FUEL ................................................................. 77
5.2 ACCURATE HYDROGEN MEASUREMENT .................................. 79
5.3 POWER SYSTEM DESIGN ....................................................... 82
5.4 CLOSING POINTS ................................................................. 84

REFERENCES .................................................................................. 85
LIST OF FIGURES

Figure 1 - Selected Energy Densities of Non-Nuclear Materials................................................. 20
Figure 2 – Aluminum-Gallium phase diagram .......................................................................... 27
Figure 3 - Untreated aluminum spheres, 6mm in diameter, and have been polished for use as airsoft BB’s. .......................................................................................................................... 36
Figure 4 - Indium-gallium phase diagram showing the eutectic point between the two metals. This results in an alloy that has the lowest melting point possible between both metals. .......... 37
Figure 5 – Backscatter SEM image of a polished, untreated aluminum BB. There is visible cracking in the surface as well as distinguishable grains................................................................. 39
Figure 6 – Ternary Phase diagram of Indium, Gallium, and Aluminum at 180 °C .................. 40
Figure 7 – Diameters of treated and untreated BB’s were compared to examine how the treatment process affects overall size .................................................................................. 44
Figure 8 – A treated aluminum pellet as seen under a Hirox microscope. There is noticeable pitting on the surface. The shiny polished metal illuminated by the light is aluminum.......... 45
Figure 9 – A broken fuel piece as seen in an SEM using secondary electron imaging. Extrusion lines can be seen converging. The concavities of these lines are most likely due to a forging of some sort ...................................................................................................................................... 46
Figure 10 – An SEM image of the surface of a treated aluminum BB using backscatter imaging. There are apparent cracks in the surface and signs of corrosion due to treatment. Grain boundaries are also illuminated by the eutectic and there is also some hydroxide present as well. .................................................................................................................................................... 47
Figure 11 – Mapped area of the EDS analysis on a section sample of aluminum fuel that has been treated by an indium-gallium eutectic .......................................................... 48
Figure 12 – An EDS spectrum showing the peaks caused by X-rays being given off as electrons. The counts give an estimate of percentages of each element .............................................. 49
Figure 13 - Remus 600 Unmanned Underwater vehicle. Several design considerations made for the aluminum power system design were based off the assumption it would be used in this vehicle ................................................................................................................................. 54
Figure 14 - H2 consumption (ml/min at 0.5 bar) as a function of the power output for the Horizon H-200 fuel cell. There is an apparent non-linearity after about 150 watts in which more hydrogen is consumed for less differential power. ................................................................. 56

Figure 15 – This shows the pipe joining section with mating endcaps. One port on top is connected via tubing to a syringe pump, the other is for hydrogen flow out of the reactor. .... 59

Figure 16 – Some of the leftover waste that was left inside the reactor. There are small balls present inside this waste that were shrouded in hydroxide, which gave rise to the hypothesis that the waste choked off the reaction......................................................................................................................... 60

Figure 17 - This shows the reaction chamber with the polycarbonate top and the reactor body with the o-ring in place. No screws have been put in yet because the fuel must be added and then sealed.......................................................................................................................... 62

Figure 18 - The membrane covering the hydrogen outlet. Note the water inlet port to the upper right of the port. ................................................................................................................................. 62

Figure 19 - This is the experiment setup. A syringe pump with ganged syringes supplies a steady flow of water to the reaction chamber while a GoPro takes a time-lapse of the whole reaction. The hydrogen port outlet and the water inlet port are above the fuel mass inside the reactor. .... 63

Figure 20 – This is a graph showing the expected hydrogen flowrate compared to the measured hydrogen flowrate. The overall efficiency of the reactor was found to be 22 percent. .............. 64

Figure 21 – The filled reaction chamber showing the start of aluminum fuel reacting towards the right-hand side of the reactor. The hydrogen was bubbled underwater so that flowrates could be recorded via an inverted column of water.................................................................................................. 66

Figure 22 – This is the near the end of the test. The waste produced nearly the whole chamber. The dark spots shown are pieces of unreacted fuel which did not react due to poor treatment. .. 67

Figure 23 – The leftover treated fuel that was used in the delrin reactor test. Notice how there are shiny specimens as well as much darker, oxidized Once. Some of the shiny specimens reacted well and others would not, meaning a visual inspection method is not sufficient..................... 68

Figure 24 – The remains of the delrin reactor test. The beaker on the right shows the powdered hydroxide. The beaker on the right is a mixture of mostly leftover aluminum and some hydroxide waste. .................................................................................................................................. 69

Figure 25 – This shows various crush tests done on fuel used in the delrin reactor. The first (a) shows a crush test done on the unused fuel leftover, there are marks from where the vice-grip
teeth bit into the aluminum. Fuel taken from the reactor (b) showed similar bit marks from the vices used in (a), indicating it’s still ductile. Successfully treated fuel is shown in (c), the fuel crushed easily indicating liquid metal embrittlement had occurred. ........................................... 70

Figure 26 – Final System diagram showing the progression of steps required to react aluminum with water and flow hydrogen to the fuel cell at a constant flow rate. ........................................... 71

Figure 27 – Final experimental setup. This reactor ran for 90 minutes, generating 29 watts continually using only 34 grams of fuel. A fan was used as a demo prop to show the fuel cell was actually outputting electricity. ........................................................................................................................................... 73

Figure 28 – This is a plot of the measured and theoretical power outputs of the reactor as a function of time while reacting 34 grams of aluminum over 100 minutes. The measured reactor showed a quick startup time and maintained a relatively steady power output over an 80 minute period. ........................................................................................................................................... 75

Figure 29 - A proposed hydrogen collection system using an inverted column of water and a level sensor. Hydrogen is flowed from the top to minimize dissolution in water. ................. 81

Figure 30 - The new reactor will be used with testing moving forward. It is capable of running longer tests and higher power ranges than the current setup. The chamber has a much larger access port to the inside of the chamber as well as more ports in which too mount equipment to. ........................................................................................................................................... 83
**LIST OF TABLES**

Table 1 - Comparing Aluminum to Hydrides for hydrogen production density and cost ............ 17

Table 2 - Comparisons of different Aluminum fuels that use liquid metals as aids ................... 31

Table 3 – Estimated reaction requirements assuming a given volumetric flowrate of hydrogen. The flowrate can be adjusted to accommodate any desired fuel cell power for a given duration (minutes). .................................................................................................................................. 57
CHAPTER 1

INTRODUCTION

The pursuit of high energy density systems has resulted in the development of unique and effective energy storage devices. This is because the size and weight of a power system is often a higher priority than cost in many applications. For instance, unmanned underwater vehicles (UUV’s) are being developed for longer-range missions that current energy systems cannot sustain. Redesigning a vehicle to accommodate a larger power pack is impractical, thus the new power systems must meet the needs of existing designs. Personal electronics are a commercial example of this phenomenon and purchasing decisions are often made concerning power and size. Consumers want thinner and lighter devices while having either the same or better battery life.

Batteries provide a direct source of electricity, can be recharged multiple times, and can be discarded after use. For many applications, like unmanned underwater vehicles, current battery systems simply do not provide enough power for desired mission durations. Thus alternative methods of energy storage are being explored. Hydrogen, which has a very high specific energy density at 141 MJ/kg, is a promising energy storage method as it can be combined with oxygen in a fuel cell to generate electricity. The drawback to hydrogen power is its explosiveness when mixed with oxygen and the overall storage of the gas. Hydrogen gas is
very light, and simply compressing it does not provide a high enough energy density. Chemical means of storing hydrogen are also explored, however many of these compounds are very expensive and difficult to handle. Aluminum, however, can be reacted with water to generate hydrogen and heat and has shown to be a cost-effective and safe hydrogen storage method for many applications.

The purpose of this thesis is to teach how to design a high energy density power system using aluminum as a hydrogen source. This power system runs using a high-purity aluminum fuel that readily reacts with water to produce hydrogen and can be turned on and off repeatedly by changing the inlet flow of water. The byproduct hydrogen is then fed to a hydrogen fuel cell, which converts it into electricity to charge batteries or some energy storage system. Results have shown that the reactor outputs nearly 70% of the predicted power. With the rising need for power systems to produce power in smaller and smaller spaces, this technology shows that aluminum is a feasible fuel source to meet some of these demands.

1.1 Hydrogen as a Fuel Source

Hydrogen is well known for its use as rocket fuel due to its high specific density (142 MJ/kg). This puts it higher than almost any other non-nuclear material. Its overall energy density of just 5.6 MJ/L however, is low compared to materials like aluminum. Hydrogen can be used in fuel cell power systems as it can be reacted with air, producing water and electricity as byproducts. The biggest challenges associated with the use of hydrogen as a fuel source, as identified by the U.S. Department of Energy, are the production and storage of the gas [1][2]. Because there are no greenhouse gases produced, however, hydrogen is a very clean energy source and remains attractive to the energy industry. The ease of production and effectiveness of hydrogen storage methods are critical to its success as a fuel.
1.1.1 Hydrogen Production

In order for hydrogen fuel cells to be competitive with fossil fuels, the price of hydrogen fuel must compare to an equivalent amount of gasoline. The United States Department of Energy (DOE) has set cost and storage goals for hydrogen in order to spur innovation in the field. In 2010, DOE set a target goal for producing hydrogen at $2-3/kg which would make it competitive with gasoline as a vehicle fuel. Achieving this cost equivalence remains the biggest barrier to the adoption of hydrogen as a fuel. While fossil fuels are readily pumped out of the ground, hydrogen must be manufactured in some way. Ironically, the most ubiquitous method of producing hydrogen at present is from steam reforming of hydrocarbons. Other ways of producing hydrogen include electrolysis, solar thermochemical, photo-electrochemical, biological, and water separation methods. As hydrogen is not readily available in its diatomic state, and must be refined to such a state, it all comes down to how energy efficient the process is in procuring it. Research in hydrogen production is ongoing, however in the case of using aluminum as a hydrogen source that is competitive with gasoline, the DOE has already proved Aluminum can produce hydrogen at roughly $20/kg in an optimal process [3].

1.1.2 Hydrogen Storage

In 2010, the DOE set a chemical storage goal for hydrogen such that any substance must have a gravimetric capacity of no less than 6 percent by weight. This goal is already met with cryogenics, however cryogenic hydrogen containers are very large themselves and are not easily manipulated. Hydrogen gas has a density of 0.0899 g/L, making it the lightest gas in the universe, followed closely by helium. Hydrogen’s low density makes it an ideal lifting gas, as it is relatively the same cost as helium. With respect to the aluminum-water reaction, the optimal gravimetric hydrogen capacity of this reaction is 3.7 percent, which puts it well below the DOE
standards. As aluminum is below both DOE standards for storage and production economic metrics, it is unlikely that with current technology hydrogen will replace fossil fuels. These goals are very high, specific only to transportation, and do not take into account other factors such as practicality, portability, cost per weight, compactness, and comparability to other hydrogen generation methods. Aluminum has a place in the energy market outside of mass-transportation energy.

1.2 Hydrides and Other Hydrogen Sources

Hydrides are another means of generating hydrogen via a chemical reaction. They are compounds in which hydrogen atoms are bonded to a more electropositive element or group and are designed to have high gravimetric hydrogen densities [4]. Metal hydrides are shown to have the most promise as a chemical means of storing hydrogen as they will readily react with water. Some of these metal hydrides come close to satisfying the requirements published by the DOE for hydrogen storage with respect to reaction thermodynamics [5]. The best hydrides have a low bonding energy between the electropositive element or group and the hydrogen atom, while containing as many bonded hydrogen atoms as possible. This results in a compound that requires less energy to make, and also yields more hydrogen per kg of reactant.

Metal hydrides with high gravimetric hydrogen densities include lithium borohydride, calcium hydride, and sodium borohydride. Issues with current hydrides include the cost associated with production, as well as the fact that some of them are toxic and can also produce toxic byproducts when reacted with water. However, since they have gravimetric densities that are within the desired range as defined by the DOE, these hydrides are considered strong candidates for feasible sources of hydrogen. Aluminum has been compared to other hydrides, as seen in Table 1.1, in order to highlight the differences in total hydrogen yield per unit mass and
volume. In terms of cost per amount of hydrogen, aluminum is several orders of magnitude better as a solution as it is a readily available material. It has a low gravimetric density, relative to other hydrides, but if an aluminum fuel can be made in a cost-effective manner, it would be competitive with hydrogen simply from a cost standpoint due to the abundance and economic advantage of using Aluminum. In fact, a DOE annual report in 2014 even confirmed that hydrides, though effective at satisfying most DOE requirements for hydrogen storage, are simply too impractical for use on a large scale [2].

<table>
<thead>
<tr>
<th>Hydrogen Produced at STP (Liters)</th>
<th>Aluminum</th>
<th>Sodium Borohydride (NaBH4)</th>
<th>Calcium Hydride (CaH2)</th>
<th>Lithium Borohydride (LiBH4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moles of Reactant</td>
<td>0.030</td>
<td>0.011</td>
<td>0.022</td>
<td>0.011</td>
</tr>
<tr>
<td>Mass of Water Consumed</td>
<td>1.61</td>
<td>0.40</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>2.7</td>
<td>1.07</td>
<td>1.7</td>
<td>0.66</td>
</tr>
<tr>
<td>Liters of Material Required (mL or cc)</td>
<td>0.297</td>
<td>0.395</td>
<td>0.553</td>
<td>0.368</td>
</tr>
<tr>
<td>Cost of material ($/kg)</td>
<td>2</td>
<td>600</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Cost (dollars/Liters of H2)</td>
<td>0.002</td>
<td>0.253</td>
<td>0.470</td>
<td>0.365</td>
</tr>
</tbody>
</table>

**Table 1 - Comparing Aluminum to Hydrides for hydrogen production density and cost**

Given their high gravimetric densities, hydrides have uses in applications that require only small amounts of material, such as where mass is a limiting factor, or heat production must be minimized. Thus from a simple cost standpoint aluminum will be a more effective fuel than hydrides if these factors are not major concerns.
1.3 A Usable Aluminum Fuel

Aluminum is the most abundant metal in the Earth’s crust and is a highly desired source of energy due to its high reactivity and high energy density (83.8 MJ/L), which is more than twice that of gasoline (32.4 MJ/L). Aluminum also has the ability to react with water. This reaction is highly exothermic and produces hydrogen and aluminum hydroxide as byproducts (Eq. 1), which makes it an attractive fuel to use in high energy density systems. Using aluminum as a fuel has proven to be difficult because of the rapidly-forming aluminum oxide coating that develops on the surface of exposed raw aluminum. Removing or inhibiting this oxide layer is difficult, not only because it is very stable and exists at a much lower energy state than the raw aluminum, but also because it does not react at all with water and so inhibits forward progress of the reaction [6].

\[
2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2 + Q \tag{Eq. 1}
\]

Small pieces of aluminum, such as ball bearings and extrusions can be treated with an indium-gallium eutectic to form a fuel that is reactive in water. The treatment works by exposing the aluminum to a heated bath of an indium gallium eutectic for a given period of time. The treated fuel is then removed from the bath and allowed to cure for some time. This curing time allows the indium-gallium eutectic to penetrate the grains of the aluminum microstructure, while any excess left on the surface is centrifuged off and recovered. The aluminum is activated via liquid metal embrittlement due to the presence of eutectic gallium and indium in the grain boundaries, which forms a two-phase mixture with the surrounding aluminum bulk. This process allows the treated aluminum fuel to remain mostly inert in oxygen environments, but highly reactive in water.
When the aluminum fuel comes into contact with water, the aluminum on the surface reacts with the surrounding water, forming aluminum hydroxide and hydrogen gas. As the reaction continues, the fuel breaks apart, increasing the reactant surface area and exposing more pure aluminum ready to react with water. When reacted with a finite amount of water, the reaction heats up, which causes it to proceed at a faster rate and come closer to completion. How the water reacts with this specific fuel is not yet fully understood. There are several current theories, all of which are the topic of continued research. One theory is that the fuel acts as large conglomerate of micro-galvanic cells; the energy released by polar water molecules “completing the circuit” comes in the form of both heat and kinetic energy. The monocrystalline aluminum grain acts as a less noble anode, while the surrounding eutectic acts as a noble cathode. Thus, when dropped in water, the eutectic rapidly corrodes the aluminum in an electrochemical reaction. This theory is also consistent with why the fuel corrodes much more slowly than when exposed to oxygen in the atmosphere.

Previous attempts have been made at aluminum fuels by activating it with other substances, including gallium, indium, and tin [7], [8], [9]. Research on liquid metal embrittlement of aluminum, using gallium, is extensive and dates back to the 1960’s [10]. The fuels created in these previous endeavors, however, had either too low a hydrogen yield, or required too much activation agent for them to be practical or economical. For instance, an aluminum alloy containing 50% gallium will react to near completion, however half the weight of the fuel is gallium. This is cost-restrictive because Gallium is non-reactive and must be collected after the reaction is completed as it is very expensive [9]. Thus, any aluminum fuel must have the highest aluminum content possible in order achieve the highest energy density possible. The current aluminum fuel used in this thesis has achieved a 98% completion
percentage while containing only 2% gallium-indium eutectic by mass, making it the most energy dense aluminum currently known to the author.

1.4 Hydrogen Storage in Aluminum

Aluminum has a strong affinity for oxidizers, which allows it to react in water to produce hydrogen, aluminum hydroxide (see Eq. (Eq. 1), and heat. Aluminum is a suitable hydrogen source due to the quantity of hydrogen that can be released from its reaction with water. A 2.7 kg piece of aluminum (1 liter of the metal) is capable of producing 302 grams of hydrogen; the hydrogen has a potential energy of 42.9 MJ. Aluminum is also capable of releasing an additional 42.9 MJ of heat which can be used in several ways, including thermodynamic and mechanical applications.

![Figure 1 - Selected Energy Densities of Non-Nuclear Materials [11]](image-url)
The importance of aluminum lies in its energy density, a small volume of material able to produce such a large quantity of energy is what makes it such an attractive fuel. This is important for hydrogen power systems, as storage and safe handling of gaseous hydrogen is a challenge. The aluminum-water reaction is also a clean reaction. Aluminum Hydroxide ($2\text{Al(OH)}_3$) is often used in pharmaceuticals and as a fire retardant because of its stability as a molecule.

The reaction of aluminum with water presents an interesting design challenge, as the relative volume of reactants is significantly different. One liter of aluminum fully reacts with 5.4 liters of water, producing 5.7 liters of aluminum hydroxide ($2\text{Al(OH)}_3$), assuming that the resultant hydrogen byproduct is bled off. A system that stores aluminum hydroxide waste on board will have a starting energy density of 7.5 MJ/L. This assumes the total potential energy of hydrogen is converted into electricity. As most fuel cells will run with an efficiency of 40 to 60 percent depending on their size, quality of manufacturing, and other factors, an energy density of 4.5 MJ/L is theoretically possible. This does not factor in a storage vessel or size of the fuel cell, however gives it a higher energy density than lithium ion batteries, which is between 2 and 3 MJ/L. Using the potential energy of hydrogen produced by the aluminum reaction makes the aluminum power fuel cell a viable energy source. Further, finding a method of effectively utilizing the large amount of heat energy produced by the reaction could increase the energy density of system even more.

1.5 Decomposition of Aluminum

The first stage of aluminum processing comes with refining aluminum from its raw oxide state. Work with aluminum began with extracting it from its oxide state. Current research is aimed at decomposing aluminum metal back to its oxide state to extract energy from it. In fact, the challenges that need to be overcome to practically decompose aluminum are similar to those
associated with its manufacture. For instance, aluminum’s strong affinity for oxidizers was one difficulty that had to be overcome. The thin oxide film that develops on the surface of raw aluminum prevents scientists from getting powdered aluminum to agglomerate into a solid. The same oxide forms when a large piece of aluminum is reacted with air. Oxygen quickly oxidizes the raw surface, and the rest of the aluminum is trapped underneath the very stable, thin coating.

1.6 Conclusion

The aluminum water reaction does not meet the requirements of the DOE for use in mass transportation as it does not have a high enough gravimetric hydrogen density and it is simply too costly per liter of H2 produced. This is because aluminum requires energy to produce and requires two grams of water for every gram of aluminum to react. The utility of aluminum fuels lies is in the simplicity, abundance of aluminum, cost relative to other chemical hydrogen producers, and ease of handling. Thus, aluminum may be too expensive for mass transport of hydrogen, but it remains far cheaper, and more stable, than hydrides or other chemical storage methods. Aluminum’s high energy density also shows that it can produce significant amounts of heat and hydrogen in a compact space, making it an excellent fuel for high energy-density systems or as a cheap and mobile hydrogen source.

With respect to the power system which is the topic of this thesis, aluminum is the ideal hydrogen source because it is cheap, simple to use, and the reaction is easy to control simply by throttling the rate of water flow into the reaction chamber. The waste of the reaction can be recycled, in order to create more aluminum. Any remaining gallium or indium can be reclaimed and re-used in further treatment cycles.
An aluminum fuel that is both stable in air and reactive in water is a highly desired technology because it is simple to operate, easily transported and handled, and is capable of generating large quantities of hydrogen per unit mass of aluminum. This makes it an ideal fuel for high energy density systems. Aluminum fuels can be more practical than hydrides due to cost and the amount of heat produced in the reaction is much higher as well.

The power system under study here uses an aluminum fuel treated with an indium-gallium eutectic. In order to design an efficient system that is accurately characterized, the chemistry of this fuel must be understood. There are two key reactions: the interaction of liquid metal with aluminum, and the interaction of the aluminum fuel with water. The metal-metal reaction determined by the degree of aluminum pre-treatment, determines how much liquid metal will be present, as well as how complete the reaction will progress. This is the primary drive for increasing cost, as well as the amount of fuel needed in the reactor to provide the desired continuous power output. The fuel-water reaction must be understood and characterized, as this will determine the best method for delivering water to the reactor, and also will be used to measure the success of the treatment process. In order to understand why the eutectic-based fuel studied here is superior to other, previously discussed aluminum fuels, the fundamentals behind these reactions must be explored.
2.1 The History of Aluminum

Before the invention of the Hall-Héroult Process in 1886, aluminum was considered a precious metal, and at one point it was more than twice the value of gold or platinum. Napoleon even had his own personal cuirass of armor made from aluminum, and believed it to be an untapped resource that could be used to great effect in war. To date, the top of the Washington monument is capped with an aluminum pyramid, because when construction of the monument was completed in 1884, Aluminum was still considered a precious metal. Aluminum is abundant in the Earth’s crust, primarily found in a stable ore called bauxite. As Aluminum in its purest form is a highly reactive metal: reduction to a purely reduced form is very difficult to accomplish due to the three free outer-shell electrons. Lavoisier, a notable French scientist, was the first to predict aluminum’s existence in 1782 describing it as, “the oxide of a metal whose affinity for oxygen is so strong that it cannot be overcome by carbon or any other known reducing agent”[12].

It wasn’t until 1825 however when Danish Scientist H.C. Oersted produced the first sample of pure Aluminum. It was found to be a light, malleable, and strong metal with excellent corrosion resistance. Following Oersted’s discovery, new processes were developed to produce Aluminum in larger quantities. The majority of these were costly processes and which yielded only small amounts of pure aluminum, contributing to its consideration as a special metal. It was not until the invention of the electrolytic process that the price of aluminum dropped.

The electrolytic process was the next logical step forward in aluminum manufacturing and is founded on years of empirical knowledge generated by metallurgists and scientists over roughly a century. It was the simultaneous invention of American inventor Charles Martin Hall and Frenchman Paul L. T. Héroult, who worked independently of one another, arriving at their
conclusions almost simultaneously. Thus they are both credited with the invention. The electrolytic process of aluminum involves dissolving aluminum oxide in cryolite, which is a fluoride salt of aluminum, and then electrolyzing it. This causes pure and molten aluminum to deposit on the cathode while other impurities develop on the anode [13].

The curious thing is that both Davy and Deville, who were early pioneers of aluminum manufacturing, had both tried electrolytic of aluminum, but abandoned the idea. Hall was the one who eventually found that cryolite was a suitable salt that would readily and easily dissolve aluminum. Despite prior work, Hall and Héroult isolated the process that lead to the rise of a massive industry that would result in the production of alloys are, by weight, stronger than steel. The space age, aluminum beverage cans, and the aerospace industry were all enabled by the Hall-Héroult process of aluminum electrolysis.

### 2.2 Disrupting the Oxide Layer

Aluminum is capable of reacting with water to produce large amounts of hydrogen and heat; a naturally occurring aluminum oxide coating forms and inhibits the reaction. Though only a few nanometers thick [14], this coating is both very stable and inert, preventing further reaction between water and air and the underlying material. Disrupting this oxide layer, or preventing its formation, allows the aluminum underneath to continue reacting. Despite prior inventions that claim to render aluminum reactive by disrupting the oxide layer, none have been demonstrated to be commercial viable as of yet. Because of this, there is a need for technology that can maintain Aluminum reactivity.

One such method is to use an acid to continually etch and strip the oxide layer to corrode the aluminum underneath. This reaction consumes almost all of the aluminum, and is a nearly complete reaction, releasing heat, hydrogen, and aluminum hydroxide as reaction products. The
acid etching process was first described in 1907 in a patent filed by Hans Foersterling and Herbert Philipp [15]. Foersterling and Philipp invented a system that reacts aluminum with a strong acid to produce a steady flow of hydrogen. These designs, however, are generally impractical as large amounts of very strong acids are required in order for sufficient aluminum to be reacted, making them difficult and dangerous to handle.

Another method of disrupting the oxide layer is to use low temperature liquid metals like gallium, which is a liquid metal at room temperature (around 29 °C). Gallium has been demonstrated to have an affinity for wetting aluminum surfaces, and is capable of penetrating the oxide layer and diffusing along grain boundaries of the aluminum microstructure. With gallium inside the microstructure, a two-phase mixture is formed, as aluminum is soluble in gallium in low concentrations at room temperature. A binary phase diagram of aluminum and gallium shows that a liquid mixture of gallium and aluminum can exist across a large temperature range (Figure 2). At room temperature, there is a liquid mixture of both metals present inside the grain boundaries. The joint phase diagram suggests that this mixture is gallium rich. Liquid gallium causes grain boundary separation and leads to liquid metal embrittlement of the bulk aluminum.
2.3 Interaction of Aluminum with Liquid Metals

Aluminum fuels that are activated using gallium, indium, tin, or some combination of these three metals can be practical and economical as hydrogen sources if used properly. This is because they are relatively safe to handle with minimal personal protective equipment (PPE), and can be cost effective if used in small amounts and recycled [17]. Fuel for this power system is identified as having been properly treating by assessing the degree of embrittlement; if individual aluminum pellets can be easily crushed by a pair of vice-grips then adequate metal embrittlement has occurred. The liquid eutectic has fully penetrated the grain structure of the aluminum pellets.
Inadequately treated aluminum fuel will fail the crush test by deforming in a ductile manner, rather than crushing. Research on liquid metal embrittlement is extensive, including the use of gallium, indium, tin, mercury, and other metals. Current work suggests, however, that the science behind how liquid metals wet grain boundaries is not fully understood and there are many factors that govern its effectiveness.

A successful treatment begins with embrittlement of aluminum by wetting and penetration of grain boundaries by a certain liquid metal. The presence of a liquid metal in the grains can affect the fracture toughness of the solid metal depending on the type of solid-liquid metal interaction, how deep the liquid metal has penetrated the microstructure of the solid, and the relationship between the liquid metal and the tip of a developing crack[18]. One important thing to note when considering different solid-liquid metal couples is that the respective fracture toughness of each pairing can vary greatly, even from the base fracture toughness of the pre-treated solid [10]. As stated by Hugo and Hoagland in their paper on aluminum embrittlement by gallium: “in order for this to occur, the surface of the solid metal must be wetted by a certain liquid metal” [19]. Thus a sample of aluminum whose grains have been wetted with pure gallium may exhibit significantly different mechanical properties than one whose grains have been wetted with a liquid eutectic of gallium and another similar metal like tin, or indium.

With ductile metals like aluminum, failure generally occurs via slow discontinuous crack growths. This process is greatly accelerated when a liquid metal, like gallium, enters the microstructure. In order for liquid metal embrittlement to occur in a ductile material, the liquid metal must be adsorbed by a crack tip on the surface of the metal and penetrate deep enough into the microstructure to cause intergranular fracture [20] [21]. As a result, it is generally easier to
cause liquid metal embrittlement of a metal piece that has been cold worked, thus it has more surface cracks for the liquid metal to exploit.

Liquid metal embrittlement of aluminum via gallium is a well-known phenomenon and research on it is extensive, however the mechanism behind how gallium travels along the grain boundaries is not fully understood [18]. There is evidence that shows it is dependent on multiple factors. A study in 1976 done at Laboratoire de Metalurgie in Paris investigated the absorption of gallium into aluminum grain boundaries by changing the grain boundary size of aluminum via cold rolling [22]. They found that the amount of gallium absorbed as well as the ductility of the aluminum was dependent on how large the aluminum grain boundaries were (as a result of the cold rolling), the time in which the aluminum was soaked in the gallium, as well as the temperature of the gallium.

Rabkin et al. proposed a model for the kinetics of how liquid gallium travels along aluminum grain boundaries. They claim that the entrance of liquid gallium atoms into an aluminum grain via a crack in the surface caused changes in the crystal lattice, resulting in elastic strain of the lattice [23]. This change in strain puts the bulk out of equilibrium slightly and results in a net force on the liquid metal, pulling it further into the structure [24]. Hoagland et all observed this process occurring at several $\mu/s$, showing that this is a very fast process, and grain boundary diffusion rates are orders of magnitude higher than bulk diffusion rates, thus polycrystalline aluminum is the preferred microstructure for liquid metal embrittlement [16] [21].

There are many factors that affect the severity of liquid metal embrittlement in aluminum. Various liquid metals used have shown to have different effects on aluminum grains. How these liquid metals affect aluminum depend on the temperature at which they’re applied, grain size, the
alloying elements of the aluminum, and any internal stresses that exist in the aluminum. Thus there are many different possible ways aluminum can be treated using just liquid metal embrittlement. This means that a change in any of these parameters could ultimately have an effect on reaction completion and the cost of fuel depending on how much liquid metal is needed to successfully treat.

2.4 Types of Aluminum Fuels

Liquid metal embrittlement is just one method of treating aluminum so that it can react in water. Other methods include chemical catalysts that help corrode aluminum rapidly in water, in-situ diffusion of aluminum into liquid metals, and casting aluminum with other metals that prevent the protective oxide layer from forming. In order to compare these different methods, a couple factors will be considered: amount of liquid metal used and hydrogen yield from the process. These two variables correlates directly to cost-effectiveness and practicality. If too much liquid metal is used, the fuel becomes heavier, yields less hydrogen per unit mass, and becomes more expensive. If the hydrogen yield is low, more fuel is required and thus it becomes less competitive compared to other hydrogen generation methods.

The treated aluminum fuel used in this thesis is compared to the highest yield cast aluminum fuels: ball milled powders, and aluminum diffusion methods. It will be shown that the aluminum fuel in this thesis has both a high hydrogen yield and a low liquid metal content relative to other methods of liquid metal embrittlement. The in-situ diffusion method is different because aluminum can theoretically be continually added to a pool of liquid metal, like gallium, submerged underwater. Aluminum dissolved into the large mass of liquid metal and reacts with the liquid metal-water interface continually.
The trouble with some aluminum-water reaction methods is the abundance of waste that is produced. The aluminum-water reaction produces aluminum hydroxide, which is in the form of a fine powder (average particle sizes of $>1\mu m$). However, it becomes a thick gelatinous substance when exposed to water. This substance generally throttles the reaction as the aluminum hydroxide acts as a physical barrier between exposed aluminum and water, thus slowing the reaction. One important feature of the treated fuel in this thesis is that hydroxide does not slow down the reaction. It is unknown however as to why this is, however it may have to do how the aluminum-water reaction occurs with this specific fuel.

### 2.5 Chemistry of the Aluminum-Water Reaction

The reaction of aluminum and water is a hydrolysis reaction as it involves the splitting of water molecules into $\text{OH}^-$ and $\text{H}^+$ ions, respectively. Hydroxide bonds to the aluminum, and the hydrogen atoms bond with one another, forming aluminum hydroxide and hydrogen gas. The leading theory for aluminum exposed to or treated by certain liquid metals is that the liquid metals will prevent a stable oxide layer from forming on pure aluminum, and when in contact with water, the aluminum ions will split water molecules. The reaction proceeds as the liquid metal continually and rapidly corrodes unreacted aluminum until completion of the reaction [28].
This theory does not entirely explain why some fuels react to completion and why others will not, when presumably both fuels were treated with the same methods. For instance, there are various different aluminum fuels that react to varying degrees with different types of water [27][29][30]. The reasons behind this variation are beyond the scope of this thesis; speculation, however, and an understanding of the different treatment methods show no real trend or correlation between different studies, as there is no adequate data currently known to the author.

Another theory could be that there is some sort of galvanic reaction occurring as well. Aluminum has an electrical potential of -1.66 V, whereas gallium’s potential is -0.53 V and indium’s is -0.34 V [31]. In order to split water, a minimum potential difference of 1.23 V is required. There is a potential difference of 1.32 between aluminum and indium, which is greater than the minimum requirement, thus there is most likely some sort of corrosion occurring in fuels that contain indium. When aluminum is treated with a liquid metal, the liquid metal penetrates grains and surrounds mono-crystalline bits of aluminum. The treated aluminum can be thought to have hundreds of small galvanic cells, existing in a bulk of aluminum. As water comes into contact with the two metals, the more noble metals like gallium and indium form a micro-galvanic cell with the less noble metal, aluminum. Thus the aluminum will corrode, yielding aluminum hydroxide and hydrogen as byproducts. The liquid metal embrittlement helps to increase the surface area and number of galvanic cells than if the aluminum had not been treated. There is little research into this theory, but it will be further discussed herein.

2.6 Conclusion

There are many different types of aluminum fuels produced by various manufacturing and treatment methods. Many of these have been studied and documented in the literature and are the subjects of numerous patents. Few to none of these, however, have been shown to be economical
with respect to their ability to generate hydrogen on-demand, obtain high reaction completion, and be used in a power system. It will be shown that this process is unique to others which have been previously documented in that the treatment method, utilizing gallium and indium and developed through an iterative process of discovery, results in an aluminum fuel which satisfies all of these benchmarks.
A Usable Aluminum Fuel

The fuel used in this power system is unique compared to other fuels in that it has a high reaction completion, large mass per unit (0.3g), and low gallium and indium content. Other processes also claim that there must be a covering of liquid metal on the surface of aluminum in order to activate the fuel [32]. This is because these processes claim there is rapid dissolution of aluminum into the liquid metal boundary, which then hydrolyzes with water. This is not the case with the fuel presented here in this thesis, as all excess indium-gallium eutectic is removed from the surface in order to conserve eutectic and reduce the cost of the fuel. In essence, this is a “dry” fuel, as opposed to previous fuels which relied on a liquid metal surface coating. Dry fuel also reacts just as well, even with no visible liquid metal on the surface. Treatment of aluminum BBs to create the dry fuel is also unique in that it can be used to treat many different alloys of aluminum to varying amounts.

3.1 Metallic Reaction during Treatment

Dry aluminum fuel, created through liquid metal embrittlement of aluminum BBs produced from raw aluminum subjected to some form of cold working, like forging and extruding, has been produced. Reactive aluminum fuel was first made using aluminum spheres 6mm in diameter (Figure 3). Since then, rods, bars, and a plate have been treated, the largest
sample of aluminum having a volume of 35 mL (2.5 in.³). The first step to preparing the treatment bath is to create a eutectic of gallium and indium; this is about 20% indium by mass and the rest is gallium (Figure 4). The eutectic is then heated in a water bath to 160 °C and aluminum is placed in the bath.

Figure 3 - Untreated aluminum spheres, 6mm in diameter, and have been polished for use as airsoft BB’s.
Figure 4 - Indium-gallium phase diagram showing the eutectic point between the two metals. This results in an alloy that has the lowest melting point possible between both metals. [33]

When it comes into contact with the eutectic bath, both the aluminum and the oxide coating deform due to thermal expansion. The coefficients of thermal expansion for aluminum and its oxide are $2.22 \times 10^{-5}$ and $5.4 \times 10^{-6} \text{ m/} (\text{K})$, respectively. Using just the coefficient of thermal expansion approximation to determine stresses (Error! Reference source not found.), the differential strain between aluminum and aluminum oxide with a temperature difference of $135^\circ \text{C}$ (from $25^\circ \text{C}$ to $160^\circ \text{C}$) is $2.3 \times 10^{-3}$. Since the aluminum is expanding more than the oxide, thermal stresses can cause the oxide layer to crack. Using the relationship of stress and strain to the material’s modulus of elasticity (Error! Reference source not found.), the resulting stress differential between the bulk and the oxide is about 1 GPa. The yield stress of
aluminum oxide in tension is about 0.25 GPa, which is well below the expected thermal stress; because of this cracking is likely to occur and enable penetration of the bulk by the liquid metal eutectic.

$$\varepsilon = \alpha \Delta T$$ \hspace{1cm} (2)

$$E = \frac{\sigma}{\varepsilon}$$ \hspace{1cm} (3)

Since there is a minimum stress that causes cracking, a rough minimum treatment temperature can be solved for as well. Assuming 0.25 GPa is the minimum stress needed to crack the oxide layer and using the same constitutive equations, the lowest treatment temperature that should show similar results is 100 °C.

Since there is cracking at the interface of the aluminum with the gallium and indium, this allows the gallium and indium to penetrate into the aluminum via the grain boundaries and preexisting defects from manufacturing. As these pellets are extruded and forged, there is an abundance of crack sites, which as shown in prior studies is critical to facilitating liquid metal embrittlement. These defects can be seen on the surface of a polished aluminum sphere. Figure 5 shows a backscatter SEM image of the surface of an untreated BB. Noticeable cracks and grains are apparent on the surface, which serve as diffusion pathways for gallium and indium.
Figure 5 – Backscatter SEM image of a polished, untreated aluminum BB. There is visible cracking in the surface as well as distinguishable grains.

The process of making fuel is highly dependent on the diffusivity of the indium-gallium eutectic in aluminum grains. Diffusion into solids is a complex process because it can depend on many different physical parameters. For instance, grain boundaries are the interfaces of monocrystalline grains, thus there is generally more space in this boundaries, as the atoms of both surfaces will not always align with one another. Atoms can diffuse along grain boundaries up to several orders of magnitude faster than diffusing through a monocrystalline bulk [34] [35]. The highlighted grains of Figure 5 show there is a two-phases present and that there is an indium-gallium-aluminum mixture inside the grain. Figure 6 is a ternary phase diagram of aluminum, indium, and gallium at 180 °C. This is above treatment temperature, but it gives insight on the composition of the liquid phase in the grain boundaries of the aluminum. This diagram shows that at even 180 °C, aluminum is practically insoluble in indium, but some solubility is possible
in the gallium. This casts doubt on the theory that aluminum simply dissolves in the eutectic and reacts with water on the surface. It indicates some other mechanism must be at work that is allowing the aluminum to react.

Figure 6 – Ternary Phase diagram of Indium, Gallium, and Aluminum at 180 °C

In order to get a successful treatment of aluminum fuel so that only minute amounts of eutectic are used and only small amounts of aluminum are lost, lower and upper bounds must be applied to the treatment parameters. If the aluminum is allowed to sit on top of the eutectic for too long at a high temperature, significant corrosion may occur, resulting in a less efficient process. Thus the aluminum needs to stay in a certain amount of time so as to allow enough eutectic to penetrate crack sites and get into the grain boundaries, but not long enough that significant corrosion occurs.

The minimum temperature at which aluminum can be treated was solved for earlier to demonstrate cracking of the oxide layer. This allows the eutectic to enter the aluminum grain
structure via defects in the surface. There is also a time dependence factor so as to allow the BB’s to cure and adequate eutectic to be absorbed. The aluminum needs to absorb enough eutectic liquid metal so that embrittlement will occur. Using Fick’s Second Law of Diffusion (Eq. Eq. 4), we can estimate how long it takes for the gallium and indium to penetrate the grains of the aluminum.

\[
\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \quad \text{Eq. 4}
\]

Fick’s second law helps determine how diffusion causes concentration to change with time. The diffusion constant \( D \left( \frac{cm^2}{s} \right) \) is assuming the diffusivity of the liquid metal does not change as it penetrates further into the aluminum, which is the case for most cases. This distance penetrated is denoted as \( x \), which has units of cm. Concentration, \( c \) in this equation, has units of \( \frac{kg}{cm^3} \). There are many solutions to Fick’s second law as it is entirely dependent on boundary conditions of both the solute (gallium-indium eutectic in this case) and the solvent (aluminum). For the sake of simplicity, we will use an error function solution, which gives an common approximation of a constant concentration of liquid metal \( c_2 \) into an infinite region of material. A solution using the error function, Eq. 5, “relates the concentration (c) at any position (x) (depth of penetration into the solid matrix) and time (t) to the surface concentration (c_2) and the diffusion constant (D)” [34].

\[
\frac{c_2 - c}{c_2 - c_2'} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right) \quad \text{Eq. 5}
\]

This assumes different concentrations and can be used to various depths of penetration. If we want to find only the depth of penetration as a function of the eutectic’s diffusivity in aluminum grains and the time of exposure, we assume concentration inside is zero, thus \( \frac{c_2 - c}{c_2 - c_2'} \) is
effectively 1. This approximation, Eq. 6, assumes a constant temperature, but gives quick and relatively accurate estimate on how quickly diffusion occurs.

\[ 1 = \text{erf} \left( \frac{x}{2\sqrt{D}t} \right) \]  
\[ \text{Eq. 6} \]

To further simplify this expression, we will ignore the error function as we are only getting an estimate time of diffusion for a given depth Eq. 7.

\[ x = \sqrt{4Dt} \]  
\[ \text{Eq. 7} \]

The diffusivity of gallium in aluminum grain boundaries at 325K is about $5 \times 10^{-6} \text{cm}^2 \text{s}$. The diameter of a BB is 6mm or 0.6 cm, thus if we assume a flat plate being treated on both sides we can find an upper bound for curing time. The treatment process only lasts 120 minutes, but the fuel must sit for at least 24 hours before it can be used effectively. The diffusion constant of the eutectic in aluminum is not as significantly affected by temperature inside of a grain boundary as the diffusion constant through monocrystaline aluminum. This is because the grains already provide sufficient space for the liquid metal to travel. Thus we will use the above diffusion constant for the whole process, from treatment in liquid metal, throughout the curing time. In order to penetrate 3mm in an aluminum media (half the diameter of a sphere) using an indium gallium eutectic, it takes about 1 hour and 15 minutes. This is within an order of magnitude of the observed treatment time, thus we can set upper bounds on how long the fuel must sit. Assuming the diffusion coefficient through a large bulk of material is lower than the observed constant calculated for smaller pieces of aluminum, $10^{-7} \text{cm}^2 \text{s}^{-1}$, we will get about 63 hours. These numbers both make sense and confirm the treatment times observed in this process and justify letting the fuel sit after heated treatment. This allows the eutectic to further make its
way down smaller grain boundaries and into the aluminum further, thus making it more brittle and resulting in higher reaction completion percentages due to smaller corrosion sites and galvanic cells being formed.

The aluminum remains in contact with the heated eutectic for about 120 minutes while a person makes sure the entire surface comes into contact with the eutectic. During this time, gallium and indium will diffuse only a marginal amount into the bulk. The aluminum is then removed from the bath and allowed to cool. Any remaining eutectic wetted to the surface is removed via centrifuge and is then recycled back into the bath. Following the treatment process, the treated aluminum must sit for 24 to 48 hours to cure to allow the absorbed eutectic to finish diffusing throughout the aluminum bulk. Figure 7 shows a treated aluminum sphere following the treatment process. By weighing the aluminum BB’s both before and after, a probability density function was generated (figure 3) to show the how their mass changed in the treatment process. The average mass of untreated BB’s was 0.297g and the average mass of the treated BB’s was 0.302g.
Figure 7 – Diameters of treated and untreated BB’s were compared to examine how the treatment process affects overall size.

These results show a relatively low mass is gained, about 0.005g, when the fuel is treated. This is because the aluminum is not left in the heated bath of indium-gallium eutectic long enough for significant corrosion to occur. There is some pitting in the aluminum surface, but more mass is gained by the presence of the eutectic, thus there is mass transfer occurring. Some aluminum is dissolving into the eutectic and some eutectic is entering the microstructure. Also, as since the treatment process is in a bath and a centrifuge is required to separate any additional gallium and indium on the surface of the treated aluminum, there may be a larger percentage of gallium and indium on the surface than is needed, which means larger shapes with lower surface area to volume ratios are more favorable. Pitting sites may be facilitating deposits of eutectic on the surface as well. As a result, there is still a lot that needs to be done in terms of determining the optimal temperature at which to treat and the duration of treatment, but the current process still produces the most effective aluminum fuel ever made.
Figure 8 – A treated aluminum pellet as seen under a Hirox microscope. There is noticeable pitting on the surface. The shiny polished metal illuminated by the light is aluminum.

These aluminum spheres were originally used as BBs for airsoft guns. Following treatment, the spheres become embrittled by the liquid eutectic and were cracked into halves using vices. Figure 9 shows a split aluminum sphere under the SEM. There are apparent forming lines that are highlighted by charging on the image due lack of conductivity of aluminum hydroxide and aluminum oxide. These formed due to being in contact with the oxygen and moisture in the air. There are also apparent extrusion lines that are highlighted by charged aluminum hydroxide that formed on the surface.
Figure 9 – A broken fuel piece as seen in an SEM using secondary electron imaging. Extrusion lines can be seen converging. The concavities of these lines are most likely due to a forging of some sort.

3.2 Reaction with Water

Following eutectic bath, the aluminum bodies are allowed to sit for 48 hours so as to allow the diffusion part of the treatment to complete. These aluminum grains are highlighted by the single-phase mixture of Indium, gallium, and aluminum as shown in Figure 10. Under the SEM, they look like scales on the surface of the aluminum. This SEM image was taken on the surface of a treated aluminum sphere, which was rubbed clean. Since these treated bodies react violently in water, the surface of the bodies give insight on the reaction characteristics as it is where the reaction starts.
Figure 10 – An SEM image of the surface of a treated aluminum BB using backscatter imaging. There are apparent cracks in the surface and signs of corrosion due to treatment. Grain boundaries are also illuminated by the eutectic and there is also some hydroxide present as well.

Conventional theory is that gallium inhibits the forming oxide layer on aluminum, and as a result aluminum dissolved in the single-phase mixture in the grains will react with water as it comes into contact with it. This depletes the concentration in the mixture, causing the raw aluminum still in contact with the mixture to dissolve and thus travel to the water-mixture interface and thus a runaway reaction occurs as aluminum in the bulk travels through the indium-gallium eutectic to the water to react. However, as indicated by the phase diagram of indium, gallium, and aluminum, aluminum is all but insoluble in indium, which means that this may not be the only mechanism in which the aluminum is reacting with water. In order to confirm the presence of indium in the aluminum grains, an energy-dispersive X-ray spectroscopy analysis
(EDS analysis) was done on a sectioned piece of treated fuel (Figure 11 and Figure 12). When the BB was sectioned, the indium-gallium eutectic coagulated on the surface, resulting in higher concentrations of eutectic than is actually present in the grain boundaries.

**Figure 11** – Mapped area of the EDS analysis on a section sample of aluminum fuel that has been treated by an indium-gallium eutectic.
Figure 12 – An EDS spectrum showing the peaks caused by X-rays being given off as electrons.

The counts give an estimate of percentages of each element.

As there are two phases present in the aluminum bulk (liquid and solid) and both are different compounds, an alternative theory is that the treated aluminum fuel is made up of many tiny galvanic cells which, when given a solution to allow electron transport, rapidly corrode. As discussed earlier, the potential difference needed to split water is 1.23 V. The voltage differential between aluminum and indium is 1.32 V, which means this theory may be true. The most likely scenario in the case of this fuel is both reactions are occurring – aluminum is rapidly diffusing into the indium-gallium eutectic and reacting with water at the surface, but there is also a galvanic reaction which is aiding the corrosion of aluminum further. Regardless of oxide forming, the galvanic reaction will still occur, this is probably why such a high reaction completion is observed.
3.3 Reaction data

Using an inverted cylinder and a level sensor inside the cylinder, aluminum fuel created with this treatment process is evaluated for degree of reaction completion by measuring the hydrogen produced, and comparing this value to a theoretical yield. Initial results show that the treated aluminum fuel yields 95% ± 3% of the expected hydrogen, this shows that the fuel is highly efficient as well as containing low concentrations of Indium and Gallium. This is because the overall mass of the aluminum pieces were used in approximating hydrogen yield, thus there is already an inefficiency built into the calculation as the gallium and indium are recoverable at the end of the reaction. This can

3.4 Eutectic Concentration in the Fuel

Determining gallium and indium concentration are very important in determining the viability of the dry fuel, as they are expensive metals. During the reaction, no gallium and indium are consumed as they are more noble metals than aluminum. Following the reaction, the indium and gallium are recovered by mixing the reactants with low molar muriatic acid. Aluminum hydroxide is highly soluble in acidic solutions, thus the eutectic is released into a clear solution, and Aluminum is reacted out. In order to accurately represent how much indium and gallium were in treated aluminum spheres, four aluminum spheres were reacted in each test. The remaining gallium was collected and its mass determined via high-resolution scales. Gallium recovered from each aluminum sphere is 0.005g ± 0.002g. This is about 2% of the fuel by mass, however there is significant pitting on the surface of the treated surface and eutectic can be wiped off even after centrifuging, which means the internal concentration of gallium and indium is likely lower and can be further lowered. Characterizing the variation in Gallium and Indium
concentration from the exterior to interior of the aluminum sphere will be the topic of further work.
CHAPTER 4

DESIGN OF AN ALUMINUM POWER SYSTEM

The first step in designing this aluminum power system was gaining insight on the reaction kinetics of the fuel and sufficient knowledge of the reaction byproducts. There are three main areas of design: the reaction vessel, waste management, and controls. The reaction must take place inside a sealed reaction chamber which directs dry hydrogen to the fuel cell. The reaction produces heat via a reaction with water, thus any steam produced has to be dealt with since the fuel cell takes only dry hydrogen. The aluminum hydroxide produced in the reaction is a fine powder and becomes gelatinous and sludgy when wetted by water. This must either be kept inside the reaction chamber or expelled in some manner as more fuel is introduced into a reaction chamber. Controls for chemical systems can be very difficult as as the system response may be delayed and can get out of hand quickly if not designed carefully. The reaction chamber must create a flow of hydrogen to the fuel cell; this means that unless there is some sort of reservoir of hydrogen then the reaction must produce exactly the same amount of hydrogen per second. Else risk the fuel cell being starved, or over-pressurizing the system with hydrogen, which can be dangerous.
4.1 Functional Requirements and Design Considerations

The original goal of this project was to design a power system that would extend the current range of unmanned underwater vehicles (UUV) like the Remus 600 (Figure 13). Many design considerations for this power system were made on the assumption that it would be used inside of a REMUS 600. The REMUS demands a power system capable of producing 200 watts continually for 5 days with the ability to power on and off as well. However, an aluminum power system generating 200 watts for 5 days demands 9.5 kg of fuel, which takes days to manufacture with the current method. In order to avoid complications that detract from debugging a prototype system, it was decided to run a lower power system at a shorter duration so as to conserve fuel and make testing more practical as it would unsafe to leave a running system unsupervised.

Figure 13 - Remus 600 Unmanned Underwater vehicle. Several design considerations made for the aluminum power system design were based off the assumption it would be used in this vehicle.
Functional requirements were generated in order to give a basic framework for the overall design:

1. Generate 100 watts for 8 hours continuously via a Horizon H-200 fuel cell
2. Pressurize hydrogen in reaction chamber up to 1 bar (15 psi) to deliver a steady flow of hydrogen
3. Store all waste inside reaction chamber up to 2 liters
4. Use less than 5 watts of power for electronics

Design considerations were then created, which are driven primarily by the aluminum fuel and fuel cell. Firstly, the hydrogen must be delivered dry, as any water will degrade the longevity of the fuel cell. Also, stock parts were favored over anything custom machined. This refers primarily to the reaction chamber as little was known about reaction dynamics of large quantities of fuel. A simple, robust, and reliable prototype system was desired more than a complex one.

### 4.1.1 Fuel Cell Selection

Most fuel cells are bought on a kilowatt scale, thus finding one that could achieve the desired 200 watt range limited our options. The fuel cell used for this power system is the Horizon H-200 PEM fuel cell, which has a max power output of 200 watts. The drawback with this fuel cell is that it requires 15 watts for the power electronics and solenoids, thus reducing the overall efficiency of the system. In terms of hydrogen conversion though, this fuel cell runs optimally between 50 and 60 percent depending on the hydrogen input and desired power range. Also it was found that some water vapor in the hydrogen will not hurt the fuel cell.

When it comes to power output, the closer the fuel cell becomes less efficient with hydrogen as it approaches peak power. The hydrogen consumption rate per unit power is
relatively linear at first, but has diminishing returns after about 150 watts (Figure 14) according to the service manual. The same trend is apparent with their lower range fuel cells. Thus a 200 watt cell allows for slightly higher wattages while also maintaining the best efficiency possible. Also, in order for the fuel cell to function properly, it must be delivered a steady flow of hydrogen for a specific power input. This means the fuel cell cannot variably change its power output to fit a given hydrogen input, thus any feedback loops must be centered on producing a steady hydrogen flow. Even though the H-200 fuel cell was one of the only options to pick from, it is a good option for a prototype system because it is forgiving with inputs and power output.

**Figure 14** - H2 consumption (ml/min at 0.5 bar) as a function of the power output for the Horizon H-200 fuel cell. There is an apparent non-linearity after about 150 watts in which more hydrogen is consumed for less differential power.
4.1.2 Aluminum Requirements

The amount of aluminum fuel needed for the fuel cell to run at any power setting can be calculated using stoichiometry, energy density calculations, and the efficiencies given in the user manual. A 100 watt power output alone requires a specific hydrogen flow rate. Figure 14 shows H₂ consumption by the fuel cell at half an atmosphere gauge pressure. Thus for 100 watts, it needs roughly 800 mL/min of hydrogen gas at 0.5 atmospheres. Using this as a starting point, we can back calculate using the stoichiometric ratios of the aluminum water reaction that gives how much aluminum is required. Table 3 shows estimated values for a reactor that needs to produce 102 watts for 8 hours. The mean reaction completion of current fuel is 94%, which means the mass of aluminum required needed a correction factor. Also, water consumed is assuming a perfect reaction, thus an extra 30 percent more is added in case it wets the hydroxide and does not reach the unreacted fuel. This helps ensure a complete reaction inside the chamber.

| Volumetric flow rate of H₂ at 1.5 bar (L/min) | 0.8 |
| Volumetric flow rate of H₂ at 1.0 bar (L/min) | 1.2 |
| Duration of mission (minutes) | 480 |
| Total volume of water needed for reaction (L) | 1.2 |
| Total mass of aluminum fuel needed for mission (kg) | 0.49 |
| Hydrogen produced (L) | 576.0 |
| Fuel Cell Power (watts) | 102.0 |

Table 3 – Estimated reaction requirements assuming a given volumetric flowrate of hydrogen. The flowrate can be adjusted to accommodate any desired fuel cell power for a given duration (minutes).

4.2 Reactor Design

With parameters set for the power system, the next step was to determine how the reaction proceeded inside of a reaction chamber. In order to be cost efficient and have a starting point to gather data and intuition, stock parts were used wherever possible. There were many unknowns
that simply could not be predicted without testing and learning how the fuel behaves. Thus several reactors were designed and built using different hypotheses of how the fuel would react and how reaction products would form and manifest themselves in a sealed environment.

The biggest unknowns were waste accumulation, hydrogen leakage, and fuel completion. The waste complicated everything because it acts as a barrier between water and fuel. This means that if the reactor was running for a certain amount of time and then shut off, it would take time to restart it as water has to make its way through the waste to unreacted fuel. Hydrogen is one of the smallest molecules, which makes sealing it difficult. Thus we needed to gain intuition on how leaky it was using different reactor variations. Reaction completion is arguably the most important objective. If high reaction completions can be obtained inside a small, sealed space, then the overall efficiency of the reactor would be high, thus validating aluminum as a viable fuel.

4.2.1 Hydrogen Leakage

In order to react the Aluminum in a steady and controlled fashion, it was assumed a steady flow of water or small bursts of water would mitigate any sudden bursts of hydrogen that might occur during the reaction inside the chamber. Thus for initial tests, a syringe pump was used so that relatively low flowrates could be obtained for small reactor tests. The first reactor consisted of a pipe section with 2.5 inch threads on either side with screw-on endcaps. Ports were added to one side so that water could be continually dripped on top of a batch of fuel inside. The purpose of this test was to show how much hydrogen would be generated from a known amount of fuel and how leaky these threads would be when Teflon tape is applied to help seal.
Figure 15 – This shows the pipe joining section with mating endcaps. One port on top is connected via tubing to a syringe pump, the other is for hydrogen flow out of the reactor.

It was determined that only a fraction of the reactor would be filled in order to see how the reaction would occur without restricting space. The volume of this reactor is roughly 400 mL, yet it was filled with only 15 mL of aluminum, thus giving it plenty of room to expand. The results of this test were mostly inconclusive however. This is because the reactor showed to be very leaky and was proven by simply submerging the reactor underwater. The hydrogen had a high affinity for escaping via the threads. Teflon tape and large threads, as hypothesized, were not suitable for sealing hydrogen. What was learned is that the hydrogen flowrate out of the reactor is relatively steady, thus indicating there is a direct correlation between the hydrogen flow rate out and the water inlet rate. Some knowledge was also gained about the waste, it indeed
did expand, but there was some leftover fuel which was concerning shown in Figure 16. It was originally determined that the waste choked the reaction and prevented water from reaching the fuel. Thus another test needed to be done, but with a visual means to determine how the reaction took place when water is dripped down into the reaction chamber.

![Image of leftover waste](image)

**Figure 16** – Some of the leftover waste that was left inside the reactor. There are small balls present inside this waste that were shrouded in hydroxide, which gave rise to the hypothesis that the waste choked off the reaction.

### 4.2.2 Observing the Reaction

A new reactor was then designed so that we could gain insight on how the reaction occurs inside when water is dripped down on top of the fuel. This test was the see how waste buildup would occur, how much space the waste would take up, what effect it might have on unreacted fuel, how it affected the ongoing reaction, and how steady a hydrogen flow rate was possible. As the aluminum reacts, it generates a fine powder of aluminum hydroxide, which is less dense than solid aluminum. It has a varying bulk density depending on how compact it is. Thus a reaction
chamber must allow expansion of the fuel as it reacts. Figure 17 shows a round reactor made from a single piece of black Delrin. The top is a polycarbonate sheet which forms a seal with the reactor via an o-ring.

The chamber itself has a volume of 500 cm$^3$ and is designed to allow a 5:1 volume expansion of the reacted fuel, thus it is designed for 100 cm$^3$ (or 270g) of aluminum fuel. The reactor has only two ports: an inlet for water, which is pumped in via a syringe pump, and an outlet for hydrogen gas. Over the hydrogen outlet there is a thin membrane which is made of pure PTFE laminated onto a non-woven layer polypropylene. Figure 18 shows the membrane, which is bonded onto over the hole by epoxy. The purpose of this membrane is to prevent liquid water from escaping the chamber and mitigate the amount of steam leaving the chamber so hydrogen flow rates can be accurately measured.
Figure 17 - This shows the reaction chamber with the polycarbonate top and the reactor body with the o-ring in place. No screws have been put in yet because the fuel must be added and then sealed.

Figure 18 - The membrane covering the hydrogen outlet. Note the water inlet port to the upper right of the port.
The test conducted in the reactor was using 270g of fuel, which was at the maximum capacity of the reactor design. It was also determined that this fuel would be reacted over five days, thus a water flowrate of 0.075 mL/min of water are needed. If the fuel reacts with the water completely, it produces 9.7 watts of thermal power. The fuel used was treated for two hours at 160 °C and allowed to sit for longer than two days. Since waste buildup is a concern, the inlet and outlet ports were placed above the aluminum fuel, so that when water is introduced to the reactor, it would simply drip down the reactor wall to contact the fuel. Figure 19 shows a setup of the experiment with a syringe pump and a GoPro to record the experiment over five days with 270 grams of aluminum fuel inside, note both ports are placed above the fuel.

**Figure 19** - This is the experiment setup. A syringe pump with ganged syringes supplies a steady flow of water to the reaction chamber while a GoPro takes a time-lapse of the whole reaction. The hydrogen port outlet and the water inlet port are above the fuel mass inside the reactor.

Hydrogen was measured at various intervals throughout the test. The collected data with hydrogen however showed that the flowrate of water is does not produce the expected flowrate of water out. The hydrogen flowrate out was used to calculate how efficient the reactor was overall.
Figure 20 shows the theoretical hydrogen flowrate overlapped by the measured hydrogen flowrate. They’re overlapped as the total volume of hydrogen measured can be compared to the theoretical yield of hydrogen. Though the yield is not encouraging for the reactor, the steady hydrogen flowrate observed initially gives insight on how pump parameters can be adjusted to meet a specific hydrogen flowrate for future reactors.

![Chart](chart.png)

**Figure 20** – This is a graph showing the expected hydrogen flowrate compared to the measured hydrogen flowrate. The overall efficiency of the reactor was found to be 22 percent.

Despite the low efficiency, the gathered data shows that the hydrogen flowrate out of the reactor is relatively stable and does not generate any large spikes of hydrogen gas as originally feared. It shows a relatively consistent hydrogen production and a relatively quick ramp-up time. The first hydrogen flow was detected at 26 minutes into the test, indicating that the water took time to move from the fitting to the fuel due to the surface tension of the water. Also, around
hour 48 shows there is a rather drastic cutoff in hydrogen production, which means the fuel was either choked off, or no usable fuel remained in the reactor.

The time lapse footage showed how the reaction occurred throughout the test and gave valuable qualitative data. Figure 21 and Figure 22 show the reaction chamber before and after completion of the test. It appeared that the point of water insertion did not affect how the reaction occurred. The reactor in Figure 22 shows significant condensation inside the reactor window, meaning water did not have any trouble reaching the bottom of the chamber. This means a new reactor could be design without a major concern about how fuel would react. Steam generated by the reaction helped react surrounding fuel pellets at a fairly consistent rate. The next step was to understand why such a low reaction completion was observed. Leak tests showed that the o-ring was not allowing hydrogen to escape and the fittings were well seated.
Figure 21 – The filled reaction chamber showing the start of aluminum fuel reacting towards the right-hand side of the reactor. The hydrogen was bubbled underwater so that flowrates could be recorded via an inverted column of water.
Figure 22 – This is the near the end of the test. The waste produced nearly the whole chamber. The dark spots shown are pieces of unreacted fuel which did not react due to poor treatment.

4.2.3 Finding the cause of low reaction completion

Tests done on the leftover treated BBs used showed there were some bad specimens, these were generally very shiny and showed no pitting or scarring of the surface, indicating that little to no eutectic either contacted the surface or simply could not penetrate the surface (Figure
These pieces of bad fuel hardly reacted in water at all, thus the test was doomed to have a low reaction completion with the start.

Figure 23 – The leftover treated fuel that was used in the delrin reactor test.

Notice how there are shiny specimens as well as much darker, oxidized once.

Some of the shiny specimens reacted well and others would not, meaning a visual inspection method is not sufficient.

The waste that was recovered was sorted into hydroxide and leftover fuel remains by hand (Figure 24). The waste in the leftover aluminum beaker was mostly whole and intact pellets, which means the pellets were all but inert when exposed to water. In comparison to hydrogen yield (22 percent completion), it was found that the ratio of leftover aluminum to the original amount recovered was 88.3 percent, meaning 11.7 percent of the aluminum was reacted. This means there is likely a significant amount of hydroxide waste in the leftover aluminum beaker that was affecting the measurement. The low completion percentage and visual state of
the BB’s left only two explanations. The first is that the aluminum hydroxide chokes off the reaction, or the fuel was improperly treated to begin with.

\[\text{Figure 24} \quad \text{The remains of the delrin reactor test. The beaker on the right shows the powdered hydroxide. The beaker on the right is a mixture of mostly leftover aluminum and some hydroxide waste.}\]

Initial tests of fuel in limited water showed it was going to completion, which did not match the theory that aluminum hydroxide was choking the reaction. The first reactor did not have the same looking waste as delrin reactor did, which further pointed to a treatment issue. Thus visual testing was determined inadequate in identifying if fuel was treated properly. As liquid metals like
gallium are known to embrittled aluminum, we went back to the basic physics of why the aluminum fuel works. Leftover samples of the fuel batch used in the delrin reactor were selected and subjected to a crush test via a pair of vice grips. The results showed that the poorly treated samples of aluminum did not crush, but only deformed in a ductile manner. Properly treated fuel however crushed into smaller pieces very easily, thus indicating liquid metal embrittlement had occurred.

![Figure 25](image_url) - This shows various crush tests done on fuel used in the delrin reactor.

The first (a) shows a crush test done on the unused fuel leftover, there are marks from where the vice-grip teeth bit into the aluminum. Fuel taken from the reactor (b) showed similar bit marks from the vices used in (a), indicating it’s still ductile. Successfully treated fuel is shown in (c), the fuel crushed easily indicating liquid metal embrittlement had occurred.

Thus the low reaction completion of the fuel was a result of poorly treated fuel. It was determined that there was too high of an aluminum concentration inside the eutectic bath after multiple treatments, thus at the end of each treatment session, a layer of water was put over the eutectic so as to react out aluminum ions. This assured that every time forward, aluminum would be treated with fresh eutectic, ensuring consistent fuel batches.
4.3 Final Reactor Design

With the knowledge of how the aluminum fuel reacts in bulk, the leakiness of hydrogen, and how to consistently make fuel, a final design capable of generating 100 watts was able to come together. The final system diagram (Figure 26) is very linear. This does not show feedback loops and controls, but the concept is straightforward: water is dripped onto a large batch of treated aluminum fuel. The fuel reacts, producing aluminum hydroxide, hydrogen gas, and steam, thus pressurizing the reactor up to 15 psi (1 atmosphere gauge). The steam and hydrogen flow up through a vertical condensing column, where any condensed water falls back into the reaction chamber. The hydrogen still has high humidity, but for the sake of simplicity and because the fuel cell in reality works fine with humid hydrogen, it was decided not to use a desiccator. The hydrogen moves through a regulator which steps the pressure down to 7 psi straight into the fuel cell.

![Diagram of the final reactor design](image)

**Figure 26** – Final System diagram showing the progression of steps required to react aluminum with water and flow hydrogen to the fuel cell at a constant flow rate.

The final system design was made entirely out of stock parts and built for simplicity rather than constrain with space (Figure 27). The components for this system were selected to be low power and small in size however. This is because when the machine is scaled up and iterated into
a new design, new parts would not have to be specified. The reaction chamber is a 0.5 gallon
specified air horn tank meant for use with trucks. These tanks, which are powder coated and
rated for 200 psi of pressure, conveniently have 5 NPT ports, which when wrapped with Teflon
tape, are sufficient to sealing hydrogen. Thus a safety factor of an order of magnitude was in
measure since pressurizing hydrogen with custom parts can be dangerous. A blowout valve rated
for 40 psi was even placed in the reactor in case the reaction ever went runaway. The loads
connected to the fuel cell were a dissipating resistor board and a pair of computer fans. The
resistor board took the majority of the electrical power and the fans were added for dramatic
effect. The overall layout of the system looks scattered and messy, however with proper scaling
and optimization of parts, it will quickly become more compact and efficient.
Figure 27 – Final experimental setup. This reactor ran for 90 minutes, generating 29 watts continually using only 34 grams of fuel. A fan was used as a demo prop to show the fuel cell was actually outputting electricity.

The controls for the system were run open loop initially. Using the hydrogen flow rate to water input rate determine in the delrin reactor, a correction factor of 0.4 to 0.5, we were able to control the first reactor test relatively easily. The pressurized chamber acted as a buffer for the system, if the pressure dropped low enough, the code was changed to allow more water to flow into the reactor. The closed loop control system operated very similarly. The reaction chamber was not allowed to vary further than 12 and 18 psi. Thus the water level would increase or decrease by 25 percent or more depending on what the pressure readings were. Apart from
controlling the flowrate of water into the reactor and reading the pressure transducer data, the system ran on its own, with the help of power supplies to run the electronics of the fuel cell and microcontroller.

4.4 Results and Discussion of Reactor

The test involved reacting 34 grams of aluminum fuel over the course of 100 minutes. The amount of fuel selected was arbitrary in order to test the control loops of the system by giving it an estimated water flow rate. This meant that we could not run it using the open loop values used in a prior experiment, and forcing us to test the resiliency of the programming. The power of the system was recorded using the dissipative resistor board. The current was passed through a precision 0.1 ohm resistor. The voltage was measured across this junction to determine the overall current passing through, thus giving the current. The voltage at the fuel cell outlet directly from the cell was also measured and recorded as a function of time. With the current and voltage, we were able to figure out the overall power output of the machine and plot it versus the expected power output Figure 28.
Figure 28 – This is a plot of the measured and theoretical power outputs of the reactor as a function of time while reacting 34 grams of aluminum over 100 minutes. The measured reactor showed a quick startup time and maintained a relatively steady power output over an 80 minute period.

In order to determine the overall efficiency of the reactor, the measured power was integrated over the time period to determine the total electrical energy produced by the fuel cell. Using Riemann sums, over 144 kJ of energy were produced by the fuel cell. The theoretical Energy output of the Fuel cell with 34 grams of aluminum is 207 kJ of energy, thus the overall efficiency is 69.6%.

For a proof of concept reactor, an overall efficiency for 69.6 percent. As there are several potential errors that are not fully accounted for. First, the startup of the reactor was not executed, there was some struggle with turning the fuel cell on, which resulted in some gas having to be purged from the chamber over the course of 5 minutes. The fuel cell used also has some issues – the device has a purge valve that uses hydrogen to flush water produced by the catalytic plates. There is a solenoid that controls this flow, however the one mounted on the fuel cell gets stuck
open much longer than it is designed. Leaking of hydrogen is also a probable cause for lost efficiency. The condensing column uses many fittings and adapters ganged together, and only soft tubing with barbed fittings was used between the regulator and fuel cell. Soft tubing was used because the fuel cell only has barbed fittings. In the future, these will all be switched out with hard tubing and metal seals, thus reducing the total amount of leakage.
FUTURE WORK

The aluminum fuel used in this thesis is different in that it has a high reaction completion and only utilizes small quantities of indium and gallium. Despite the extensive research that has already been done on aluminum fuels and liquid metal embrittlement of aluminum, there is a lot more that needs to be done to understand how and why it works. This thesis goes only as far as to provide hypotheses for the how the fuel is treated and why it reacts so well in water. Thus more data is needed to see if these hypotheses are valid or not. The current power system is designed for functionality and simplicity. The next step is to shoot for higher system efficiency and size reduction. If both of these targets are met, it will result in a system with a much higher energy density.

5.1 Advancing the fuel

The most successful fuel is made using 6 mm airsoft BB’s of an unknown alloy. Other known alloys of aluminum have been treated successfully as well, but not quantified with data yet as the samples were too large to collect hydrogen in. The first step is thus to determine empirically how effective the current treatment process is with different alloys of aluminum. It has been shown that cold working such as forging and extruding are beneficial to successful treatment. As the compositions of these alloys are carefully controlled, connections can be drawn between the effectiveness of treatment and the presence of various elements in aluminum. This is
determined by overall hydrogen yield and percentage of eutectic inside the bulk. If cheaper alloys with higher aluminum content are preferred, this will reduce the cost of processing significantly as well as potentially improve hydrogen yield.

Eutectic content inside the fuel is one of the largest cost drivers for the fuel. Currently, successfully treated aluminum fuel contains 2 \pm 0.5\% eutectic by mass, which is roughly equal to the cost of the aluminum. If this can be reduced further via a more efficient treatment process, it will help make the fuel more economical as well as increase potential hydrogen yield.

The current fuel making process has a cycle time of roughly 4 hours and yields 300 grams of fuel. This is because it takes 30 minutes for the eutectic to heat up, 2 hours for pellets to treat, 30 minutes for them to cool down after treatment, and they are then centrifuged to remove any excess eutectic. Some samples have shown similar reactivity for lower treatment times which improves it significantly, however the process is wasteful enough that other methods should be explored. For instance, in order to assure the eutectic contains no aluminum at the beginning of each treatment, muriatic acid or water is poured on the surface and allowed to react. This produces a significant amount of hydroxide, which takes time to develop as well. Thus other treatment methods will be explored in order to reduce cycle time, labor, and decrease eutectic content.

As there are still unknowns as to how and why the treatment process works, there are many experiments that must be done in order to frame an optimal method to treat aluminum fuel. The hydrogen yields and eutectic content of current make it a viable hydrogen source, however there is room for improvement. The treatment, an optimal alloy of aluminum must be identified as well as a preferred formation process, the application method of eutectic, time of exposure to heat, and finally the temperature of treatment are all variables that affect the treatment process.
and must be optimized in some form. These can all be quantified by how much hydrogen is yielded from treated aluminum, thus an accurate hydrogen collection system is needed.

5.2 Accurate Hydrogen Measurement

The effectiveness of fuel is determined by how much hydrogen it generates per unit mass. The current average efficiency of the fuel is 94 percent, however the goal is to reach 98 percent efficiency, allowing for impurities and treatment elements. The most popular gas measurement methods involve using inverted column of water or gas syringes, however measurements made using these methods carry too much allowable error. Also there is a need to measure volume of hydrogen gas produced as a function of time. This will give insight on reaction kinetics and give data that shows how fuel completion varies as a function of how much water it is given to react with. Thus other means of collection hydrogen must be explored.

Gas syringes are considered to be effective means of measuring gas volumes. The trouble with these devices is ensuring minimum sticking occurs between the sealing o-ring and the wall of the syringe. Also, the volumes of most syringes are on the order tens of mL, but most fuel samples produce hundreds of mL. There are larger syringes available, however these are not rated for hydrogen and have lower resolutions. Gas syringes are a viable backup plan for hydrogen measurement, but they are not desirable means of measurement for this application.

Most setups that use inverted columns of water involve the reactants in a flask, whose products are bubbled underneath the inverted cylinder. Buoyant forces carry the gas bubbles to the top, where they collect and displace further water. A 0.3 gram treated aluminum sphere will produce between 350 and 410 mL of hydrogen in a reaction with water, which is approximately 0.017g of hydrogen. An inverted column of water using a 500mL cylinder has a net volume of
water of roughly 1L including the beaker in which displaced water is dispensed. The solubility of hydrogen gas in water at room temperature is about 0.0015g of gas per 1kg of water [36]. A maximum of 9 percent of the produced hydrogen can dissolve in the water. Bubbles have internal pressures due to surface tension, which results in higher solubility, thus it is likely a significant amount of hydrogen gas dissolves in water before it ever reaches the top of the column to collect.

Using an inverted column of water does have its advantages. If the hydrogen is introduced into the column in a manner which minimizes dissolution, then over the time length of the experiment it can produce accurate data. If hydrogen is introduced from the top of a cylinder, the interface area between the hydrogen gas and the water is much smaller than if it is bubbled up from underneath. Also, a level sensor can be integrated with an inverted column of water, which can give accurate volume measurements as a function of time. A proposed design
combines both the use of a level sensor and feeding hydrogen from the top with an inverted column of water Figure 29.

**Figure 29** - A proposed hydrogen collection system using an inverted column of water and a level sensor. Hydrogen is flowed from the top to minimize dissolution in water.

This design is made entirely from polycarbonate, which is very inert and capable of sealing hydrogen. The level sensor is a strip whose resistance changes as a function of water height in the column, thus it can be calibrated for this inverted cylinder. Using 2 inch inner diameter tubing with the sensor, it provides a resolution of ±0.2mL, which is well within the allowable tolerance. Also, to minimize dissolution of hydrogen into the water, Styrofoam balls will be floated on the surface, thus reducing surface area even further. This setup is quick to fabricate and build, and will provide much more accurate data than current measurement techniques.
5.3 Power System Design

The current power system was designed for practicality and ease of use. The next step is to scale up the power generated as well as compact components on the reactor. The reaction kinetics of fuel of the power system 30 watts are stable and easy to manage due to excessive space and steady water input. Little is known however about how the fuel will react when the power is increased up to hundreds of watts or even kilowatts or when the waste is constrained. Also, if the system needs to be stopped for a period and started up again after a while, the reaction may be different and the startup time may be delayed depending on how much waste is in the reactor. The components, electronics, and fuel cell all need to be organized in a way that reduces the overall system volume.

There are still many unknowns about how this system will act as different parameters are increased to their limits, however specific design considerations help guide the process and provide a starting framework. The reactor setup in this thesis utilizes a half gallon air horn tank which is cumbersome and makes compacting the design difficult as the ports are all on different side. A new reactor was designed very similar to the current one, however it was designed with the potential of running much longer tests, higher power ranges, as well as provide a more versatile platform to mount instruments, pumps, and other pieces of the system (Figure 30). Another benefit of this new reactor is the ability too easily access the contents of the reaction chamber. The air horn tanks only have 5 NPT ports which makes extracting waste difficult, thus reusing them is not a practical option. This reactor shape and size is not known to be optimal, however it fulfills important design parameters of a simple, robust, and reliable reaction vessel.
Figure 30 - The new reactor will be used with testing moving forward. It is capable of running longer tests and higher power ranges than the current setup.

The chamber has a much larger access port to the inside of the chamber as well as more ports in which too mount equipment to.

As certain parameters are increased or changed, new components must be selected. This includes finding a new pump, pressure transducers, and a high power fuel cell. The current fuel cell was chosen due to lack of options within the 200 watt power range, however in kilowatt ranges, there is a wider selection of fuel cells to choose from. Also a new condenser must be designed to accommodate the larger reactor which raises more unknowns, such as if water will passively reenter the reactor, or if excess water will simply be collected and reused somehow. Choosing these components to be forgiving as well as operable in a wide range of parameters will be a higher priority than size and compactness. Moving forward with this power system,
more data is needed to characterize system response as well as system layout before it is
designed for application use.

5.4 Closing Points

Aluminum is currently not a cost effective fuel source in transportation as the price of
fossil fuels are so cheap in comparison, however it does serve a purpose in other technologies. It
has the potential to size down and reduce the overall weight of a power system due to its high
energy density. This can be done for a small fraction of the cost of other chemical hydrogen
sources and in a much safer manner, as the fuel is safe to handle and transport. Also, it can react
with almost any water source, thus pure water does not have to be moved with the reactor. The
portability and robustness of a system like this means it can also be used in extreme
environments where most other power systems cannot operate. There are many applications for
the this aluminum fuel as it carries a lot of potential, however there are still many unknowns
from the treatment process up through an aluminum power system that must be answered before
it can be effectively used.
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87