

Scrap Aluminum as Fuel

by

Shannon Miller

Submitted to the Department of Mechanical Engineering
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Abstract

The new development of a low cost, low risk aluminum fuel production method has extended the viable use cases of aluminum as a fuel. Scrap aluminum has the potential to provide fuel in disaster relief zones when infrastructure is ruined and scrap metal is abundant. Additionally, converting scrap aluminum to fuel can provide an alternate option to traditional recycling methods. The following paper presents various methods used to process and treat scrap aluminum and the resulting efficacy of these methods. Four different fuel production methods are presented. Parameters such as method of reforming scrap aluminum, percent mass eutectic in fuel, eutectic coating time, and pretreatment of aluminum cans are varied. The various methods achieved a wide range of efficiencies with the best being 57%.

Thesis Supervisor: Douglas P. Hart

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1. Introduction

1.1 Background on Aluminum waste

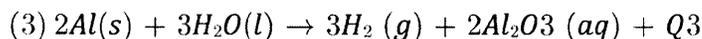
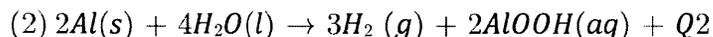
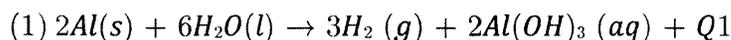
In the United States, Aluminum cans and packaging are the largest source of aluminum in municipal solid waste (MSW) [1]. Aluminum accounts for 1.4% of total municipal solid waste with a total weight of 3.6 million tons of aluminum in 2015 [1]. Globally, 6.5 million tons of aluminum were produced in 2018 [4]. The total recycling rate for aluminum containers in the US was 36.4%, with beer and soft drink cans having the highest rates of recycling at 54.9 % [1]. This adds to 0.7 million tons of aluminum cans in the US in 2015[1]. However, it is important to consider the lifecycle of the aluminum recycling process. In some cases, aluminum is transported large distances from the point of collection to be recycled. Transporting materials long distances increases cost and environmental impact of recycling. A low capital method of turning aluminum into fuel could be of particular use to low income countries which do not currently have the infrastructure to carry out traditional aluminum recycling. According to the World Bank, low income countries spend much more on waste collection rather than waste disposal, while in high income countries, the majority is spent on waste disposal [3]. For this reason, an alternative to traditional recycling which provides energy and a means of reusing waste could have positive environmental impacts while also supporting local economic growth.

Natural disasters create a large amount of debris. It is estimated by Puerto Rico's Solid Waste Authority that Hurricane Maria created 6.2 million cubic yards of waste and debris [2]. In the EPA's document "Planning for Natural Disaster Debris", they outline that many of the materials generated by natural disasters are recyclable [3]. The EPA recommends that all debris management plans include the recovery of debris for recycling as it has positive environmental, economic, and cultural impact [3]. Following natural disasters, many times the vital infrastructure for energy and water are destroyed. If scrap aluminum could be made into fuel, the aluminum debris created by natural disasters can be used as fuel to help communities recover from these disasters.

1.2 Aluminum Activation Process

Aluminum has an energy density of 83.8 MJ/L which is over double the energy density of gasoline and more than 10 times higher than lithium ion batteries. It is difficult to release the internal chemical energy of aluminum as it is inert in air and water due to an oxide layer that forms almost immediately and prevents reaction. In order to bypass this, Aluminum has been ground into a fine powder and reacted through combustion. Aluminum powder combustion is used in situations where high energy density is critical, such as rocket fuel, but it is incredibly dangerous and poses serious health risks. To avoid combustion, various methods have discovered that the oxide barrier can be bypassed in the presence of gallium and indium allowing the aluminum to react in the presence of water and release large amounts of thermal and chemical energy. This chemical oxidation could take one of three forms, Aluminum

Hydroxide ($\text{Al}(\text{OH})_3$), Aluminum Oxyhydroxide (AlOOH), or Aluminum Oxide (Al_2O_3) as shown in equations 1, 2, and 3.



At atmospheric pressure and temperatures of 70 C the aluminum-water reaction occurs via Equation 2. When fully reacted in this manner, a single kilogram of aluminum will release 15.7 MJ of heat energy per kilogram, and 1245 L of hydrogen gas. Due to this high energy density, Aluminum fuel reaction with water has been considered promising for a long time. However, the methods for producing water-reactive aluminum fuel have not been feasible due to safety concerns and cost. When aluminum is powderized it is reactive with only small amounts of gallium and indium, but poses serious risks for explosivity and inhalation. Alloying the aluminum with large fractions of gallium (Ga), indium (In), or tin (Sn) and surface treating the aluminum with gallium and indium are safer options, but are considered cost prohibitive as gallium and indium are rare metals and incorporating large mass fractions of them into a fuel is very expensive. However, a surface treatment method developed by Slocum in recent years allows for the development of effective fuel with minimal concentrations of gallium and indium. Creating fuel with this method requires only small concentrations (2-6%) of gallium and indium by mass, and maintains high reactivity (>80%). The Slocum method involves placing raw aluminum in a heated gallium and indium eutectic bath. While this method only involves 2-6% eutectic by mass, significantly more eutectic is needed to create the bath. To lower overhead costs and make fuel in a more controlled manner, Fischman developed a slight variation to Slocum's process. In Fishman's

method, a container of aluminum spheres is heated to 120 C and a small amount of eutectic (~5% by mass) is then added to the container. The container is mixed thoroughly by shaking and left at 120 C for 90 minutes. It is shaken vigorously every 20 minutes to ensure the eutectic fully coats the aluminum spheres. This is the method that was primarily used in the following experiments. A detailed description of the fuel creation process is described in the **Appendix A**.

1.3 Measuring Reaction Yield

In order to measure the reaction yield of a piece of aluminum, Fischman designed a method to measure the volume of gas produced when aluminum was reacted with water. Given a known mass of aluminum to be reacted, and the fact that the aluminum-water reaction always produces 3 moles of H₂ gas for every 2 moles of reacted aluminum, the expected moles of hydrogen produced from a complete reaction can be calculated. The moles of hydrogen can be converted to the volume of hydrogen using the ideal gas law. Finally, the ideal volume of hydrogen can be compared to the measured volume of hydrogen to determine a percentage of reaction completion. The experimental setup is depicted in **Figure 1** reproduced from Fischman. The complete procedure for measuring the reaction completion can be found in the **Appendix B**.

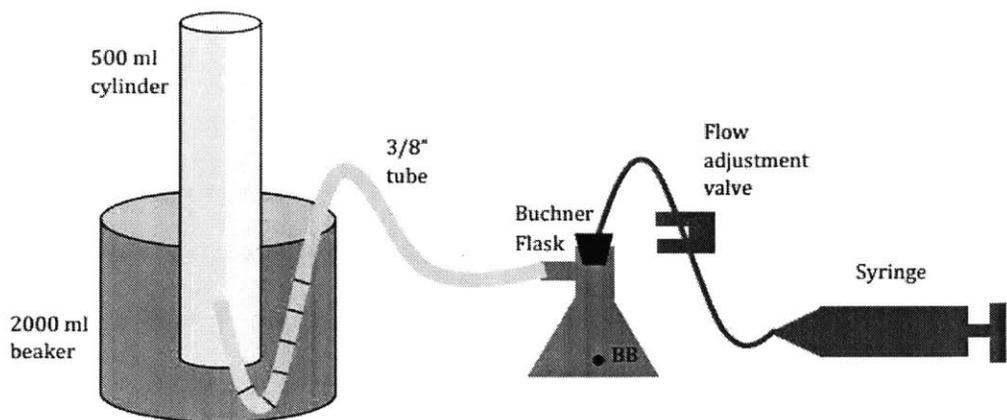


Figure 1: Experimental setup for determining percentage of reaction completion

2. Production of Fuel from Aluminum Cans

2.1 Method 1: Pliers

As a first step to determine the feasibility of using aluminum beverage cans as fuel, simple pellets were made using pliers and a vice. An aluminum can was rinsed out and otherwise left completely untreated. Squares of approximately .75 inches were cut from the can and then folded and compressed using pliers and a vice. These pellets were then prepared using the standard surface coating fuel production method described in **Appendix A** with a slightly higher concentration of eutectic by mass. Due to the small masses of fuel being produced, 10% eutectic by mass was added instead of 5%. A finished pellet following fuel production is shown in **Figure 2**.



Figure 2: Fuel pellet prepared using Pliers and standard surface coating method

This pellet was then tested following the procedure outlined and was determined to have an efficiency of 38%.

2.2 Method 2: Hemi-Spherical Jig

In order to make more standardized fuel that has truly been reformed into a new pellet, the cans must first be shredded and then recompact. A Bonsai C169-B paper shredder was used to shred the cans into smaller pieces. These shreds were then placed in a machined aluminum jig as seen in **Figure 3**. The jig consists of a simple hemisphere $\frac{1}{2}$ " in diameter milled into a piece of aluminum.

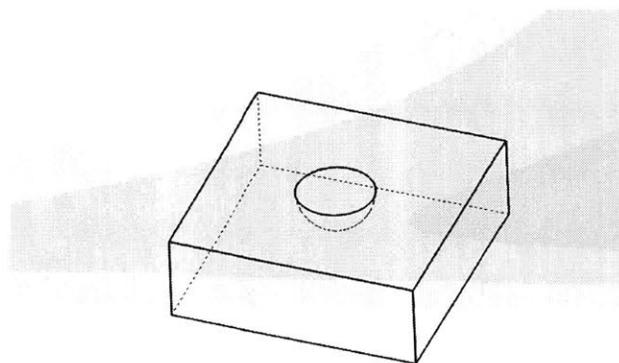


Figure 3: Diagram of Spherical jig used in Method 2

Shreds were placed in the jig and a hammer was used to compact them. This method had many issues. The shreds were not adequately constrained in the jig and the impact from the hammer often caused the shreds to bounce out rather than compact. When the shreds did begin to compact, additional hammering did not result in further

compacting. Instead, the shreds became more brittle, fracturing into pieces. Fuel pellets were not able to be successfully made with this jig.

2.3 Method 3: 1/4" Jig

In order to fix these problems in the next iteration, it was important that the shreds be constrained on all sides during compaction and the force be constrained. The second jig consists of an aluminum block with cylindrical pocket .25" in diameter and a small pin through hole as seen in **Figure 4**. A steel cylindrical rod of diameter .25" is used to transmit force. Shreds were loaded into the pocket and an arbor press was used to provide compaction force down through the cylindrical pin. The cylindrical pin was then removed and a needle was used to poke out the pellets through the back small pin hole.

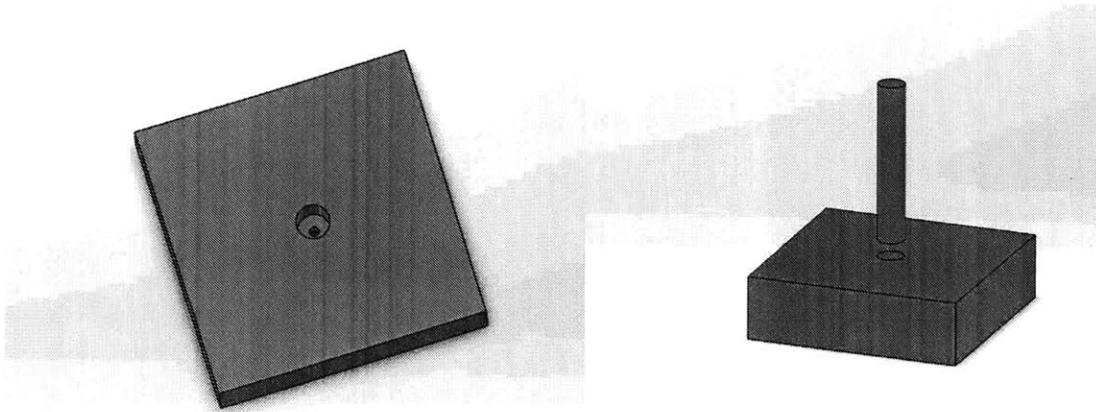


Figure 4: Diagram of 1/4" jig used in Method 3

This method successfully compacted shreds into pellets. These pellets were then made into fuel using the standard surface coating method. An image of a pellet following eutectic coating can be seen in **Figure 5**.

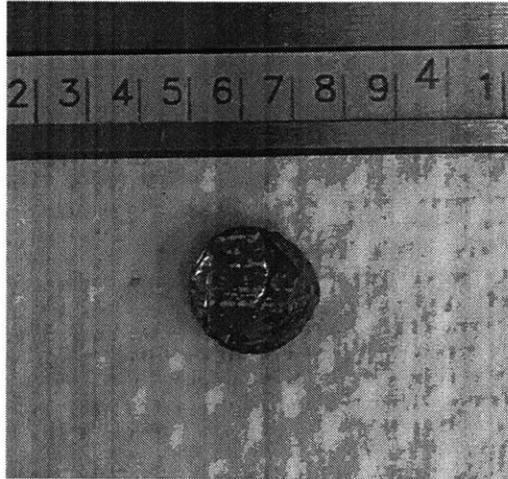


Figure 5: Fuel pellet created using Method 3 and eutectic surface coating

These pellets reacted with 35% efficiency. While the jig set up did successfully create pellets, it was a slow, labor-intensive process. The shreds produced from the paper shredder were not small enough for the set-up so the cans had to be cut into small shreds by hand. Additionally, even with the pin hole for removal, it took significant effort to remove the pellets from the jig after compaction and this effort sometimes resulted in the destruction of pellets.

2.4 Method 4: $\frac{3}{8}$ " Jig

To remedy these problems, create a more cohesive pellet, and hopefully improve efficiencies, a new set up was designed. The major change involved the addition of a second block to serve as the end stop, as seen in **Figure 6**. First, shreds are loaded into

the $\frac{3}{8}$ " through hole in the top block. Second, the $\frac{3}{8}$ " pin is pushed down with the arbor press compressing the shreds using the bottom block as a stop. Finally, the bottom block is removed and the pin is pushed all the way through, dislodging the pellet.

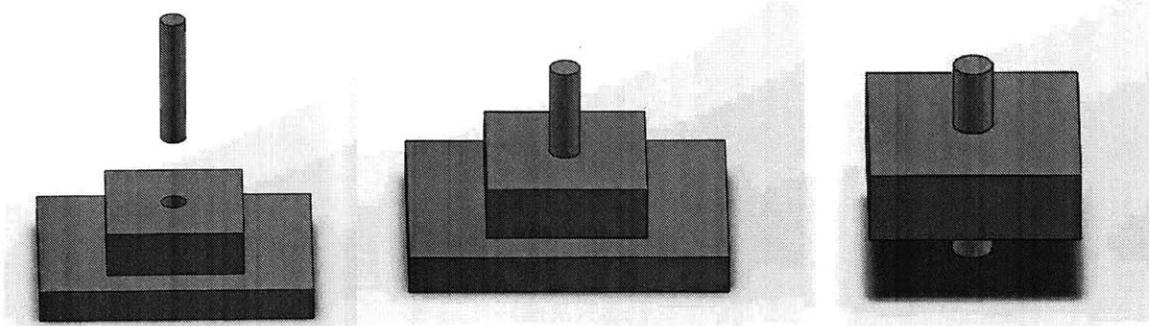


Figure 6: A series of three images depicting the process of fuel production using Method 4: $\frac{3}{8}$ " Jig. In the first image, top block with $\frac{3}{8}$ " through hole rests on bottom block. In the second image, the pin is compress shreds. In the third image, the bottom block is removed and pellet is dislodged.

This revised method made removal of pellets much easier. Pellets were made from regular aluminum cans and aluminum cans which did not have paint (a peel off label which was removed). A photo of these pellets following fuel production can be seen in **Figure 7**.

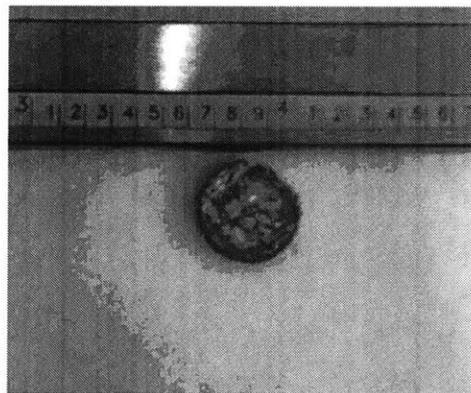


Figure 7: Fuel pellet created using Method 4 and eutectic surface coating

The pellets made with regular cans and cans without paint reacted with efficiencies of 6% and 12% respectively. This marked a significant decline in performance compared to past trials and it is not entirely known what caused this decline. One problem faced during fuel production is the flaking of the pellet. The pressures achieved on the arbor press in the current setup are not sufficient to compact shreds to a level that can withstand shaking. Upon shaking some shreds become dislodged from the pellet and fall apart. Particularly, shreds at the very top and very bottom layer off the pellet generally flake off during the first round of vigorous shaking. It is suspected that a major reason for the loss of efficiency is flaking which is preventing eutectic from penetrating the pellets. During the standard fuel production method, eutectic coats the surface of the aluminum and then progressively works its way through the entire piece of aluminum. In the case of the pellets from compacted cans, it is suspected that the eutectic initially coats the outer layer of the pellet, but during shaking the outer layer flakes off which could be causing the remaining pellet not to be sufficiently treated by eutectic.

2.5 Pretreatment of Aluminum Cans

To better characterize the factors affecting the efficiency of the aluminum beverage cans, a second trial was conducted with Method 4: 3/8" Jig. In this trial, all paint and coatings were first removed from the cans and the time on the hotplate was increased from 90 min to 120 min in an attempt to allow the eutectic to more thoroughly penetrate the pellets. In order to remove paint, the cans first must be pressure cooked for 20 mins using a standard off the shelf pressure cooker. The cans are then rubbed with acetone to remove the paint. A full description of the paint removal process can be found in the Appendix. Fuel pellets were then prepared using Method 4:

3/8" Jig and the standard surface coating method with a 30 minute increase in time on hot plate. These pellets can be seen in **Figure 8**.

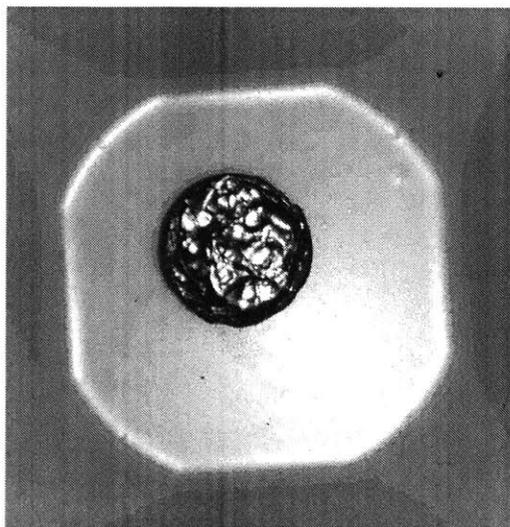


Figure 8: Pellets prepared using aluminum cans with paint removed, Method 4, and eutectic surface coating method

These pellets were reacted with an efficiency of 13%. However, it was noticed that the pellet did not fully react. A significant portion of the pellet remained. The mass of the pellet before the reaction was 0.396 g and the mass after reaction was 0.368 g meaning the majority of the aluminum did not react and it follows that a low efficiency would be achieved. The mass of the pellet after the reaction was taken immediately after the reaction and the pellet was wet which could be a significant source of error in the measurement. **Figure 9** shows the pellet after the reaction.

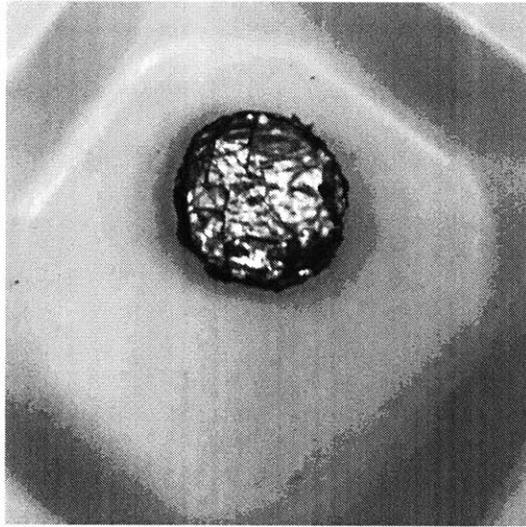


Figure 9: Pellet from Figure 7 following the reaction

Some of the small “flakes” that had become detached during the shaking process were tested and achieved efficiencies of 41%. The flakes from the pellets achieved an efficiency over 3 times higher than the pellets themselves. This supports the theory that the major reason for a loss of efficiency is flaking which prevents eutectic from penetrating the pellets.

2.6 Flakes Testing

In order to better characterize the aluminum cans efficiency at a basic level, flakes were prepared using the shake method and the bath method. Flakes of approximately 0.2"x0.2" were cut from an aluminum can untreated and a can pretreated with the previously described paint removal method. **Figure 9** shows how the flakes appeared prior to eutectic treatment.



Figure 10: Flakes of Aluminum can prior to eutectic treatment

Flakes with and without paint were prepared in the bath and shake methods. For the bath method, a small jar is filled up .25" using a pipette and is preheated to ~120 C on the hotplate. The aluminum squares were placed in the eutectic bath for 20 min on one side and then flipped for 20 min on the other side. The first time this experiment was attempted a crusty gold layer formed on the surface of the eutectic bath and prevented proper coating of the aluminum flakes. It is assumed this layer is due to oxidation. In order to prevent this layer from forming in future trials, argon was added to the jar of eutectic prior to heating. **Table 1** presents a summary of the experimental values found.

Method	Paint/no paint	Time (min)	% Aluminum	Reaction yield
bath	Paint	20/side	24.22	38.62%
bath	no paint	20/side	70.97	54.31%
shake	Paint	90	52.63	56.55%
shake	no paint	90	56.24	57.10%
shake	no paint	120	52.79	32.83%
shake	Paint	120	50.98	36.19%

Table 1: Summary of results from aluminum can flake experiments

3. Summary of Results

A summary of methods used to produce fuel and the resulting efficiencies are shown in Table 2.

Description	Paint?	time heated with eutectic (min)	Diameter (in) x Height (in)	% Aluminum	Reaction Yield (%)
Standard Method-store bought aluminum pellets	no	90	.275 in diameter sphere	95	95
Method 1: Pliers	yes	90	.270 x .13	89	38
Method 3:1/4" Jig	yes	90	.250 x .15	88	35
Method 4: 3/8" Jig	yes	90	.375 x .14	92	6
Method 4: 3/8 " Jig	no	90	.375 x .14	90	12
Method 4: 3/8 " Jig	no	120	.375 x .14	87	13
tested 2 samples from above			flakes from what fell off during shaking	87	41
Flakes Bath	yes	20/side	flakes	24.22	39
Flakes Bath	no	20/side	flakes	70.97	54
Flakes shake	yes	90	flakes	52.63	57
Flakes shake	no	90	flakes	56.24	57
Flakes shake	no	120	flakes	52.79	33
Flakes Shake	yes	120	flakes	50.98	36

Table 2: Summary of methods used to produce fuel from aluminum cans the resulting efficiencies

The first row of the table presents the data from the fuel made using store-bought aluminum pellets. Using these aluminum pellets and the eutectic surface coating method, aluminum fuel with 95% efficiency was produced. This is the benchmark by which the aluminum fuels created from scrap aluminum can be compared. The fuels created using scrap aluminum fell significantly below this mark with the highest scrap aluminum efficiency at 57% and many other methods tested falling further below this mark. There are many reasons why the scrap aluminum did not achieve similarly high efficiencies, but the largest contributor is likely the inefficacy of treatment by eutectic. A major problem encountered is the flaking of pellets which is likely causing the eutectic to ineffectively penetrate the pellet.

4. Future Work

To remedy the flaking problem, pellets must be formed under greater pressure. The hope is that a pellet formed under high pressure will more closely resemble a single pellet of aluminum, rather than many small pieces. In this way, the eutectic treatment of the scrap-aluminum pellets should function similarly to the eutectic treatment of pre-bought aluminum spheres and therefore similar efficiencies should be achieved. A new method is currently being developed which employs the use of a hydraulic press, rather than an arbor press. A modification to the current jig has also been designed and is currently being machined. The main change in the new jig is the use of hardened steel. After a method is successfully determined for producing fuel pellets from scrap aluminum with adequate efficiency, a machine can be developed to produce these pellets. The machine would be required to intake scrap aluminum and output pellets with minimal human intervention.

5. Appendices

Appendix A: SOP for Fuel Production Using a Surface Coating Method

Created by Jason Fischman

Procedure:

1. Weigh out the desired amount of aluminum to be treated
2. Put aluminum into lidded jar, close lid, and place on hot plate
3. Weight out Ga-In eutectic, equal to ~5% of the original aluminum mass from step 1
 - a. Different mass fractions can be used for different desired eutectic concentrations.
4. Place eutectic on hot plate
5. Turn hot plate to ~200c, wait for 20 min
 - a. Entire jar of aluminum should be heated. Although there will be a temperature gradient over the height of the jar, the topmost aluminum should not be cooler than ~70c and the bottommost aluminum should be approximately 120c.
6. Once the desired temperature is achieved, pour the aluminum into the jar of eutectic, mix thoroughly
 - a. Lidded jars are recommended so that the lid can be closed and the entire jar can be shaken.
 - b. Aluminum should be mixed until the eutectic can be seen to coat all surfaces of all aluminum pieces
7. Leave aluminum and eutectic on hot plate for 1.5hr, mixing approximately every 20 min
8. Remove aluminum jar from hot plate
9. If excess eutectic is observed on the surface of the aluminum, centrifuge aluminum pieces to remove excess eutectic from the surface
 - a. Centrifuging is done at 4000 RPM for 1 minute
 - b. Rocks should be placed at the bottom of the centrifuge in order to allow eutectic to pool there without still coating aluminum

- c. If there is sufficient treated aluminum that the centrifuge needs to be run several times, leave the jar of excess treated aluminum closed whenever not being handled. This is done in order to decrease the surface oxidation of the treated aluminum
10. Put centrifuged aluminum pieces into airtight containers and fill with argon if possible
11. Because some eutectic will inevitably stick to the walls of the treatment containers used, the aluminum should be weighed before and after treatment to determine the average eutectic concentration
12. Clean jars and beakers using a mix of muriatic acid and water

Notes on eutectic:

The eutectic is a mixture that is 20% Indium by mass and 80% Gallium by mass. The eutectic can be made by taking a block of indium and cutting off ~1 gram chunks into a beaker until the desired mass is achieved. Then put a bottle of gallium in a pool of water and heat it until it is completely melted. Once the gallium is melted, pipette 4x the mass of the indium it into the beaker that contains the chunks of indium. This mixture should then be left on a hot plate at 100 C for ~20 minutes without mixing. The eutectic is mixed in a percentage such that at room temperature it can only remain liquid in the 80/20 ratio used. This means that if there is too much of either metal the excess will precipitate out and leave a liquid that is properly 80/20.

Notes on cleaning eutectic:

Pouring small amounts of muriatic acid into beakers or pipettes covered in eutectic will cause the eutectic to ball up and precipitate. This muriatic acid can then be heavily diluted and disposed of. The balled-up eutectic at the bottom of the beaker can then be pipetted or poured into a desired storage container. Before using the eutectic for fuel treatment, it is advised that the eutectic be rinsed with water to remove any muriatic acid on its surface.

Notes on safety:

It is advised to assume everything in the lab and on the lab bench is covered in Gallium. Do not bring lab notebook into space, but rather take notes on paper and copy over data later. Wear gloves when touching anything and wash hands often.

All exposure of muriatic acid to aluminum or to eutectic that likely has aluminum dissolved within it should be done within the fume hood. If beakers or jars that contained a mix of muriatic acid and aluminum or muriatic acid with recently used eutectic must be taken out of the fume hood, wait until they have finished reacting entirely, and dilute heavily with water before removing from hood.

Appendix B: SOP for Measuring Reaction yield Based on H₂ Production

Created by Jason Fischman

Equipment:

500 ml narrow cylinder

2000 ml, 5" diameter beaker

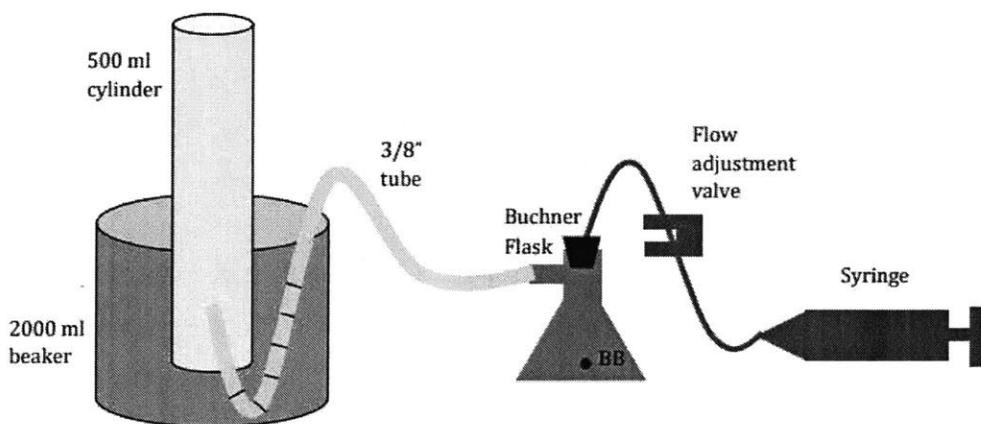
3/8" ID flexible tube with tick marks every inch

50 ml Buchner flask with 3/8" barbed connection

Cork for flask that has hole in it, in this hole is placed a tube connected to syringe

Flow adjustment valve

Diagram of Setup:



Procedure:

1. Fill both the 2000 ml beaker and 500 ml cylinder with water, quickly overturn 500 ml cylinder into 2000 ml beaker.
2. Feed 3/8" ID tubing into 500 ml cylinder so that its end is several inches up the tube as shown in the diagram.

3. Connect the other end of the 3/8" ID tube to the barbed fitting on the Buchner flask.
 - a. Wet the barbed fitting before connecting to ensure a better seal.
4. Record the number of tick marks seen on the 3/8" tube in between the water-level of the 2000 ml beaker, and the minimum location of the tube where it begins to curve upwards into the 500 ml cylinder.
 - a. This distance represents the total amount of water that will be displaced by gas in the tube before any bubbles reach the 500 ml cylinder. Recording and accounting for this volume will allow for more accurate measurements.
5. Connect tube from output of syringe into the input of the cork.
 - a. Place flow adjustment valve on the tube and ensure that it is set to "open."
6. Place a BB in the Buchner flask and seal the flask with the cork
 - a. Wet the cork before pushing it in to ensure a better seal
7. Use the syringe to push 5ml of water into the flask, turn the flow adjustment valve to "closed" when done.
8. Immediately after injecting water into the flask, use a stopwatch or clock to begin recording measurements of the gas flow out of the flask. Gas should begin to flow down the 3/8" tube and begin to bubble up into the 500 ml cylinder.
 - a. Measurements of the h₂ production should be taken by recording the water level in the pipe or cylinder to within 2.5ml every 15 seconds. These should be taken until the reaction is believed to be complete.
 - i. The reaction should be considered complete when no observable change in gas level was observed after 1 minute.
9. Once the reaction is believed to be complete, open the flow valve and inject an additional 5ml of water into the flask. This ensures that any underacted aluminum can come into contact with the excess water. Close the flow valve when complete.
10. A final gas measurement should be recorded after the water level of the cylinder is again observed to have remained unchanged for at least 1 minute.
11. Now that the reaction is complete, the flask should be placed in a bath of cool water and let sit for several minutes.

- a. When placing the flask in the bath it is best to agitate the flask and water for faster cooling.
12. The water level in the 3/8" tube should be seen receding as the flask cools and the volume of gas in the flask + tube system decreases. Record the number of tick marks that the water level has receded once the flask is considered fully cooled.
- a. Flask is considered fully cooled when the water level can no longer be seen receding, this can take several minutes.
 - b. This measurement accounts for the effect of increased temperature on the system and allows the tester to account for any observed increase in volume that may have been due to increased temperature rather than the actual production of additional gas.

Note on Cleaning: All beakers should be cleaned with a mix of water and dilute HCl. They should then be rinsed and dried thoroughly before being used.

Appendix C: SOP for Removing Paint from Aluminum Cans

1. Fill a pressure cooker with approximately 1-2 inches of water
 - a. Minimum amount of water required dependent on type of pressure cooker used
2. Add empty, clean aluminum cans to pressure cooker and place on high heat
3. Pressure cook the aluminum cans on high heat for 20 min
 - a. After 20 min, turn off heat and wait for pressure to reduce before opening pressure cooker
4. Remove cans and allow them to cool
5. Use a cotton ball or paper towel to rub the surface of the can with acetone
 - a. Continue rubbing with acetone until all the paint has been removed

6. Bibliography

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