Project: Hybrid Electric Fuel Cell for Portable Electronics

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Abstract:

Harris Corporation is interested in developing a hybrid fuel cell-battery system using a Direct Methanol Fuel Cell to power a cellular phone. Our task is to develop such a system and resolve the packaging issues regarding heat management and structural durability to ensure the product's safety. This will involve characterizing the power needs of a specific cell phone and creating a hybrid system using off-the-shelf components in combination with custom circuitry and packaging.

Departments: Mechanical Engineering

Number of Groups: 1

Confidentiality Concerns: No

Other information: None

1. Executive Summary

Portable electronics often suffer from cripplingly short battery life. In the case of cellular phones, dead batteries can result in inconveniences and lost productivity. Hybrid fuel cell systems have the potential to greatly extend the operational life of cell phones to weeks or months without needing a recharge or fuel refill. Harris Corporation, an international telecommunications company, is interested in developing such a product and has enlisted the help of a team of University of Michigan students in order to create a demonstrable prototype.

A fuel cell has a high energy density compared to a battery and can provide power over long periods of time, but they lack the power to fulfill the requirements of a cell phone during heavy use. A hybrid system uses the fuel cell combined with a battery to power both high and low current needs. A Direct Methanol Fuel Cell is a good fit for portable electronics because methanol has a high volumetric energy density at ambient pressure and it is a liquid at room temperature, so it is easier to store than hydrogen, another common fuel. Several issues arise when trying to package a fuel cell in a size suitable for electronics. There are safety concerns when dealing with a flammable and toxic substance such as methanol, especially because fuel cells generate heat. We must manage the heat in a way that is safe and ensure that the system is packaged in such a way that methanol will not leak onto the user, any electrical components, or any hot surfaces. Also, the hybrid system must be developed in such a way that does not decrease the ease of use, convenience, and affordability to which users have grown accustomed.

There were two main aspects in the creation of this hybrid cell phone product that were treated as separate paths our team traveled down, but which were connected in key areas. On one side, we needed to create a power delivery system consisting of the fuel cell, battery, and circuitry which could reliably power the cell phone in different modes. On the other side, we had to create a package that could contain all of the components in an optimal configuration. These two aspects meet at two important issues: size and heat management. The configuration of the fuel cell impacts its performance, which in turn dictated whether we needed to adjust cell size (and thus package size) to make up for power output. The fuel cell generates heat which must be dissipated by the package, however because the cell produces more power at elevated temperatures, some measure of heat can be contained by a properly designed package to boost output.

We have developed an initial prototype and conducted a series of tests in order to validate design parameters. An off-the-shelf fuel cell was purchased and fully characterized in order to validate theoretical power results. Hybrid circuitry was designed, prototyped and validated using the fuel cell to power a load and charge a battery simultaneously. This circuit will help determine the power delivery profile and battery charging time. The fuel cell was also tested for heat output at maximum power output levels and then, using this data, we developed a theoretical model of our package and then built a prototype. We tested this prototype to measure operating temperatures for the design during heavy use. These tests will allow fine tuning of the package to retain the proper amount of heat. Finally, we used a 3D printer to create a mock-up of our design to demonstrate how each component would be configured inside of the product. The design is about twice the size of a current flip cell phone and uses a cartridge design to allow the user to refill the methanol when it is depleted. This project should serve as a cornerstone for future teams, who will be able to use our designs and testing methods to ready the product for mass production.

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2. Introduction

A need exists for a way to extend the operational life of portable electronics, particularly cellular phones. Cell phones are nearly ubiquitous and people have come to rely on them to communicate while on the move. This can increase business productivity, the ability to coordinate family and social events, and the ability to contact authorities in case of emergency. While battery technology has improved, cell phone advancements such as bigger displays, more complex software, and more complex hardware features continue to increase power demands. Frustrations are always high for cell phone users who find their batteries drained by long conversations or high-power activities such as internet browsing; thus, there is a market for technologies that will allow users to prolong their cellular activities and a fuel cell has the potential to prolong those uses nearly indefinitely.

A fuel cell can be thought of as a continuous battery, except where as a battery's chemicals can become exhausted, a fuel cell will continue to produce power so long as it is fed fuel. Harris Corporation, a communications and information technologies company, has recognized this opportunity and has requested the help of a team of University of Michigan students in order to pursue an entry into this market. Harris has specified that a Direct Methanol Fuel Cell (DMFC) be utilized in the design, because methanol is a cheap and readily available fuel with high volumetric energy content. A cell phone has a spectrum of power needs, ranging from the low-power 'standby mode' when the phone is not in active use and requires about 8.4mW, to the high-power 'talk mode' when the phone is being used to make a call and needs about 1.0W. Because of this issue, Harris desires the system to be hybridized with a battery. This will essentially reduce the complexity, cost and weight of the design, because the fuel cell will only be necessary to charge the battery and power the cell phone in standby use, whereas the battery will supply most of the power when the cell phone is in talk mode.

Safe operation is the chief concern. Methanol is a poisonous and flammable material, even when heavily diluted with water, and fuel cells tend to operate at elevated temperatures. The design must have careful heat management techniques in order to allow the fuel cell to operate at optimal levels, while ensuring that the methanol is not in danger of combusting and that the battery and electronics are protected from overheating or potential damage from liquid spills. Packaging these components in a way that ensures proper heat management is important, as is creating a rugged product that will not fail under duress and has reasonable physical dimensions so as to not negatively impact utility.

There are three key aspects that factor into the design of a DMFC hybrid system to power a portable device: the power system, heat management issues, and device packaging concerns. Each topic is equally important to the product and has been approached separately. However, the final design challenge involved factoring all of these issues into one product. The design process is depicted in Figure 2.1, below. A literature review was conducted to gain a technical understanding of each topic and engineering specifications were then generated. We then developed processes for characterizing the power and heat generation capabilities of our fuel cell and methods for managing that heat and packaging the components. Heat and power generation experiments were conducted with an open table-top prototype; that is, they were not completely packaged. We were able to demonstrate our system's ability to power a cell phone with this setup, as well as determine how much heat the fuel cell produces. Packaging the components and dissipating the heat were approached with a two prototype package designs. We were able to test one prototype for internal and external operating temperatures in order to refine our heat packaging design, and we created a 3D printed prototype to demonstrate how components of the product would be configured within the package.

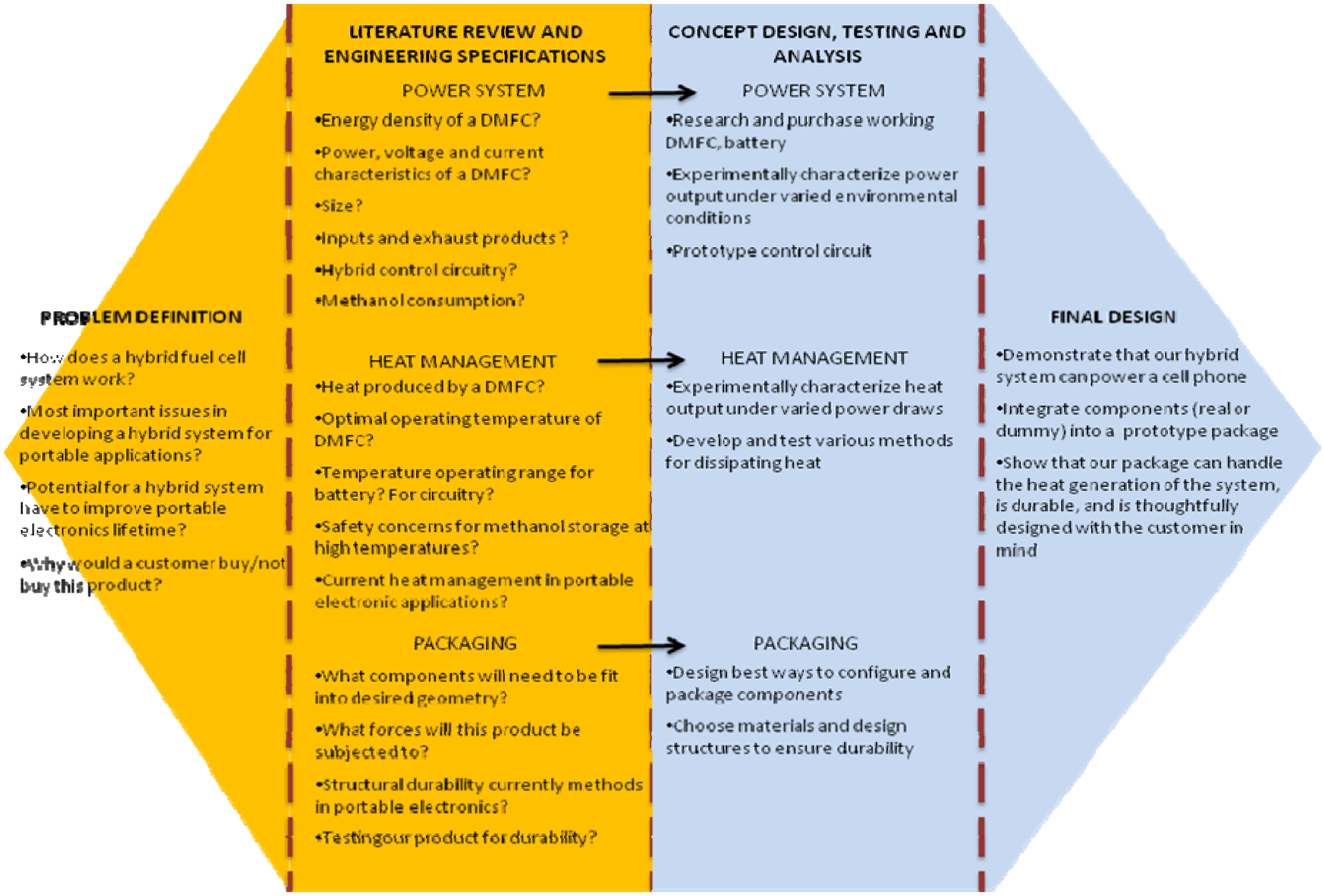


Figure 2.1: Design Process

3. Technical Background

The hybrid power system requires four main elements for it to function: a fuel cell, methanol, a battery, and the circuitry to make it all work together. Additionally, we needed to devise methods to manage heat within the fuel cell and protect the hybrid system from damage. Each of these aspects must be understood to ensure that the parts are being used effectively and safely. Research was conducted on these parts, and an explanation of each one follows.

3.1. Cell Phone Technology

As a first step in understanding where to start with our hybrid design, we must know what the characteristics of the device we are attempting to power. There are many different parameters which are required to characterize a cell phone's power consumption. A standard cell phone operates with an input voltage between 2.5 and 4.2 volts, while the current consumption changes with the two modes of use, varying from 2.26mA during standby to 180-190mA for talk mode. However, these specifications are only averages. A typical power use map of a second generation Global System for Mobile Communications (GSM, the most widely used wireless technology) phone is provided in Appendix E. It shows that the peak current consumption of the phone runs as high as 275mA. This information led us to assume a 70% duty cycle in order to calculate the average current consumption. To simplify the design requirements, we specified the current draw of these modes to be 5mA and 190mA respectively. We also assumed that the battery's current draw rate is constant and all the voltage regulators are linear. These are reasonable assumptions because they are based on current cell phone products. This then enabled us to divide the battery capacity by the current draw to determine the operating lifetime. For a standard 750 mA-hr lithium-ion battery, a total of 3.7 hours is possible for talking and nearly 13 days when not in use.

Our team also conducted research on the effects of elevated temperatures in electrical components. This research concluded that a silicon device can fail catastrophically if heated too much. Higher temperatures can also cause electrical characteristics to frequently undergo intermittent or permanent changes [8]. No direct study was found on cell phone electronics; however, a common computer processor has a maximum operating temperature of around 50 °C. But, as the life of an electronic device is directly related to its operating temperature, keeping the temperature a minimum is ideal. Each 10°C temperature rise reduces component life by 50%. Conversely, each 10°C temperature reduction increases component life by 100%. Therefore, it is recommended that the electronic components be kept as cool as possible for maximum reliability and longevity.

3.2. Direct Methanol Fuel Cells

DMFC technology is an integral part of our final design so we must have a thorough understanding of the inner workings and characteristics of these devices to optimize our design. The following section details our research on how a DMFC operates, their power potentials, and their theoretical heat outputs.

3.2.1. Fuel Cell Technology

Fuel cell technology is rapidly becoming a viable alternative to current energy generation systems. Applications can vary widely, from the small requirements of portable electronics to the large power outputs for hybrid vehicles to the even larger scale needs of a power plant. The expectation is that fuel cells will one day be able to replace and improve significantly upon existing fossil fuel power capabilities while still maintaining environmentally friendly standards.

How a fuel cell operates depends on the type of fuel cell being used, but in the general sense it involves the creation of electrical current by ionizing hydrogen before combining it with an oxidant to form water. Because this process converts chemical energy directly into electrical energy, it is capable of much higher efficiencies than a combustion engine, which is limited in potential by the Carnot Cycle.

The most basic and widely used versions are Proton Exchange Membrane (PEM) fuel cells. These employ an electrolyte in between two large conducting plates, an anode and a cathode, as shown in Figure 6.1. The electrolyte is a barrier which allows the ionized hydrogen atoms created at the charged terminals to pass through to the other side while preventing other molecules and atoms from doing so. The charged plates in turn funnel the electrons released by the ions into an external circuit and power a load.

Specifically for direct methanol fuel cells, this process involves the breakdown of methanol fuel into carbon dioxide and hydrogen ions. As can be seen in Figure 3.1, methanol (CH_3OH) is pumped into the left hand side of the fuel cell. It then is broken down into carbon dioxide and H^+ ions by a catalyst, typically platinum or ruthenium. The carbon dioxide is emitted as exhaust, while the hydrogen ions pass through the electrolyte. On the other side of the cell, oxygen is fed into the system, which reacts with the incoming hydrogen to produce water vapor. The liberated electrons pass through a circuit to power the load.

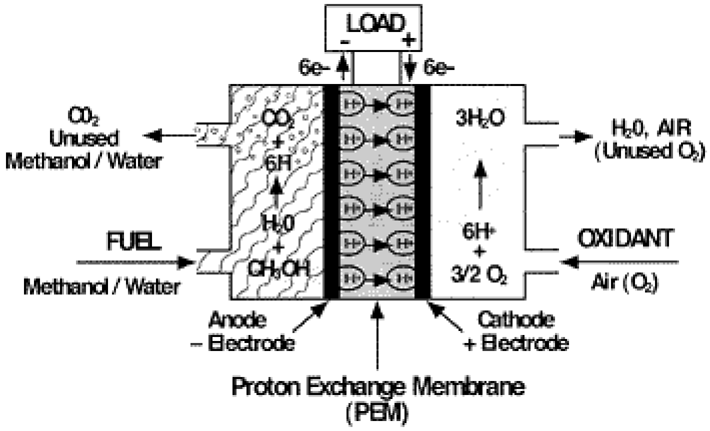


Figure 3.1: Inner workings of a Direct Methanol Fuel Cell [9]

DMFCs have a few crucial benefits which make them ideal energy providers for portable electronics. Typically, hydrogen PEM cells are desired as they only produce water as a byproduct and are more efficient. However, handheld electronics need to be compact and portable, making size and weight serious considerations in the design process. This is what makes methanol an attractive fuel option, as described in Section 3.2.2 below.

Special attention must be paid to the heat generation within our product. Heat emitted from the fuel cell must be carefully controlled so that it does not damage other components or harm the user. At the same time, ideal efficiencies of DMFCs occur at elevated temperatures. In fact, methanol fuel is sometimes directly heated to improve power output. This means some combination of heat ventilation and containment will be required. We therefore focused our research on both exhaust systems for cooling the device, as well as shielding and insulation options for maintaining proper temperature gradients. Heat may also impair the safety, performance, and reliability of a cell phone. An electric system has the potential to emit smoke or catch fire if the device generates more heat than anticipated. Excessive heat may also degrade the performance of the device by lowering its operating speed, and in the worst case, damage the cell phone. Of course, high temperatures can be harmful if the user is not protected from direct contact as well.

3.2.2. Methanol as a Fuel

In terms of energy density, the same volume of methanol has significantly more potential energy then compressed hydrogen would (roughly 1200 Wh/kg to 350 Wh/kg [10]), owing to its chemical composition and density. As a comparison, methanol also has about five times the specific energy density of lithium-ion batteries. [11] This higher energy density corresponds to the potential for a smaller package design. Another benefit is that methanol is a liquid at room temperature and pressure, giving it the advantage of not needing the special storage conditions liquid hydrogen does.

Moreover, methanol production is already a well established industry, making it readily available and inexpensive. Produced mainly from natural gas, its characteristics include being colorless, soluble with water, flammable, and toxic. Such properties raise safety concerns which our team must overcome to ensure that consumers are protected. However, these challenges should not be difficult to resolve, as many regulations and safety precautions are well defined. [17] Methanol containers are usually made of mild steel, as it can be corrosive to certain metals and plastics if stored too long. More importantly our packaging design must consider the flash point and vaporization temperature of the fuel, at 12°C and 64.7°C respectively. [17] The flash point is the minimum required temperature for the fuel to ignite, but is also determined by the amount of methanol present. The boiling temperature is a difficulty of greater concern, as this may be around the ideal operating temperature of the fuel cell. If the liquid was heated enough to vaporize, a serious safety concern would be introduced by the resulting pressure. The gas could burst the storage tank or any fittings, and could potentially ignite and explode. Methanol vapor may also negatively impact performance of the fuel cell and other components such as fuel pumps, as well as increase the demands on volume. Further testing will be performed to find the appropriate settings.

3.3. Battery Technology

The hybrid system requires a battery which is rechargeable so that the phone operating time can be extended while maintaining Harris's size requirements. We therefore researched several different types of batteries available on the market today to assess which one can best meet these standards, which follows in this section. Also described in this section is the response of batteries to different temperature ranges, which may be an important factor in our design.

3.3.1. Battery Types

The first type investigated is the most rugged design on the market, nickel-cadmium batteries. These devices primarily are used in portable electronics which require high power bursts, such as power tools or medical equipment. With its low cost and high durability, it provides a benchmark standard which all other batteries are compared to, though it does have several major drawbacks. One significant disadvantage is the low energy density capabilities of a cell between 45 and 80 Wh/kg, which greatly reduces the operating time available before the battery needs to be recharged. [18] Another significant problem comes from a recharging issue called memory effect. When a nickel-cadmium battery is not fully discharged every few cycles it is used, large cadmium crystals will form within the battery which cannot be broken up by the incoming electrical current. This then creates a loss in energy carrying capacity, as the cell has “forgotten” how much power it could originally hold. Finally, cadmium is a toxic metal which requires careful disposal techniques to avoid environmental harm.

A step up from the nickel-cadmium batteries are the nickel-metal-hydride batteries. One benefit is the increase in energy density, which is about 30%-40% greater than nickel-cadmium. [18] A second benefit is a decreased memory effect, which means the batteries need less upkeep from users. Also, as the cells do not contain hazardous materials, they are environmentally benign. However, nickel-metal-hydride batteries have a high self-discharge rate and require it to be recharged more often when not in use. On top of this, these devices have low cycling capabilities, typically on the order of 200-300 recharge times before performance is negatively affected.

For high energy applications, lead acid batteries have offered the best solution since they were first created. They provide large currents and have very low self-discharge rates. [18] A prime example is the car battery. But, as they also have the worst energy density capacities of rechargeable batteries on the market, they may be too big and bulky to be practically integrated into small electronics. Besides the bulkiness of these batteries, they are also highly toxic and would be more of a danger to the user if mishandled.

Lithium ion batteries have claimed the portable electronics’ market. These batteries have several characteristics which make them good candidates for our purposes as well. With the best available energy density characteristics (double that of nickel-cadmium), they allow for high energy storage with small volumes. Because they have different chemical compositions than other rechargeable batteries, they don’t suffer from memory effect. This is especially important as the service required to maintain battery life is to be kept at a minimum. The devices also have low self-discharge rates, high power delivery capabilities, and high cycling lifetimes. But, as with all batteries, they do have some weaknesses including higher costs and temperature restrictions (explained in Section 3.3.2.).What's more, lithium-ion is subject to serious problems if either overcharged or undercharged, which has led to safety circuitry being installed into every cell to ensure these problems don't occur. Still, this is the most widely used battery type in cell phone applications.

Another distinct safety concern is the possibility of a battery fire. As made famous by recent laptop computer battery recalls, lithium ion batteries may contain defects from the factory that could cause fires or explosions. Essentially, metal shards or fragments can make their way into the battery chemicals and, when the chemicals become hot because of use or recharging, these fragments have the potential to puncture containers of a pressurized liquid lithium solution, resulting in catastrophic failure [19]. Because our battery will be in close proximity to a hot fuel cell, we will need to ensure that it is properly protected to avoid instances of failure.

3.3.2. Battery Temperature Concerns

Temperature has a significant effect on battery performance. Low temperature generally results in the reduction of chemical activity and an increase in the internal resistance of the battery. This higher internal resistance results in are higher internal losses during discharge, leading to a lower net capacity. In addition, higher temperatures produce higher chemical activity, which increases self-discharge and causes a net loss in total amp-hrs available. The optimal operating temperature for a lithium ion battery is about 20-40 °C. Figure 6.3 shows the effect of temperature on battery capacity [20]. As you can see, maximum (100%) net capacity occurs near 40^{o}C. Beyond 40^{o}C the total net battery capacity begins to decrease again, though this is not clearly represented in the Figure 3.2.

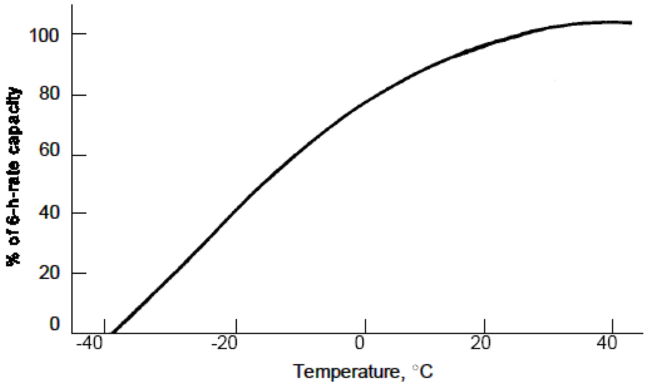


Figure 3.2: Typical effects of operating temperatures on battery capacity.

High temperatures can also potentially damage the total capacity of a battery in storage. To minimize these losses, batteries should be stored as close to 0^{o}C as possible, or else risk rapid deterioration. Table 6.1 shows a relationship between battery capacity, storage temperature, and storage state-of-charge (SOC). It is also recommended that lithium ion batteries be stored at lower SOCs. [17].

Table 3.1: Battery Storage Loses

Storage Temperature	Battery Capacity Loss per year at 40% SOC	Battery Capacity Loss per year at 100% SOC
0°C	2%	6%
25°C	4%	20%
40°C	15%	35%
60°C	25%	40% after 3 months

3.4. Heat Management in Electronics

Heat management is not a new issue in portable electronics. In fact, it is a key problem in nearly every piece of electronics with high power requirements, especially in laptop computers. Thus, heat removal methods are fairly well developed. Below are some of the more common heat removal technologies, which will be considered to be integrated into our concept generation.

3.4.1. Heat Sinks

One proven design in heat management is the heat sink. With large surface areas and highly thermally conductive materials, these designs provide quick removal of heat into the surrounding environment. The main principle behind these devices is in convection cooling from ambient air. The heat sink may be simply a block of material, or may be comprised of fins, which allow the heat to be removed at high rates away from the heat source and then be given off to the surrounding environment via surface convection. Some common heat sink materials include copper or aluminum, which can be die cast, machined, forged, or extruded into fin structures as needed. An example of an aluminum finned heat sink is shown in Figure 3.3 below. In this case, the heat sink would be placed on top of the heated component.

Figure 3.3: Aluminum heat sink uses fins to increase surface convection

3.4.2. Thermal Interfaces

Thermal interface materials are widely used in electronics cooling. These thermally conductive materials are usually used to fill the gaps between microprocessors and heat sinks to increase thermal transfer efficiency. These gaps are normally filled with air which is a comparatively poor conductor. The most common type is the white-colored paste or thermal greases [21], typically silicone oil filled with aluminum oxide, zinc oxide, or boron nitride. Some brands of thermal interfaces use micronized or pulverized silver. Another type of thermal interface material is a phase-change material. These exist as solids at room temperature but liquefy and behave like grease at operating temperature. Shown below in Figure 3.4 is a thermal interface known as a nanospreader. This product contains liquid that is vaporized by the heat source and condensed by the cooler heat sink [22]. These can reduce thermal resistivity over common thermal interface materials.

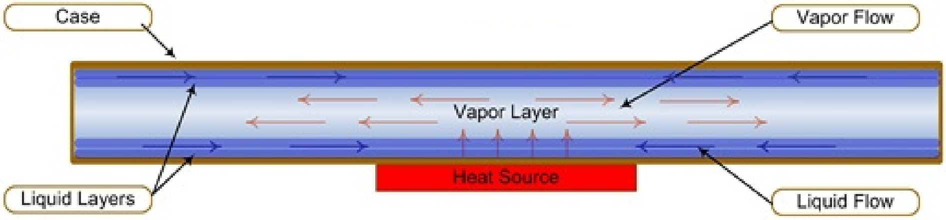


Figure 3.4: Celsia nanospreader utilizes phase change to conduct heat

3.4.3. Liquid Cooling

Liquid cooling was first integrated into electronics to remove the heat generated by the CPU in computers. A liquid cooling system circulates a liquid through a heat sink attached to the processor inside the computer. As the liquid passes through the heat sink, heat is transferred from the hot processor to the cooler liquid. The hot liquid then moves out to a radiator at the back of the case and transfers the heat to the ambient air outside of the case. The cooled liquid then travels back through the system to the CPU to continue the process [23]. Liquid cooling is an efficient system at drawing heat away from the processor and outside of the system. Unfortunately, the disadvantages of these devices come from the size requirements and technical skills needed to install a kit, which require a large amount of space to work effectively. Figure 3.5 shows a liquid cooled RAM chip for a PC. Liquid is pumped through the aluminum fins on top of the chip.

Figure 3.5: A liquid cooled RAM stick improves performance by circulating cool fluid

3.5. Structural Packaging

Components in our complete design must be protected against the internal and external hazards so that the cell phone can still operate. This includes handling a wide variety of damaging phenomena, from shock and vibration, to overheating, to even chemical and electrostatic interference. Cell phones today typically have an outer protective shell, or exoskeleton, which protect the circuitry from the environment. These shells allow for rigid structural support while taking up very little internal space, though they require more material for their thick protective covering. An additional defensive measure would be lining the space between components with rubber padding. This could help reduce the impact of different loading modes and ensure the components remain secure within the frame, but would also require additional material which increases cost. A third potential design involves machining bracers on the inside of the casing, providing internal structural support. However, this would take up some internal space and increase costs of manufacturing slightly. A full cost/benefit analysis will also have to be conducted on different combinations of these materials, to better understand where the optimal percentage of each material is needed.

During the use of the fuel cell, a small amount of water is given off from the chemical reaction of methanol. This water has the potential to damage sensitive circuitry of the cell phone and battery. Waterproof membranes offer a potential solution in protecting circuitry while still allowing air to enter the system where needed. This idea originally comes from biology and has been widely used for water resistant applications. Membranes are selective with the molecules that pass through them. Therefore, certain membranes can be manufactured to only allow air molecules through it, while blocking water molecules. Since heat dissipation is critical for our design, we have to make sure that the waterproof material can also achieve the heat requirements.

3.6. Prior Art

From our literature review of this topic, our team learned of several different designs and products already in existence which helped in understanding the project. This section explains these different devices in two parts. The first summarizes several patents which deal directly with technology we will use in our final product, and the second explains the Mobion, a portable DMFC powered cell phone soon to be on the market.

The *Portable Fuel Cell Power Supply* is a patent that concerns powering small portable devices with a fuel cell (Patent Number 6268077). [2] The idea in this patent is for a compact device that could be packaged within a cell phone to replace the battery; however it is powered using a hydrogen fuel cell rather than a DMFC. It contains similar concepts that we wish to utilize in our final design. One such concept is the use of vents to help keep the fuel cell cool, which is a cheap, effective method that our team is looking to implement into our alpha design. One difference between our design and this patent is that it does not incorporate a battery to create a hybrid system. Knowing that patents are out there that have incorporated a fuel cell within a cell phone helps us to know that the possibilities of our project are conquerable.

A second patent exists that deals with the heat generated by a fuel cell (Patent Number 3392058). [3] This patent is more than 40 years old, leaving much room for improvement with modern technology. Heat transfer is one of the biggest issues of our project and with this patent we have an understanding of how our team should attack the heat management system that we will create.

Patent Number 7014936 reduces the negative effect of condensed water from the fuel cell reaction on its performance. [4] However, this patent states an output water volume far larger than for the fuel cell we will use, which is estimated to produce less than that of typical human perspiration. This would be a greater problem area if we had to create our own fuel cell, which this patent concerns. Still, the patent can assist us in understanding how the water is produced and dealt with in a DMFC, a challenge which our team will have to resolve.

Another patent to consider involves various ways to power portable devices with miniature liquid fuel cells (Patent Number 6326097). [5] Listed within it are different configurations of packaging as well as battery/fuel cell combinations. Some applications were not incorporated into cell phones but were designed instead to be add-on devices. Others integrated ideas similar to our final design, though with distinct differences such as not including a lithium-ion battery or a description of a heat management structure. Finally, this patent has developed several ways to refuel the cells, a significant challenge for our device.

With these patents, we have a basis for production of our hybrid system with which we can improve on. We know that many different configurations should work for putting the two elements together; our goal is to assemble the parts together in a way that is most efficient. Along with efficiency, our team will have to properly handle the possible heat produced and come up with a packaging concept that will deal with the heat in a compact way.

The Mobion is a well developed direct methanol fuel cell and battery hybrid system used to power a cell phone. The technology was created by MTI Micro Fuel Cell out of Albany, New York. The key feature behind the Mobion is that it can power a portable gadget two to ten times longer between charges, making the wireless devices “truly wireless.” The company claims to have designed a more effective DMFC that produces a low amount of heat while still providing sufficient power. Their system requires no micro plumbing or micro pumps to circulate water or methanol fuel. The device also uses 100% methanol for the most effective power production. Much of their design is confidential with several patents pending, but they have resolved the issues our team faces. Therefore, a key challenge for our team is to distinguish our final product from theirs.

Figure 3.6: The Mobion incorporated into a Blackberry

Figure 3.7: The Mobion

With all this innovation, MTI has 110 patents pending, none which yet have been accepted. MTI also claims to have more effectively distributed the methanol across the entire cell to get the best power density. The design keeps part numbers to a minimum and the complexity of the system simple to make the DMFC small and compact to fit in portable devices. [6] A computer aided design picture is included in Figure 3.6. Because this is a rendering of a Mobion in a cell phone, we cannot say for certain that the company has already developed the product to replace a cell phone battery. We do know they are working with Samsung to put this idea on the market [7]. The portable DMFC device shown in Figure 3.7 is used to power other portable devices.

4. Functional Decomposition

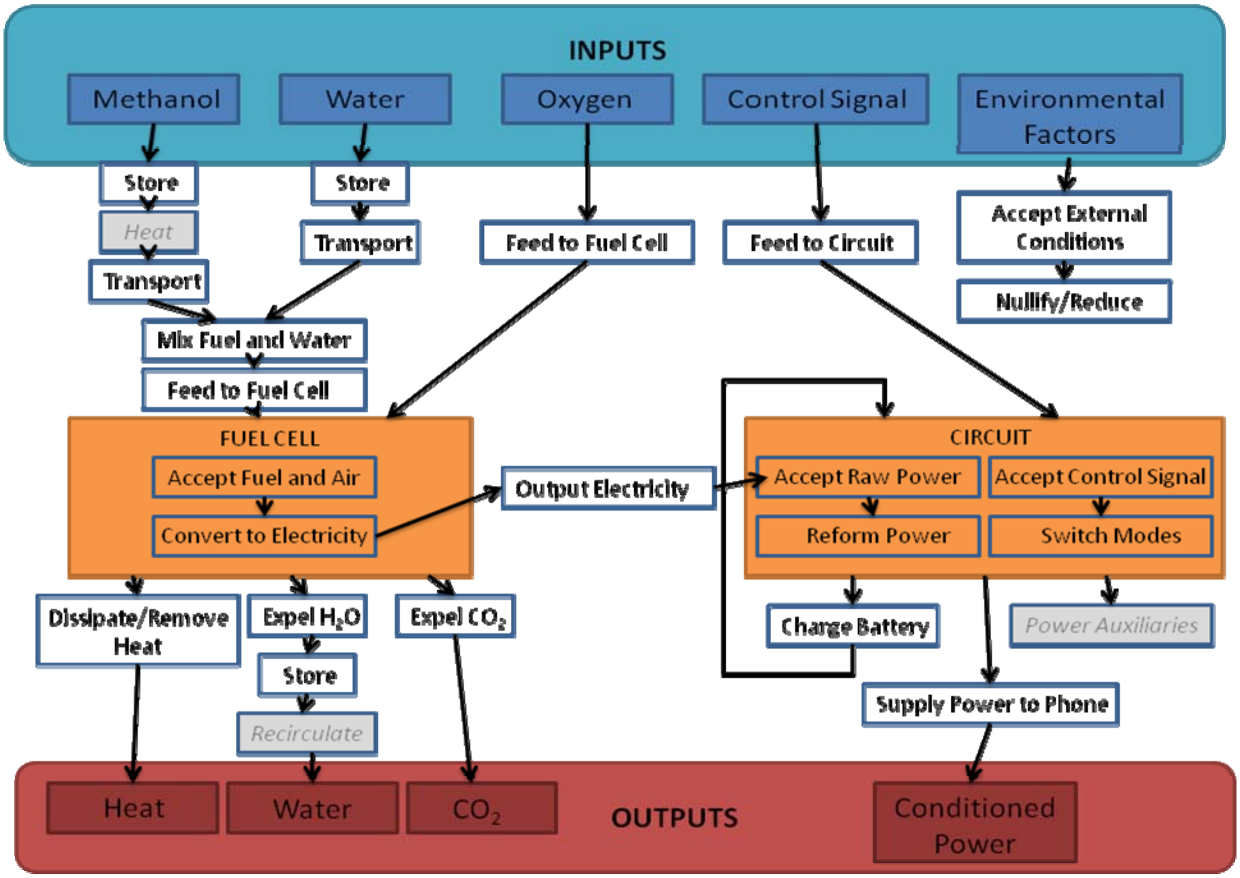


Figure 4.1: Functional Decomposition Diagram

Our project must manage five different types of inputs into its system and four outputs, as shown in our Function Decomposition Diagram (Figure 4.1). At the heart our design, methonal, water, and oxygen are used in a chemical reaction inside the fuel cell to produce electricity, a process which is described in greater detail later in this report. Enviromental factors are another input to our hybrid cell phone and must be handled accordingly. As a byproduct of the reaction, water, carbon dioxide, and some heat is created. Each of these outputs will effect our final packaging scheme. The electricity produced by the fuel cell is controlled by an input signal from the cell phone to power the different components. This signal will also regulate when battery power is needed and when the battery must be recharged. Powering the cell phone and charging the battery are the two main purposes of the fuel cell, however it will also have to power the components of the circuit and possibly other auxilaries, depending on the final design. From the circuit, the last output is conditioned power used by the cell phone.

5. Engineering Specifications

As a cell phone is typically carried in a pocket, purse, or on the hip, consumers desire a phone that is both compact and lightweight. With this in mind, Harris Corp. has specified that our prototype have a volume of about three times a standard flip-open cellular phone. Using the popular Motorola RAZR model, this gives us a required volume of 213cm^3. Setting the outer dimensions for our design helps us to approach all of our design aspects with from the right frame of mind, because size is the main concern in each of our packaging issues.

Using current smart-phones as a guide, we considered how heavy a cell phone can be without turning a significant number of customers away, and we determined that a 25% increase in weight over a typical Blackberry brand cell phone would not be unreasonable. This gives us a weight limit of 170g. However, the weight of our prototype will be severely restricted because we are using off-the-shelf components, which we have found to be generally heavy. When this prototype is designed for manufacturability, a better customer survey should be conducted to set this weight specification.

For our particular design we have set the methanol refilling cycle at once every 30 days. Even though this will be an infrequent task, it will no doubt impact the user's satisfaction with the product. Whether we use a cartridge, tank, or other method for fuel storage, we will be aiming to keep the refilling process on par with changing a battery in a current cell phone, at less than 15 seconds.

Based on the power characteristics of the cell phone and fuel cell as laid out in Section 6, we have developed a set of requirements for our hybrid power system and summarized them in Table 5.1 below

Table 5.1: Engineering Specifications for Power Delivery System Design

Components	**Parameters**		
	Current (mA)	Voltage (V)	
Cell Phone: Standby	5	2.5-4.2	
Cell Phone: Talk	190	2.5-4.2	
	Capacity (mAH)		
Li-ion Battery	750		
	Max. Output Power Density	Output Voltage	Current Density
Direct Methanol Fuel Cell (DMFC)	50 mW/cm2	0.35 V	140 mA/cm2

Safety is always a big concern for a consumer, thus temperature is a critical parameter for our hybrid powered cell phone design. In particular, we are concerned about the operating temperature of the fuel cell and of the lithium-ion battery, the boiling point of methanol, the threshold of pain on contact skin for most people, and the optimal temperature for some electronic components. Table 5.2 summarizes these temperature requirements as have been laid out in the previous sections.

Table 5.2: Temperature requirements for a hybrid fuel cell design

Requirements	Temperature (°C)
Methanol boiling point	64.7
Optimal operation of DMFC	30-80
Lithium-ion battery	40
Threshold of pain on skin contact	44
Electronics	< 50

Durability is the second chief concern when dealing with the fuel cell packaging. As methanol is transported to the fuel cell for power, care needs to be taken to ensure that the fuel circulation system is rugged and cannot be compromised under duress. If methanol were to leak on to hot surfaces or onto the user, there would be serious consequences. For this reason, we are recommending that our design be subjected to the Military Standard methods [24] for testing equipment, especially as they pertain to shock and vibration. These standards are tougher than regular consumer electronics testing methods.

Each standard will have an associated critical value of duress which the system must withstand before failure. One example is from the military drop test, which states that an electronic device should still operate after falling from 1.5 meters onto a hard surface. The force associated with this impact loading can be roughly determined based on the kinetic energy gained by the phone during free fall and on its momentum, as outlined in Appendix D.

From these equations, we were able to determine our cell phone will have to handle 1000 N of force upon impact, which includes a factor of safety of 4. A conservative estimate such as this must be made early within the design process because full application of this device is not completely known. However, as most portable phones can withstand similar loading, we feel confident materials exist which can meet these requirements.

6. Fuel Cell Testing and Verification

The performance of DMFC is one of the primary concerns in this project. Even though the design and building of a DMFC is beyond the scope of this project, the power and heat testing on the Parker TeckStak DMFC still helps us to understand the performance of a fuel cell under various operating conditions and provide supporting verification for our final design. The list of the components that are utilized for power and heat characterizations is provided in Appendix N.

6.1. DMFC Trade Study

Currently, only a limited number of companies sell DMFCs for retail, and most of these products are educational in nature. The trade study for DMFC selection is provided in Appendix N. The Parker TekStak DMFC was finally selected by our team due to its power output. In ideal conditions, one cell DMFC can produce up to 1W. Therefore it can easily power the cell phone under standby mode with extra power to charge the battery (see Section 3.2.1.: cell phone technology). However, it requires a fuel pump to circulate the fuel through the cell and an air pump to force pressured air to pass through. The air pump is required because it is an active fuel cell and does not have access for free flowing air that is needed in the reaction of a DMFC (see Appendix O for pumps specifications). Due to these limitations, the Parker TekStak DMFC cannot be directly used for our package design; however, the power characterization of this type of fuel cell still provides important supporting documentation to validate the hybrid power delivery system design and suggests optimal operating conditions. In addition, the heat testing can help to construct the relationship between the power output and heat generation of the fuel cell, and the results of heat characterization can also be used for further package heat testing (see Section 6.3.).

6.1.1. Specific Characteristics of the Parker TekStak

The manufacturer's specifications show that the one cell Parker TekStak DMFC has a nominal power output of 1W, with a stack surface area of 10 cm^2. The power characterization curve for a five-cell DMFC stack is shown in Figure 6.1, showing that its open circuit voltage is about 3.75V. Therefore, the open circuit voltage for a one cell DMFC was one-fifth of that of the five-cell, which is estimated to be 0.75V.

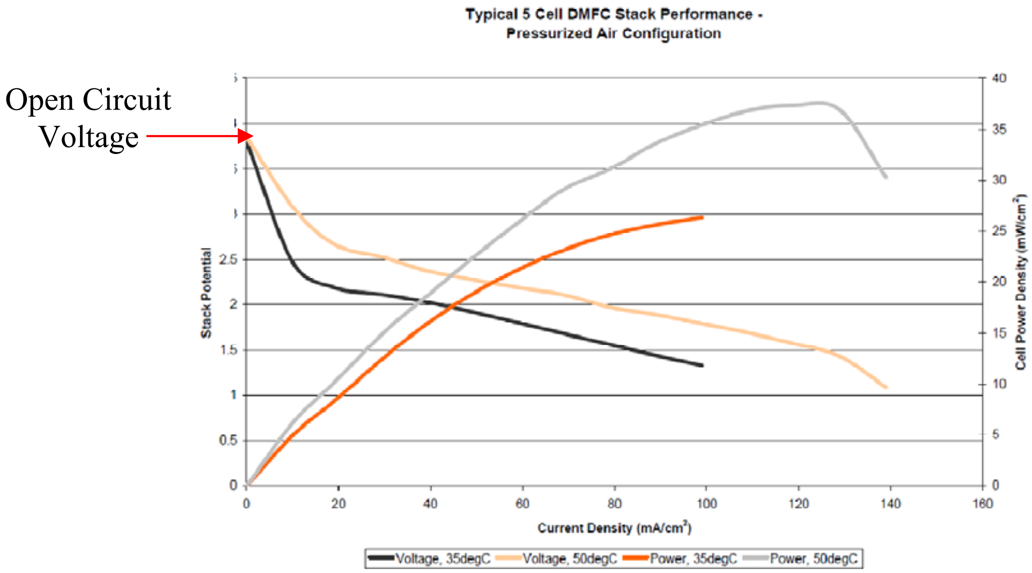


Figure 6.1: Manufacturer's power characterizations for Parker TekStak five-cell DMFC

6.2. Fuel Cell Power Characterization

The purpose of power testing is to characterize the power output of DMFC under various operating conditions, understand the effects of methanol concentration and temperature on its performance, and validate the power requirement for cell phone. Parker TekStak does not provide any power characterization curve for this one cell DMFC, however, it suggests testing the fuel cell with methanol concentration of about 2M. In addition, the temperature of the methanol is not expected to exceed the threshold of pain at 44°C. Therefore, power testing was conducted with methanol concentration of 1M, 2M, 3M, and 4M at varying temperatures of 22°C (ambient temperature), 30°C, and 40°C. Note that 1M methanol solution corresponds to 4% volumetric fraction, and various concentrations can be achieved by diluting the 99% methanol using deionized water.

6.2.1. Power Characterization: Testing Methods

The setup of the fuel cell is shown in Figure 6.2. Both a fuel circulation pump and an air pump were utilized to operate the fuel cell. Fuel and air pumps require 12V and 6V voltage inputs respectively, which are supplied by an external power source. Since our fuel pump is not a variable speed pump, the fuel flow rate was adjusted by varying its power input. This can be simply achieved by connecting different values of resistances in series with the pump. The manufacturer also suggests a fuel rate be 5mL/min, however, the lowest fuel flow rate we could achieve by our non-varying fuel pump was about 100mL/min. The effects of fuel rate on the performance of fuel cell will be discussed in Section 6.2.4. Also note that this DMFC requires humidified air input, thus a heating plate is placed to boil the water, from which the humidified air can be obtained. The temperatures of the methanol solution and fuel cell stack are also measured.

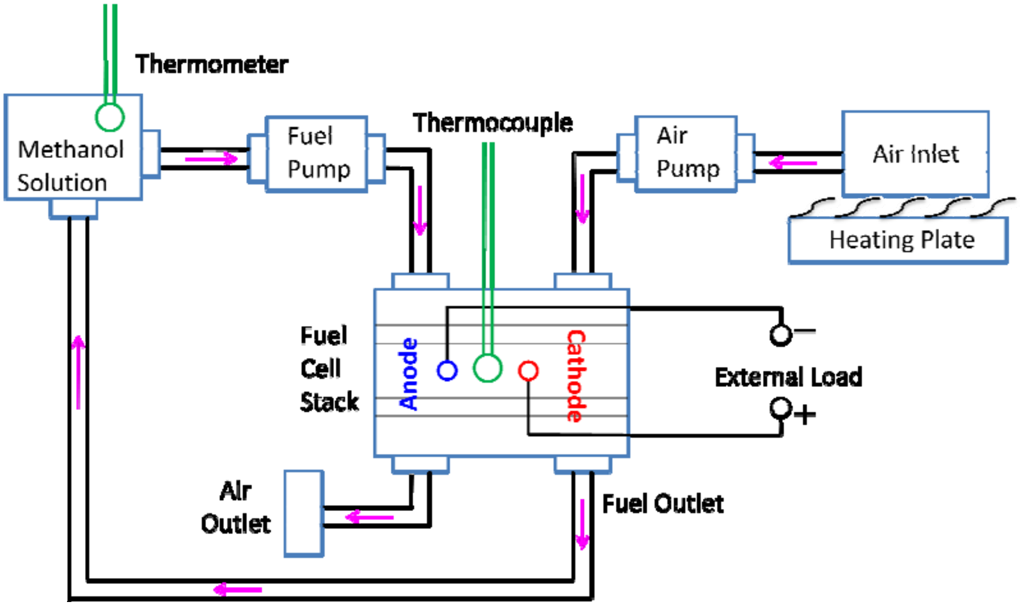


Figure 6.2: Schematic of Parker TekStak DMFC Setup

Figure 6.3 illustrates the testing circuitry for fuel cell power characterization. The external loads are the resistances ranging from 1Ω to 700Ω. A voltmeter is in parallel with the external load to measure the fuel cell output voltage, while an ammeter is in series to measure the current in the loop. The product of the voltage and current gives the power output of the fuel cell.

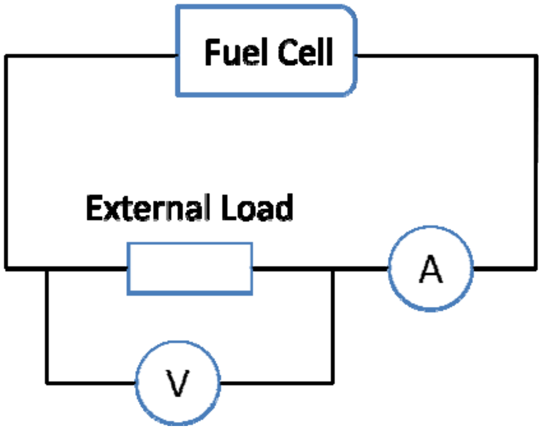


Figure 6.3: Methanol Fuel Cell Power Characterization Circuitry

6.2.2. Power Characterization: Expected Results

Since the manufacture's characterizations for a five-cell DMFC (see Figure 6.1) are presented in terms of current and power density, our expected current and power of the one cell DMFC can be obtained by multiplying these densities by the stack area, which is 10cm^2. The power characterizations shown in Figure 6.1 only shows the temperature effect on the fuel cell power output, but does not provide the methanol concentration for testing. Note that the maximum power densities at 35°C and 50°C are about 37mW/cm^2 and 27mW/cm^2 respectively, thus our expected power output should be in hundreds of mW. In addition, the temperature also affects the shape of the power curves. The power density continuously increases with the increased current at 35°C; however, at 50°C it drops at high current. There is no direct equation to describe the relationship between the temperature and the maximum power output, however, generally better power performance is observed at elevated temperature.

6.2.3. Power Characterization: Results

Various characterization curves were obtained under different testing conditions. Figure 6.4 presents the results for methanol under ambient temperature with a concentration of 1M. The shape of the curves is exactly the same as what we expected. Note that there is no power drop at high current in this testing condition. The open circuit voltage is about 0.55, which is a little bit lower than our expectation of 0.75V. However, the maximum power we obtained is only 45mW, which is way lower than our expectation of hundreds of mW.

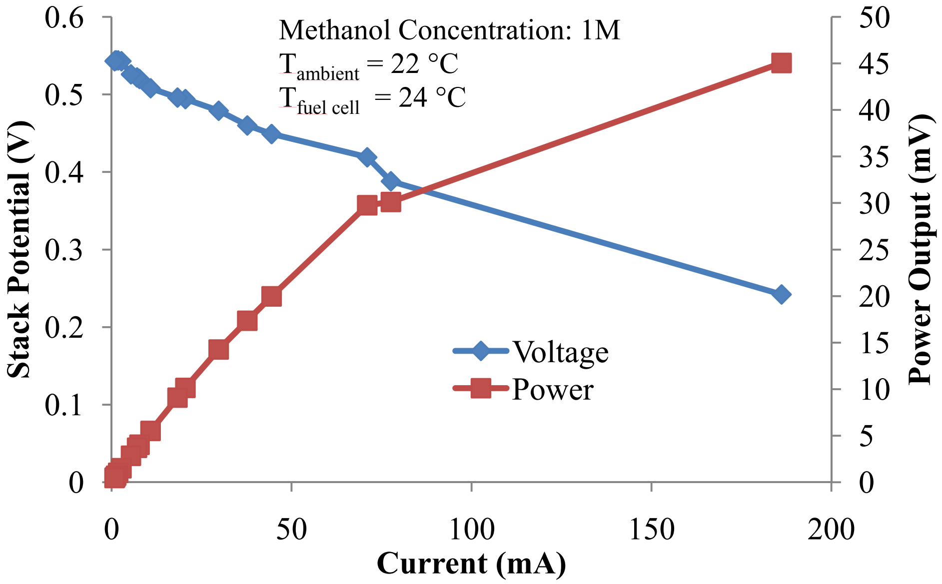


Figure 6.4: Parker TekStak DMFC power characterization curve. The methanol is under ambient temperature with a concentration of 1M.

Results of power characterizations for various methanol concentrations under ambient temperature are summarized in Figure 6.5. The fuel cell power output decreases with the increased methanol concentration, and the fuel cell tends to have the best performance with a methanol concentration of 1M. Note that the shape of the power curve also changes with the methanol concentration. Power drops at high current were observed for methanol concentration of 3M and 4M. This phenomenon was also reported by many research papers and will be discussed in Sec. 6.2.4.

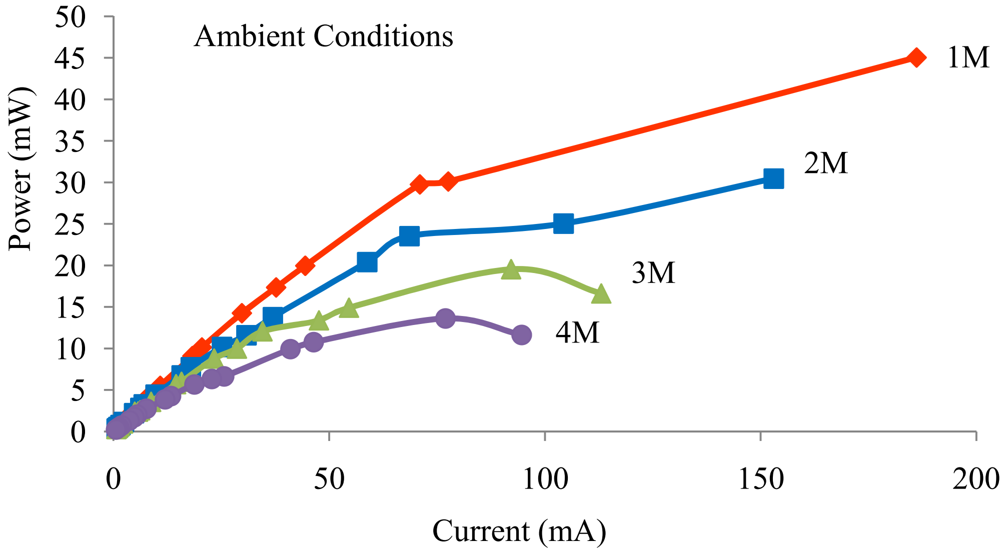


Figure 6.5: Power characterization curves under ambient conditions. The methanol concentrations vary from 1M to 4M.

The maximum power for each testing with methanol of various concentrations and temperatures is presented in Figure 6.6. The power output increases with increased temperature, which is consistence with our expectation, however, the effect of the methanol temperature on the power output is not as significant as that of the fuel concentration. The highest power output we achieved among all the testing is 51mW with 1M methanol at 40°C. Even though the fuel cell power output is way lower than our expectation, it still can successfully power a cell phone under standby mode, but requires very long time to recharge the battery (see Section 7.).

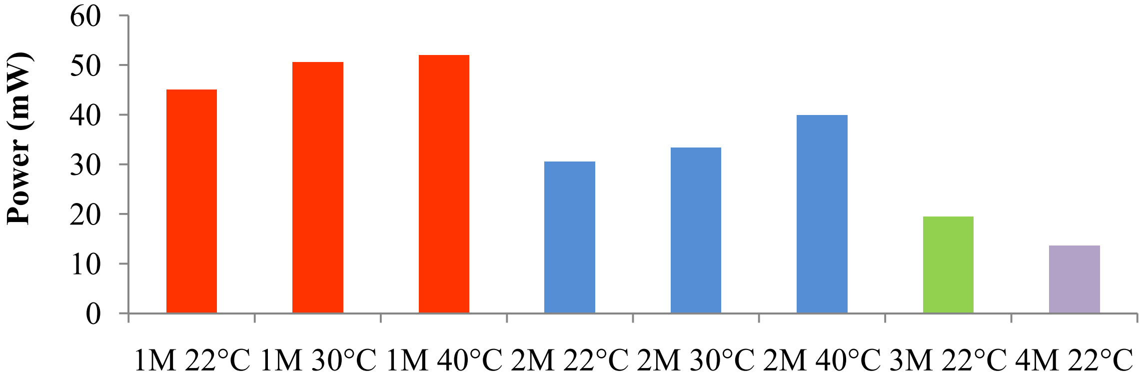


Figure 6.6: Maximum power output under various testing conditions

Both the methanol fuel and stack temperatures were measured for each testing. The results are presented in Table 6.1. Note that all of the testing was conducted in an open ambient, where the heat generated by the fuel cell can be easily dissipated into the ambient. Therefore, even when the fuel temperature reaches 40°C, the stack temperature is only about 30°C, which is lower than the threshold of pain (44°C).

Table 6.1: Methanol temperature and stack temperature. Note that the temperature of the stack is measured in an open ambient, where the heat can be dissipated easily.

Methanol Concentration	Methanol Temperature (°C)	Stack Temperature (°C)
1M	22	24
	30	26
	40	31
2M	22	24
	30	26
	40	29
3M	22	24
4M	22	24

6.2.4. Power Characterization: Discussion

Several issues including methanol concentration, fuel/air flow rate, and operating temperature will be discussed in this section to find out the possible reasons for low power output. In addition, a comparison between the active and passive DMFC will be briefly discussed to provide supporting verifications for our final package design.

A schematic of passive DMFC is illustrated in Figure 6.7. A methanol solution of varying concentration is stored in a methanol reservoir that is attached to the anode side, and the methanol was allowed to diffuse into the anode catalyst layer driven by the concentration gradient set between the reservoir and the anode. Oxygen is supplied to the cathode from the ambient air by a kind of air-breathing action driven by the concentration gradient [29]. Since no external devices such as pumps are utilized, passive DMFC is more suitable for our package than the active one.

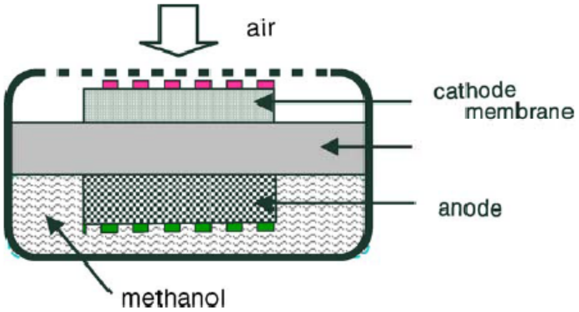


Figure 6.7: Schematic of passive DMFC

6.2.4.1. Discussion: Influence of Methanol Concentration on Power Output

Based on our testing, the passive fuel cell has the best performance with methanol concentration of 1M. This result is also reported by Liu *et al* [30]. However, Bae *et al* [A] determined the optimal methanol concentration for passive DMFC is 5M. The increased optimal concentration in passive fuel cell can be attributed to its slower methanol mass transport rate compared with an active one. Therefore, a higher methanol concentration is needed to compensate for the slower mass transport rate of methanol in passive cells. However, the crossed-over methanol can also deteriorate cell performance by generating a mixed potential and poisoning the catalyst in the cathode. Thus further increase of methanol concentration would result in performance decline due to the increased over potential at the cathode. Consequently, the optimal concentration in the passive cells is a result of compromise between the methanol transport rate and mixed potential that are influenced by methanol concentration. [29]

6.2.4.2. Discussion: Influence of Methanol Temperature on Power Output

Our testing results show that the fuel cell has better performance at elevated temperature under a range of 22 to 40°C. Therefore, for our package design, we would like to keep as much heat as possible to keep the methanol fuel warm. The increased temperature can enhance the reaction kinetics at both the anode and cathode, and therefore increases the cell power output. Considering the threshold of pain at 44°C, we did not test the fuel cell with a temperature higher than 40°C. At this moment, we cannot predict how much the power output of the fuel cell can be improved by increasing the fuel temperature. It is also possible that the manufacture’s nominal power output is achieved by using high temperature methanol; however, we have no information about this optimal temperature.

6.2.4.3. Discussion: Influence of Fuel and Air supply on Power Output

It is generally believed that higher methanol flow rate resulting in higher mass transport rates of the reactants can improve the power output. However, our testing suggests that lower the fuel flow rate may result in an increased power output. This interesting phenomenon was observed when we turned off the fuel pump and found the voltage cross the loads would increase a lot. We did not conduct detailed testing on the fuel cell without fuel pump, because this active fuel cell is designed to use fuel pump, and we cannot determine whether there will be enough fuel stored in the stack during testing if the fuel pump is turned off. This result also suggests that it is entirely possible that the passive DMFC can have an even better performance than an active one.

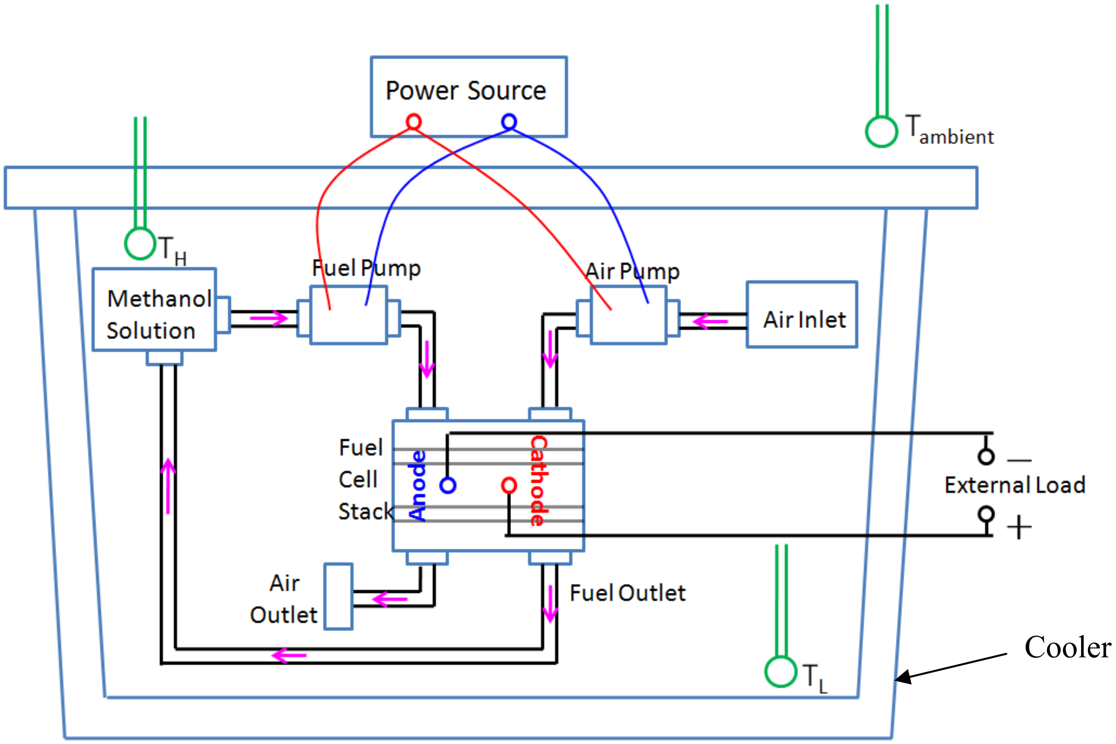
The possible reason for the decreased power output at high fuel flow rate is the accumulation of water that is produced by oxidation of the crossed-over methanol as well as by the oxygen reduction reaction (ORR) at the cathode. Since the cathode compartment is fully open to ambient air at room temperature, the water might not be removed effectively. The water may accumulate and begin flooding in the catalyst layer when an excessive amount of water is produced at the cathode. [31]

Air supply is another important issue in a fuel cell. For the DMFC that achieves a stoichiometric reaction, the volume ratio between the pure oxygen and methanol is 1.5:1. Therefore, the volumetric flow rate of the air should be almost 7 times higher than that of the methanol, considering that the volumetric fraction of oxygen in air is 21%. However, this stoichiometric condition cannot be achieved in our testing due to our limitation in controlling the pumps. We also observed that the voltage across the loads increased significantly when we blow the air at the cathode instead of using air pumps. Thus higher power output may be obtained by increasing the air flow rate. However, it is hard to control the rate of air in a passive DMFC, and we cannot determine the effect of air supply on that type of fuel cell at this moment.

6.3. Fuel Cell Heat Output Characterization

One of our primary concerns of our project was to characterize the heat generated by the fuel cell during operation. This was the main driver for the component packaging design, as it was the key issue when choosing materials and configuring the components to facilitate proper heat transfer. The material chosen would have to protect the user and other cell phone components from the heat generated by the fuel cell. At the same time, ideal efficiencies of DMFCs occur at elevated temperatures. In fact, methanol fuel is sometimes directly heated to improve power output. This means some combination of heat ventilation and containment will be required.

Figure 6.8 shows the setup for heat characterization. The fuel cell as well as its auxiliary components were placed in a cooler, with the exception of the power source for the pumps and the external loads. Note that the heat testing is conducted when the methanol solution is under ambient condition. Two thermocouples are put at the top and bottom of the cooler to determine the average temperature inside. The temperatures were measured inside the cooler as well as the outside. These temperature differences were going to help us determine the heat output of our fuel cell at ambient starting conditions.



$$\dot{Q} = \rho_{air} V C_p \frac{dT}{dt} \qquad \text{Eq. 6.1}$$

Figure 6.8: Heat Characterization Setup and Equation for Heat Output

6.3.1. Heat Characterization: Testing Methods

Our methods were to test the fuel cell at 1-4 mol methanol solutions. Because we felt that a 4 mol solution of methanol would produce more power and more heat, we wanted to base our package design off the most heat output of our fuel cell. This would help to calculate in a factor of safety because we would not want to run the fuel cell with 4 mol solution in our final design.

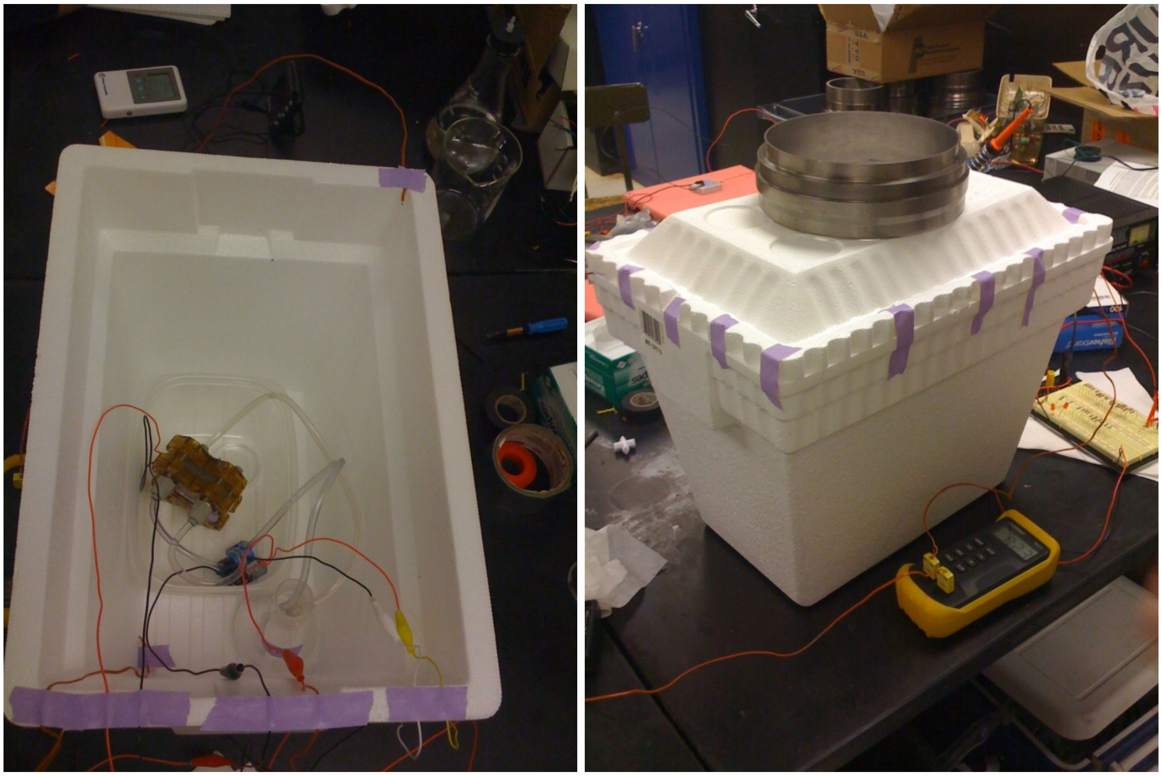


Figure 6.9: A look inside and outside the test set-up. Pictured on the left, inside cooler, are the fuel cell, air and fuel pumps, tubing, methanol fuel and flask, thermocouples and wiring. Pictured on right are the thermocouple read out and weight to keep cooler shut.

6.3.2. Heat Characterization: Expected Results

As previously discussed, the chemical reaction that takes place within a methanol fuel cell releases a measure of heat. We were able to find a study that lays out a set of equations to determine the theoretical heat output of a DMFC given the fuel cell efficiency and the maximum current output. The heat flow $\dot{Q}$ is given as:

$$\dot{Q} = \left(\frac{1-\eta_{FC}}{\eta_m}\right)\frac{\Delta H}{6F} I_{el} - N_{H_2O}^{gas}\Delta H_v \qquad \text{Eq. 6.2}$$

where η_{FC} is the overall efficiency of the fuel cell, η_m is the mass efficiency (or the ratio of methanol used to produce electricity to the total amount of methanol flow), ΔH is the heating value of the methanol reaction, F is Faraday's Constant, I_{el} is the current draw from the cell, $N_{H_2O}^{gas}$ is the molar flow of water vapor leaving the cathode, and ΔH_v is the heat of vaporization of water.

Some assumptions can be made to give an initial estimate of heat output. First, we assumed that water leaves the cell as a liquid and not a vapor. We have concluded that this is reasonable since the fuel will not operate at a temperature close to 100 °C. This eliminates the $N_{H_2O}^{gas}$ term. Second, we have found a typical fuel cell efficiency to be around 25%, so we assumed $\eta_{FC} = 25\%$. The mass efficiency is a term we do not fully understand; it relates to the amount of methanol that permeates through the membrane from the cathode to the anode. This can occur by diffusion or electro-osmosis, and results in reduced efficiency and liquid methanol exhausting with the products on the cathode. In an ideal case, there would be no permeation and η_m would be equal to one; we made this assumption, though as a team we feel there is some cross-over of methanol because while testing the fuel cell a small dime size amount of a clear liquid would end up at the air exhaust of the fuel cell. Some of this liquid could be water, but we fell some was methanol. Finally, since we are concerned primarily with the maximum heat output, we will consider the case where I_{el} is a maximum theoretical value for our fuel cell, at 1.4A. The result of these assumptions is a theoretical heat transfer rate of 1.3W released by the fuel cell at maximum power output. This result is supported by other research [14] which empirically relates the methanol concentration to power output. Based on data from this test, we found an expected heat transfer rate of around 1.5W. The difference in this estimate is that it takes methanol crossover into account. Crossover occurs when methanol penetrates through the electrolyte membrane and reacts with air on the other side; this reaction releases a large amount of heat. This will provide a good starting point until we are able to make a more accurate empirical determination.

6.3.3. Heat Characterization: Results

The heat output of the fuel cell came out to be around 5 mW. The heat generation rate ($\dot{Q}$) can be calculated by the following equation:

$$\dot{Q} = \rho_{air} V c_p \frac{dT}{dt} \qquad \text{Eq. 6.1}$$

where ρ_{air} is the air density, c_p is the specific heat of the air, V is the air volume inside the cooler, and $\frac{dT}{dt}$ is the temperature change rate. The temperature only raised 1 °C over an hour period. . Even when we thought our fuel cell was outputting 5 mW of heat we still moved on with designing and testing a prototype package we still ran tests from 0.5-3.0 Watts because we want to make sure our design could manage those heat output range. Further discussion on this subject will be discussed in our prototype Section 8.7.

6.3.4. Heat Characterization: Discussion

Testing the heat output of know device in Figure 6.3, 6.5 W of heat output resulted in 6.4 W being dissipated from the cooler. We calculated our cooler test was approximately 99% ineffective. This helped us to figure out that our DMFC was actually outputting about 1.08 W of heat from the fuel cell. This value of 1.08 W is closer to that of 1.3 W, which was our theoretical value. We never achieved 1.4 A from our cell so that is one reason why we did not achieve 1.3 W. Further discussion on low power outputs are discussed in Section 6.2. Another reason our team feels that our test was not effective was because our cooler was labeled to have no CFC's. Chlorofluorocarbons are used to help insulate the cooler, but because the cause harmful greenhouse gases, they are no longer being putting in simple coolers such as the one we purchased. This didn't help our test to be very accurate. To improve our test design, a better cooler should be used that has better insulating qualities.

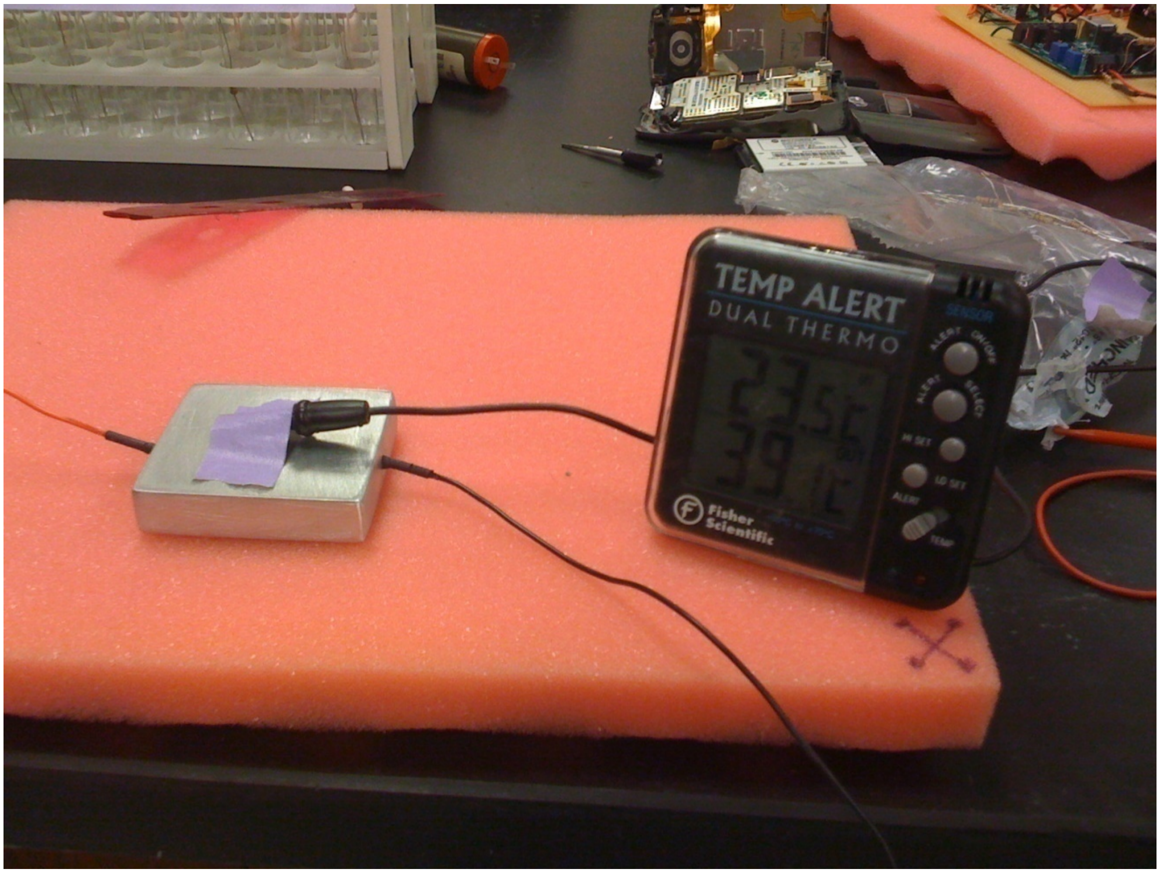


Figure 6.10: The aluminum block with resistors that was used to produce 6.5 Watts of heat, ignore the temperature reading as this picture was taken from an earlier first test to see if the set-up worked properly.

7. Hybrid Circuitry Design

A hybrid power system requires complex circuitry that is capable of managing power from two sources and delivering it to the proper component at the proper time. Our design must be capable of accepting power from the fuel cell and delivering to either the cell phone for operation or to the battery for charging. It must be able to determine when the battery needs charging and when it is full, as well as whether the cell phone requires extra power from the battery during periods of heavy use.

7.1. Hybrid Circuitry: Concept Generation and Selection

There are a number of options for configuring the components in order to integrate a fuel cell into a cell phone power system. Three concepts we examined were; using the fuel cell to power the cell phone directly, using it to simply charge the battery when it was drained, and a true hybrid system that managed the power from the battery and fuel cell so that each component is used most efficiently.

7.1.1. Concept Design 1: Direct Power

Our first concept is to use the methanol fuel cell to power the cell phone directly. In this design, a fuel cell could only be utilized under either standby or talk modes. This may be the simplest design; however, it is hard to meet the power requirements of the cell phone under talk mode which consumes 180-190 mA (Table 7.1). Due to the low voltage output from the fuel cell, a voltage booster has to be utilized, which in turn reduces the output current to 50mA. Thus, at least four to five cells should be combined in parallel to power the cell phone. This design was abandoned because the multiple cells would occupy a large volume and have a high cost.

7.1.2. Concept Design 2: Battery Charger

In our second design, the methanol fuel cell is only utilized as a battery charger to recharge the lithium battery at low voltage, and the cell phone is still powered by the battery. This design is more feasible compared with the first one; however, it may use the fuel cell inefficiently due to the large power loss during the charging. As discussed in Sec. 6.3., the power dissipation can be calculated by Eq. 6.1. Thus, the power dissipation for charging the fully drained battery is calculated to be 85 mW, if the battery is charged at a constant rate of 50 mA. Since the battery will be charged repeatedly, this power loss will be significant. We did not choose this design due to the inefficient use of energy.

7.1.3. Concept Design 3: True Hybrid

The third design utilizes both the fuel cell and battery to power the cell phone. Figure 7.1, 2, 3 present the block diagram for standby, talk, and charging+standby modes, respectively. Based on our previous analysis, a single fuel cell can provide sufficient power for standby mode; thus, the cell phone can be powered only by the fuel cell in this mode.

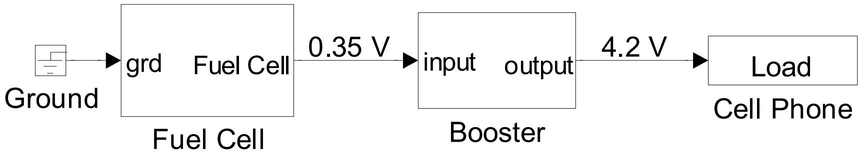


Figure 7.1: Block Diagram for Standby Mode

During talk time, both the fuel cell and battery will be utilized to achieve the required high current. Since the maximum current the fuel cell can provide is 50 mA, the remaining 140 mA will be drawn from the lithium-ion battery. Compared with the situation where only the battery is used, the combination can improve the talk time is by 36%.

When the cell phone switches back to standby mode, the fuel cell will power the cell phone and also recharge the battery via the charger. Note that under this situation the voltage booster needs to improve the voltage to 4.5 V to satisfy the battery charger. Since the standby mode may also consume about 5 mA current, the ideal charging current is reduced to 45 mA.

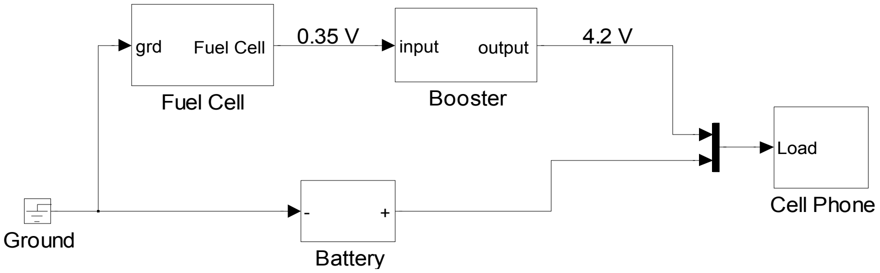


Figure 7.2: Block Diagram for Talk Mode

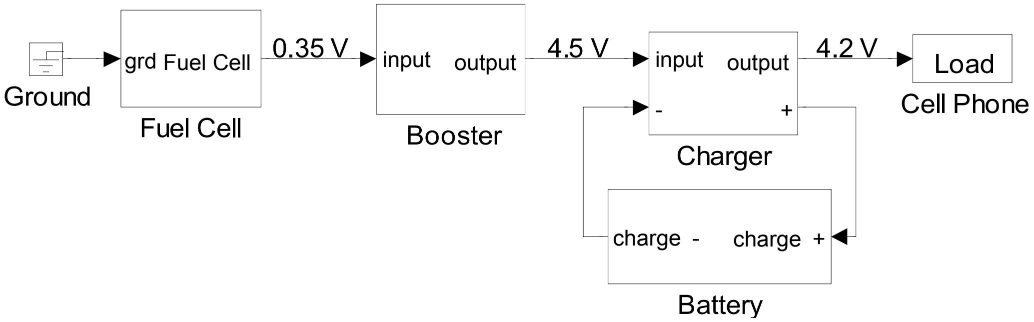


Figure 7.3: Block Diagram for Charging while Standby Mode

This true hybrid design has a complex control circuitry, but it is the most efficient way to use the fuel cell regarding the design requirements. The block diagram of the whole power delivery system is provided in Appendix I. We finally selected this design for our power delivery system based on its best use of energy and, in the end, will lower the cost because the fuel will not be consumed at a high rate.

Figure 7.4 presents the power profile for our true hybrid power delivery system design. It shows the voltage of the battery and current consumption of the cell phone under standby, talking, and charging while standby modes. We assumed that current consumption under the standby and talk modes are 5 mA and 200 mA respectively. Note that the battery voltage remains 4.2 V under standby mode, but decreases during the talk mode. When the battery voltage is below 2.5 V, the talk has to be stopped and the standby mode will be resumed to recharge the battery. If the battery has a capacity of 750 mAh with a constant charging rate of 45 mA, the maximum talk time will be 5 hours; however, it may take 16 hours to recharge the fully drained battery. The recharging time is long due to the low charging amperage, but in most cases, the battery will not be fully drained, and the recharge time will be shorter. Note that in the real case, the charging and discharging rate of the battery is not constant. During the charging process, it will be much faster at the beginning but slow down when the voltage is close to 4.2V. Therefore, we may need testing to determine the real charging and discharging time for the battery.

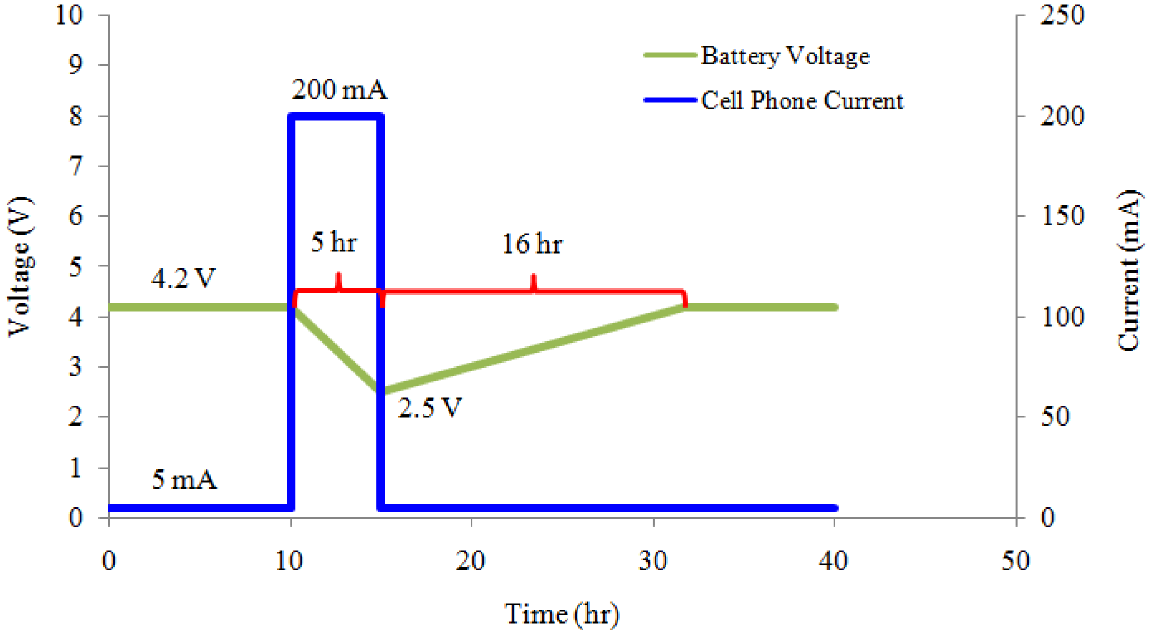


Figure 7.4: Power profile for a cell phone under standby, talk, and charging while standby mode. The capacity of the battery is 750 mA. The const charging current is 45 mA.

7.2. Hybrid Circuitry: Final Design

Our final recommended circuitry design consists of the components described as the True Hybrid concept in the section above. However, there is no need to create a separate circuit board for the hybrid circuitry; the voltage booster and charging chip should be integrated into the circuit board of the cell phone to streamline the design. This should be designed by an engineer skilled in the art of circuit layout. We will attempt a proof of concept with the circuit components as described in the Prototype Description.

7.3. Hybrid Circuitry: Prototype Description

In order to prove that this circuit configuration met the needs of our hybrid system, the circuit was built in an open format on a perforated circuit board. So that we could prototype the board independently of fuel cell testing, we used an Energizer rechargeable NiMH AA battery in series with two potentiometers to simulate the power characteristics of the fuel cell. These potentiometers can be set so that a voltage can be taken over one of them in the 0.3-0.75V range, with a current of <50mA, which is typical of our fuel cell.

Each of the necessary chips was obtained from Texas Instruments on evaluation modules (EVMs, also known as a “demo boards”) to reduce the complexity of our assembly. The booster chip EVM (model TPS61201EVM-179) accepts an input voltage range of 0.3-5.5V, and has a fixed output of 3.3V. This output voltage was lower than our ideal design, because it will not be able to fully charge a 3.6V cell phone battery. With the help of Ron Jonas, our electrical engineering contact at Harris, we were able to determine a modification to the printed circuit board which would give us the desired input to our battery charger. Adjusting one of the surface mounted resistors in a feedback loop (R5, see the specification sheet in Appendix L) by putting a 380kΩ in parallel with it raised the voltage output of the booster to 4.8V.

The battery charging EVM (model bq240301EVM) accepts an input voltage from the booster chip, which is usually around 5V. While initial tests would indicate that our 3.3V booster will be able to operate the chip, it remains to be seen what effect this lower voltage will have on performance. The charging chip has the capability to power a system and charge the battery at the same time. It also automatically selects whether to power the system with the phone battery, the input from the voltage booster, or a combination of both depending on the load requirements of the system. It also monitors the battery to ensure that it is not over-charged or over-discharged and that it does not overheat and start a fire.

The "system," which would normally be the cell phone itself, is prototyped simply as a variable resistive load. A potentiometer is used which can range from 16.5Ω to 660Ω, which will be adjusted to draw between 200mA (the talk-mode current) and 5mA (the standby-mode current). Using an actual cell phone as the load would be difficult, because it would require that the phone be dismantled and connections be made to the phone's internal circuitry.

Instead of using the Razr's original battery we used the Ultralast CR123 (3.3V, 700mAh) Li-Ion battery, commonly used for flashlights and digital cameras. This battery has the same characteristics as a typical lithium cell phone battery, except it has a cylindrical geometry and only has positive and negative terminals. A cell phone battery usually has a flat geometry that is optimized to fit in the limited space within a phone. They also have terminals for the temperature sensor and capacity sensor, which communicate the battery's characteristics and charge state to the phone. These extra terminals are unnecessary for our prototype and made connections more difficult.

This functions exactly as our final design is supposed to, but the EVMs are bulky and outfitted with screw terminals and other features that make prototyping easier but are not optimized to reduce size. Connections are made as show in Figure 7.5 below.

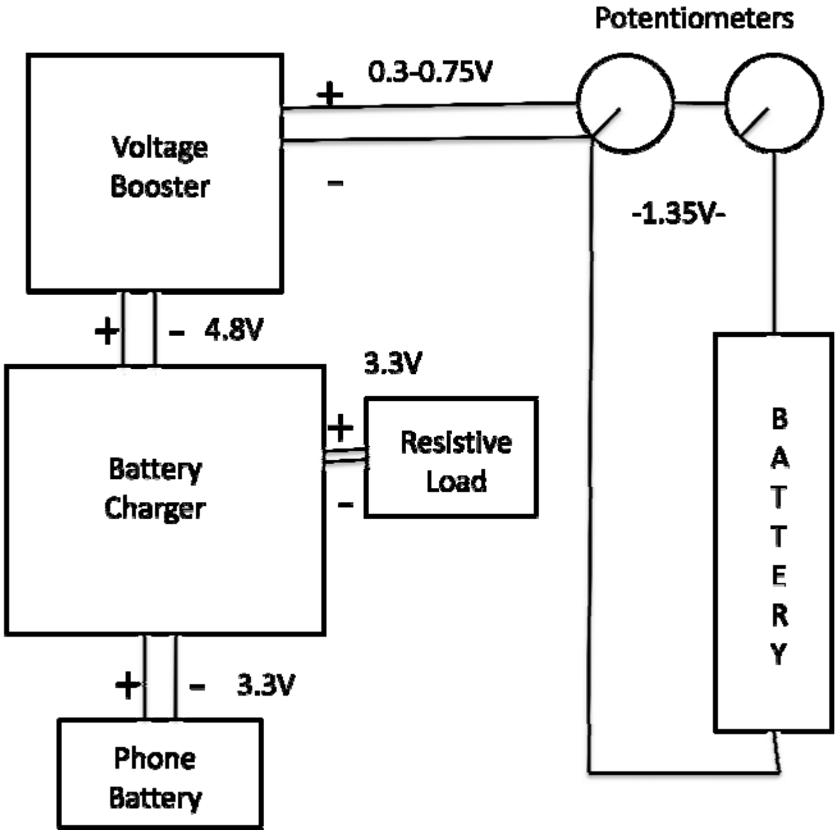


Figure 7.5: Prototype Charging Circuit with Expected Voltages

Each of the components has been purchased or otherwise obtained, and a bill of materials is given in Appendix A.

7.4. Hybrid Circuitry: Fabrication

Fabrication was completed on the prototype charging circuit with relative ease because circuit connections were straightforward. The battery cradle is held to the perforated circuit board backing with wire looped through the board holes and twisted to secure it. The potentiometers are placed onto the board with their prongs inserted into the holes and connections are soldered to the battery cradle. The booster chip EVM is not attached to the board directly, but leads are soldered onto the chip in the proper places and then soldered to the potentiometers. Output leads from the booster chip are screwed into terminals on the charging chip EVM, with a small 1.2Ω resistor used for measurements described in Section 7.5. The phone battery is wired to the screw terminals on the charging chip (also with a measurement resistor), and a simple resistor is jumped between the output terminals on the charging chip. The most difficult part of the fabrication was attaching the resistor in parallel with R5, as discussed in the previous section. To make a connection to the printed circuit board, we soldered a few strands of a multistrand wire to each patch of solder on eight end of the resistor, taking care not to jump the small conduction paths with excess solder and thus ruin the circuit. The resistor was then soldered to the stranded wire. A picture of the charging circuit is shown in Figure 7.6 below:

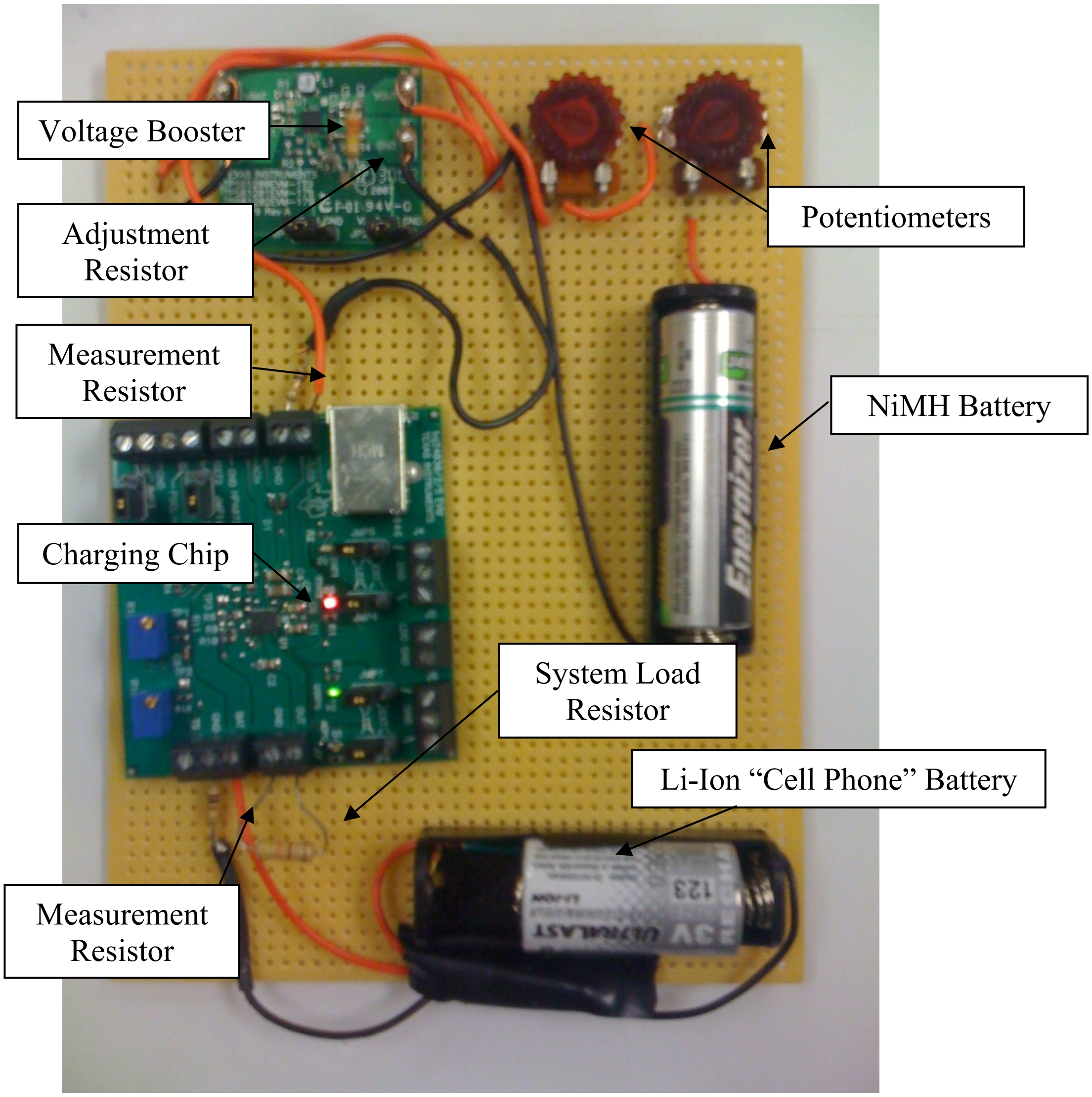


Figure 7.6: Charging Circuit Prototype

7.5. Hybrid Circuitry: Validation

Validation of the circuit prototype was a process of measuring voltages and currents to verify that the circuit reacted to changing inputs correctly and was able to manage power from both the battery and the fuel cell.

7.5.1. Circuit Validation: Testing Methods

Once the circuit seemed to be operational (the LEDs on the charging chip were lit in the correct color and combination, see Appendix M for details) the rechargeable battery set-up was disabled and the fuel cell was connected directly to the voltage booster inputs using alligator clips. The fuel cell was run on room-temperature fuel at 1M. A hand-held multimeter was used to take voltage readings at a number of places throughout the circuit; voltage was taken across the fuel cell, the booster output, the cell phone battery and the system load. Currents were calculated by taking voltage measurements across the measurement resistors that were placed in-line with the charger input and the battery loop and then using Ohm's law to determine the current. System loads were changed to simulate different cell phone power draws by simply changing the resistor to one of a different value.

7.5.2. Circuit Validation: Results and Discussion

Results of the circuit validation are given in Table 7.1 below. There were some surprising results although overall the test was successful. Essentially, when the circuit is drawing power from both the battery and the fuel cell, the power through the system should be equal to the power through the fuel cell and battery combined. When the battery is charging, the power through the fuel cell should be equal to the power through the battery and the system combined.

Table 7.1: Voltage and Current Results for Circuit Validation

System Load (Ω)	**300**	**430**	**750**	**1500**	**430**
Fuel Cell Voltage (V)	0.335	0.327	0.326	0.313	0.328
Booster Output Voltage (V)	2.68	2.68	2.66	2.98	2.68
Booster Output Current (mA)	3.33	3.33	2.58	1.92	3.00
Battery Voltage (V)	2.56	2.56	2.55	2.49	1.16
Battery Current (mA)	5.17	2.75	0.92	1.08	-0.25
System Voltage (V)	2.56	2.56	2.55	2.49	1.16
System Current (mA)	8.53	5.95	3.40	1.66	2.70
System Power (mW)	21.8	15.2	8.67	4.13	3.13

First, it should be noted that the low power output of our fuel cell had negative effects on this test as well; the maximum power from the fuel cell (minus losses through the booster) was about 8.9 mW. Thus, the system and charging currents in these tests are all very low. This also had an effect on the power delivered to the system because we were never able simulate a scenario where the phone would be in talk mode. The maximum power to the load was only 21.8mW, which is much greater than the standby power draw but more than an order of magnitude from the talk mode draw. Additionally, when the fuel cell drops below 0.3V the circuit shuts off and it must be raised back above 0.5V to restart. This phenomenon is explained in the specification sheet in Appendix L, but it proved more difficult to raise the voltage back up than we initially thought it would be.

Another interesting note is that, while the voltage booster is set up to output an open circuit voltage of 4.8V, when it is connected to the charging chip, the voltage falls below 3V. This means that the battery will never be able to fully charge beyond this value. A further observation was that the system voltage is always matched to the battery voltage (which could lead to the cell phone dying even though power is being supplied by the fuel cell).

The first three circuit tests show cases where power is being drawn from both the battery and the fuel cell. We tried to raise the system resistance to a point where the extra power of the battery would not be needed, and the fuel cell alone could power the load. We learned, however, that the charging chip will allow power to be drawn from the battery until it is effectively dead, not just partially drained. In other words, so long as there are milliamp-hours remaining in the battery, it will supply power. This is interesting, because our design would be most efficient if the battery is not used at all during standby mode, which is not possible with the current configuration. This issue is one that should be sorted out before going into production, but the circuit will still serve its purpose in the current state (just less efficiently).

We then drained the battery completely and ran another test with the 430Ω resistor. In this test (data given in the highlighted column) the fuel cell successfully supplied a charging current through the battery and powered the load at the same time. The power and current supplied to the battery and system are both very low, which again is a result of the fuel cell power output issues. However, the design is validated in that the circuit can successfully utilize power from both the fuel cell and the battery, as well as charge the battery. Further testing is called for, however, especially with a fuel cell that is generating practical levels of power. This would help to determine the true power delivery capabilities of the system as well as determine the time required to charge the battery after use.

8. Packaging Design

As can be seen in Figure 4.1, the packaging components have to address four primary inputs, methanol, water, oxygen, and environmental factors, and three outputs, heat, water, and carbon dioxide. The function diagram specifies different actions which our device will perform, listing these as broad categories to aid the brainstorming process. The sub-functions that deal with these external factors and the internal factors of the system can be grouped into five types of functions. Each one's concept generation and concept selection process is described in more detail below. A full list of each sub-functions concept generation can be found in Appendix J and rankings of the main concepts considered can be found in Appendix K.

8.1. Packaging: Concept Generation and Selection

Heat generation will be addressed in two ways: heat will be ejected to the ambient atmosphere and individual components will be protected from the temperature areas near the fuel cell. A number of concepts were generated to deal with heat rejection, but most of them were either bulky and did not fit within our size requirements, or required extra power from the fuel cell in order to operate, and any extra power draw from the cell would decrease performance. The most simple and efficient option is to simply design a series of vents in the outer casing, allowing heated air to escape through natural convection. Testing will determine if this method alone is enough to remove the required amount of heat.

We plan on protecting the interior components of the system by choosing materials to insulate them or redirect the heat elsewhere. Materials with poor thermal conductivities, such as some polymers, can maintain a large temperature gradient across them, meaning components will be protected from high temperatures. We will also look into insulating coatings, which would perform the same job but could potentially be applied directly to structural elements and would require less space than standard insulation.

The cell phone package will need to address several structural failure modes in addition to dealing with the heat dissipated by the DMFC. These include safely containing the methanol fuel, protecting the circuitry from potential heat complications, preventing damage to the system caused during normal user operation, and effective ventilation of the fuel cells byproducts. There are also several design considerations which can only be understood properly through testing which will impact the final design layout. All this needs to be accomplished while still maintaining core user and sponsor requirements such as size, weight, and cost.

Our background research reviews different categories that can help us better design and test an optimal configuration. From this, we have defined several engineering specifications that state what minimum requirements this project must meet from a conservative stand point. We then created a functional decomposition of the hybrid system and brainstormed potential mechanisms which could perform each one. These different options were next refined and whittled down to realistic choices. We could then compare the different strengths and weaknesses of each design, as well as see where our knowledge was lacking and required further testing. The end result of this concept selection produced a tentative alpha design, but this alpha design will require the production and testing of several prototypes for optimization.

8.1.1. Packaging Concepts: Fuel Storage

Methanol is a toxic and flammable substance and must be handled appropriately. Concepts were therefore primarily geared toward protecting the user, which might limit the ease of liquid replacement. Our brainstorming process highlighted two solutions; storing the methanol in a tank and a removable cartridge. The first would have the methanol replenished by a squeeze bottle or other external container into a vessel permanently fixed to the phone. The main benefit this offered was greater product lifetime, as the tank would be designed to last with the system as a whole, but at the expense of upfront manufacturing costs, user refill time, and safety concerns in supplying the methanol by hand. The replaceable cartridge would operate effectively with less durable materials without sacrificing customer time replacement and safety, but would increase the end user cost. Overall, both designs are close in comparison, but we have decided to use a cartridge system for our alpha design.

8.1.2. Packaging Concepts: Fuel Pre-heating

As fuel cell performance increases with higher temperatures, pre-heating the methanol can greatly increase the fuel cell current density capabilities. Modern methanol heating techniques often use Joule resistance heaters, but these are difficult to include in a closed structure without damaging the other components and taking up too much space. One alternative to this is to use the heat output of the fuel cell to heat the methanol before it is injected into the flow plates. This pre-circulation would involve running small tubing over the surface of the methanol with insulating material surrounding this to increase maximum heat exchange. Such a setup would increase costs and reduce available space for other components. It would also require some sort of pump or flow device so as to move the methanol across the fuel cell, which would provide even more drain on the fuel cell power. This leads us to the design whereby we are hoping to rely on not pre-heating the methanol, as the fuel cell can produce the required power output while running under ambient conditions [26]. However, this potential function will be further considered in a cost/benefit analysis of how much efficiency can be gained against how much is lost to cost, weight, etc.

8.1.3. Packaging Concepts: Fuel Circulation and Delivery

Methanol must be transported from where it is stored to the membrane of the fuel cell. This is typically done through the use of a liquid pump via plastic tubing, ensuring that there is a ready supply of methanol for the fuel cell to operate. However, these pumps tend to be bulky and expensive. One possible solution we devised was directly connecting our storage device to the fuel cell such that the membrane would be constantly supplied methanol. The fuel could then be driven by either a gravity feed or a pressure differential premade in storage. The benefits of this included smaller volume and weight requirements, much less cost, lower power needs, and higher safety ratings. However, performance of the cell would be dependent on orientation and fuel pressure, which would negatively affect efficiencies in different configurations. Other designs included micropumps, which, as the name implies, provide the same fluid flow as normal pumps but take up much less space. These are unfortunately even more expensive than their bigger cousins, and also require high power demands which our system may not be able to meet. We therefore agreed that a direct connection was the most effective way to eliminate this common problem facing portable electronic design.

8.1.4. Packaging Concepts: Exhaust/Air Delivery

The reaction of the methanol within the fuel cell produces carbon dioxide and water waste which must be removed from the system. CO_2 output from the anode side poses the complication of mixing with the methanol fuel, and more importantly mixing with incoming oxygen from the atmosphere, reducing cell power output. The water generated by the cathode side reaction is believed to be small in quantity, but still poses some risk to both damaging circuitry and causing user annoyance if not handled properly.

Currently, direct methanol fuel cells use pressurized air flows and collecting basins to resolve these complications [26]. Pressurized air is fairly cumbersome and costly process, though it can improve overall cell power potentials. One possible improvement we came up with entails cutting vents along the back of the packaging to expose the fuel cell to ambient air flow. This design offers little extra cost to the product, is safe, lightweight and space saving, but is constrained to lower rates of heat loss than air pumps and potentially degrades fuel cell power output. Another solution involves introducing a fan which will both evaporate the water and expel the carbon dioxide into the atmosphere. This could also help manage any heat generation created by the fuel cell, but would increase the packaging cost, eat up limited space and weight for the design, and strain power requirements that the fuel cell must meet.

Finally, each individual substance can be addressed separately. Water can be added to the circulation of the methanol, acting as a coolant, but may require more pumping to achieve this and will eventually dilute the methanol solution to the point where the fuel cell cannot operate. Carbon dioxide could be circulated back into the cartridge and then removed as waste when disposed. The design would reduce external temperature near the fuel cell, but may negatively reduce fuel cell performance and methanol storage capacity.

8.2. Packaging: Alpha Design

Our alpha design as a final product is far down the road in the project, but the packaging of the components is not far out of our reach. The first thoughts we had involved a system to easily replace the fuel. Basic concept ideas can be seen in Figure 8.1. To achieve this we designed the fuel storage device as a removable cartridge system (1) which would be easy to insert and eject. Finger grips (2) help the user to replace the cartridge, with the comparative location of the cartridge (3) allows it to be easily accessed. Also, the cartridge is placed at the joint of the flip phone (4) so that the fuel can properly flow when in the upright (talking) position (5).

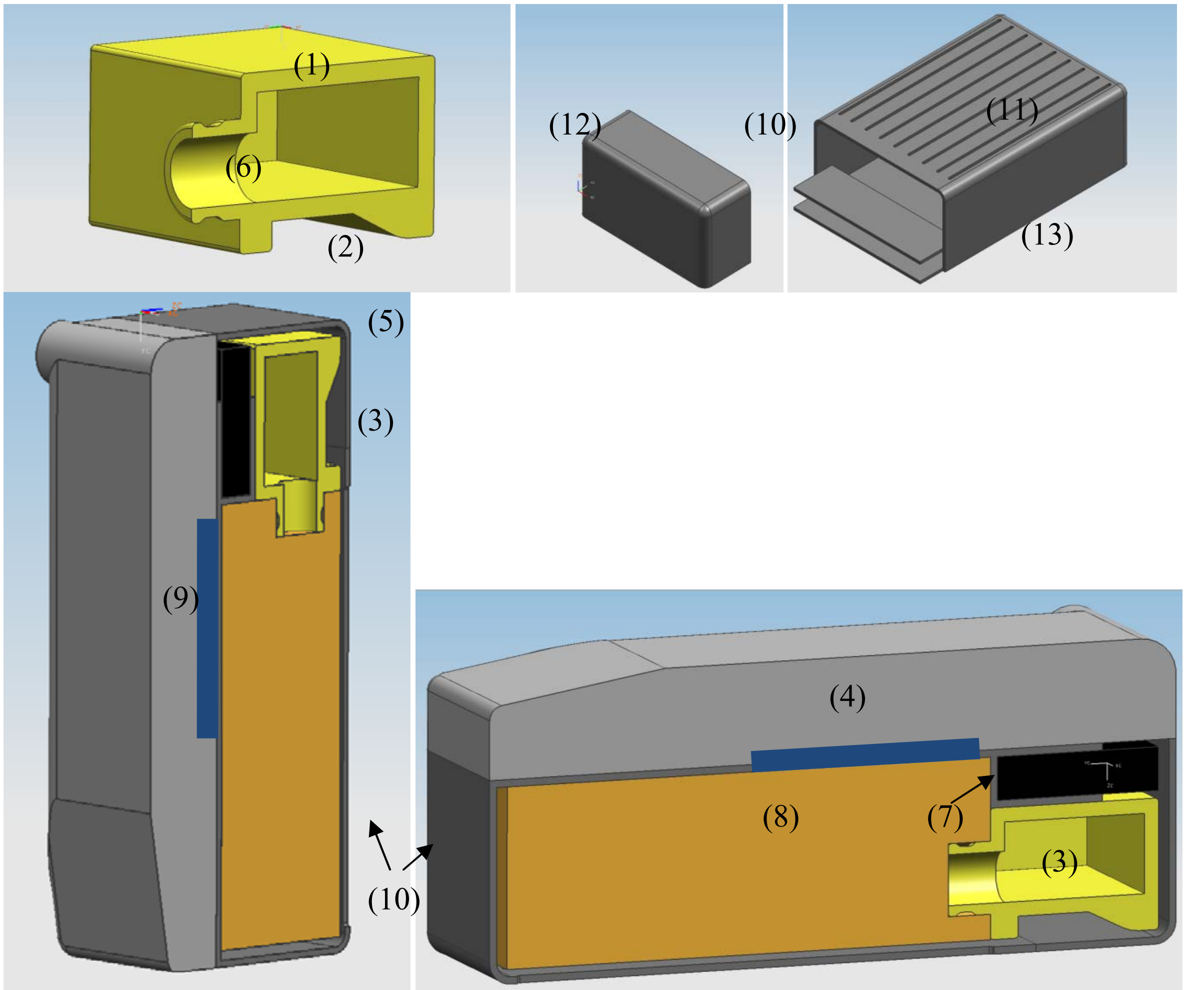


Figure 8.1: Alpha Designs (Not to Scale)

The spout (6) of the fuel container is placed directed towards the bottom so that when the phone is lying on its back the fuel will still flow to the cell. The cartridge is designed to hold 12 mL, enough space for a 10% methanol concentration to theoretically power a cell phone for 30 days. The battery (7), represented in black, is moved from the original location of the cell phone so it too can be accessed. With the new design of the hybrid system, the fuel cell (8) will cover the area where the battery was. The new void will be replaced with the circuitry (9) to power the phone and battery as well as charge the battery. The outer case (10) that protects the user and the cell phone from the heat produced by the fuel cell will be made out of either aluminum or a polymer that will be determined by our testing. Initially, we feel vents (11) placed in the casing will help to manage the heat of the fuel cell. The whole case is composed of an access cover (12) and a fuel cell cover (13). The access cover allows the user to replace the fuel and battery when necessary. Overall dimensions of total assembly (cell phone and fuel cell configuration) are 98x55x42 mm.

8.3. Packaging: Final Design

As with our alpha design, our final design will most likely not be manufactured in its entirety, but rather will serve as the basis for the test beds we have/are fabricating. However, several distinctions can be seen from our initial design and the more refined version of Figure 8.2. Whereas the first brush attempted to block out various areas which we could then fill in the prefabricated components, such as a fuel cell or battery, our final packaging design utilizes the information and dimensions we have learned from purchasing a testable fuel cell. On top of this, it attempts to optimize space requirements and heat differences so as to get the best performance.

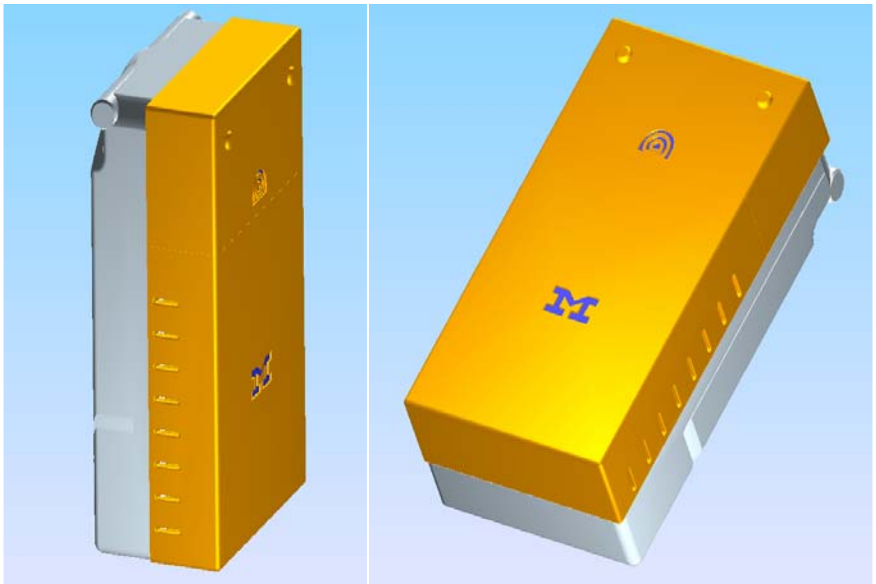


Figure 8.2: Final Design of the Maizr

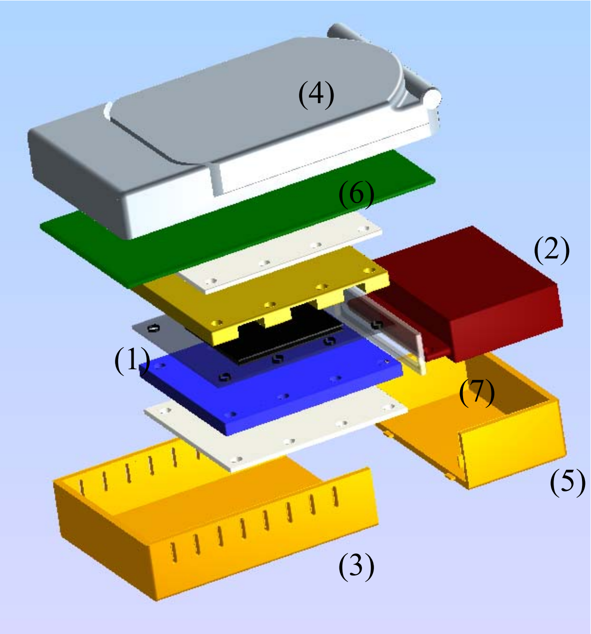


Figure 8.3: Exploded View of Final Design

Figure 8.3 shows the various components spread out relative to how they will fit into the final packaging design. The first part of note is the fuel cell (1), which can be shown in greater detail in Figure 8.4(A). The dimensions for this are based on the size of the Parker TekStak which our team obtained. One important addition to their design is the two white plates on top and bottom of the fuel cell, which are both electrically resistant and thermally insulating. The removal fuel tank cartridge (2) has been simplified from the original model so as to optimize space requirements, as it was further decided that a removable backing (5) would allow enough access for easy replacement. The geometry would also greatly simplify fabrication of this part. However, the nozzle connection between it and the fuel cell has been widened to allow more methanol flow across the MEA. This cartridge's dimensions are shown in Figure 8.4(B). Between this and the fuel cell is a protective material (7) which will ideally be thermally conductive as well as protective of the two components. This material can also help secure the methanol cartridge to the rest of the components.

The packaging case (3) has also been modified from the first blueprint. Cutting the height almost in half, its functions now include protecting the components and trapping the heat within the package to reasonable levels. Small air vents are cut out of the left and right sides to allow air flow into the phone for the fuel cell. These were found to be more efficient at supplying air flow to the fuel cell than ones placed upon the back of the cartridge as in the alpha design. As currently drawn, the walls of the casing are 2 mm thick. All of the components so far discussed fit within this hard shell, with a thick thermally insulating material (6) covering the exposed side between the components and the cell phone. Other case specifications are detailed in 8.4(C). Finally, the cell phone (4) is to be attached to the described assembly, but with some modifications. Originally, the drawings pulled out the Lithium-ion battery from its casing in the phone so as to ensure easy removal. However, in this revised mock-up, the whole back assembly, from the insulating material to the casing, has the capability to be removed so as to access the battery. In addition to this, the cell phone will incorporate the circuitry from our demo boards into its existing motherboard, which we now understand require far less space than originally thought. Both of these elements are shown in Figure 8.4(D). The overall dimensions for the final design are 98x55x31 mm.

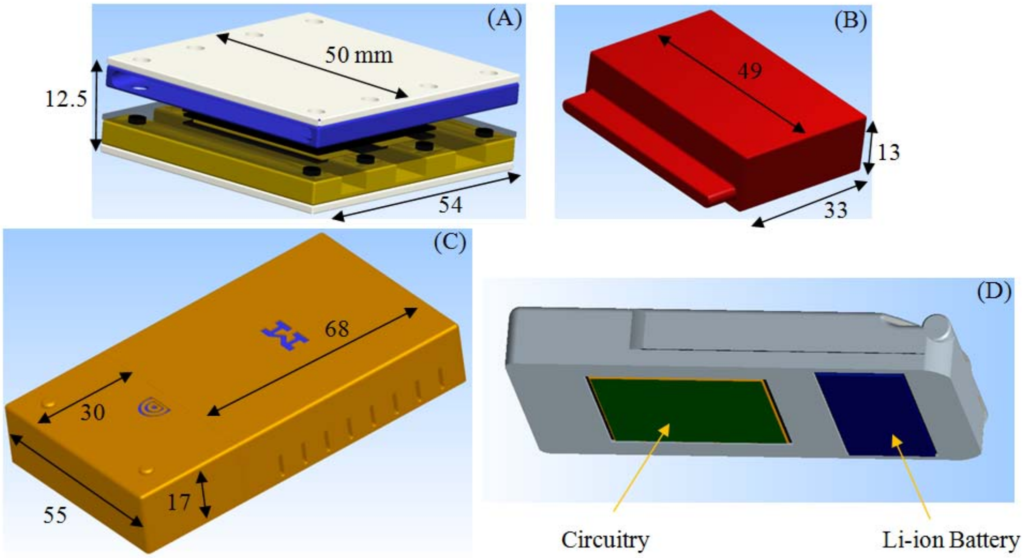


Figure 8.4: Components of the Hybrid Cell Phone; (A) Fuel Cell Assembly (B) Methanol Fuel Tank (C) Outer Packaging Case (D) Cellular Phone with Integrated Parts; All measurements shown are in millimeters

8.4. Packaging: Parameter Analysis

Exterior dimensions for the package prototype were roughly dictated by the size of the internal components, that is, the casing had to be just big enough to contain the fuel cell assembly and the methanol cartridge. We are chiefly concerned with the heat management capabilities of the packaging (described in Section 8.7.). Thus, designing the detail features such as snap fits, ridges, exact wall thicknesses, etc. to optimize the structural packaging was beyond the scope of this project. We did, however want our prototype to be structurally sound so we took steps to ensure it would not fail under duress. As has been described in Section 8.5., we chose to build our heat validation prototype out of polycarbonate due to its high strength and good thermal characteristics. Polycarbonate sheet was widely available in 3/32in thicknesses, which reduced to about 2mm after filing and sanding operations were finished on the prototype. Examining the prototype and other similar products, we decided that 2mm was a safe dimension to choose for a starting point for our final design. It will likely be overly thick when support structures and ridges are added to the design, but thick enough for our current simple design to withstand loading.

8.4.1. Parameter Analysis: Loading Calculations

Two extreme loading scenarios were examined in order to set minimum material properties given our initial wall thickness of 2mm; falling from 1.5m onto the small lower surface of the package, and being stepped or sat on by a user transferring 250lb directly to the product. In the first case, the impact force is transferred directly through the narrow cross section of the package, where in the second case the force is transferred through the larger cross section. More complex bending scenarios or impacts on corners were not considered, again because optimizing the structural design was not our main concern. A full explanation of the loading calculations with figures illustrating the described cross sections is given in Appendix C Section 14.3.1. The calculated minimum material compressive strength required for our design is 3.6MPa.

8.4.2. Parameter Analysis: Material Selection

To select a material for the package we used the Cambridge Engineering Selector (CES) software. This program allowed us to input the mechanical property calculated above, design dimensions, and a number of other qualitative material properties in order to find the materials best suited for our application. We then ranked them using the Ashby method and the material index for a light, cheap column (due to the fact that, in our loading scenarios, the package acts in compression). A detailed explanation of this process is given in Appendix C Section 14.3.1. (the material selection process is also described for the methanol cartridge is also given in this section). The two main options were Polyethylene Terephthalate (PET) plastic and Polyvinylchloride (PVC) plastic. Polycarbonate was another suitable choice that was simply too expensive for mass production. Both PET and PVC have very similar mechanical and thermal properties, but PVC was chosen because it was slightly cheaper and available in compositions with higher strength than PETs.

8.4.3. Parameter Analysis: Manufacturing Process Selection

The same CES software has the capabilities to allow the user to select a suitable process for a certain design and material. We input the following key characteristics into the software: part weight, section thickness, tolerances and batch size. Batch size was estimated given based on the current market for cell phones, especially smart-phones and satellite phones. Because the market is so large, a large production volume is reasonable and CES determined that the best process in such a case is injection molding. This process is detailed in Appendix C Section 14.3.3. The manufacturing process selection for the methanol cartridge is given in this section as well.

8.4.4. Parameter Analysis: FEA Analysis

The simple loading calculations given in Section 8.4.1 were sufficient to model purely axial loading through the case, but complex beam bending equations would be required to more correctly model how the package would react to distributed loads, especially on the large back surface. Thus, an FEA analysis was performed to validate the structural soundness of our design and selected material. The FEA mesh was built in Altair HyperWorks 9.0 and solved with the included Optistruct solver. The part was constructed with 2-D PSHELL elements with a thickness of 2mm and the material properties of PVC plastic. The model was constrained for all translational degrees of freedom along the bottom edges where the package would attach to the back of the cell phone. A distributed load of 250lb was then modeled as a pressure on the outer back surface of the package. Figure 8.5 illustrates what this looks like, where the triangles represent constraints and the arrows represent the pressure. The stress values are given in a color coded contour, where red is high stress and blue is low stress. The maximum stress of 4.4MPa is in the upper surface where the support wall attaches to it. This is well within PVC's yield strength of 41.4MPa (this is an average value for PVC compounds.) The other major stress areas on the upper corners of the package were under 4.0MPa. Figure 8.6 shows a refined mesh around the area of maximum stress.

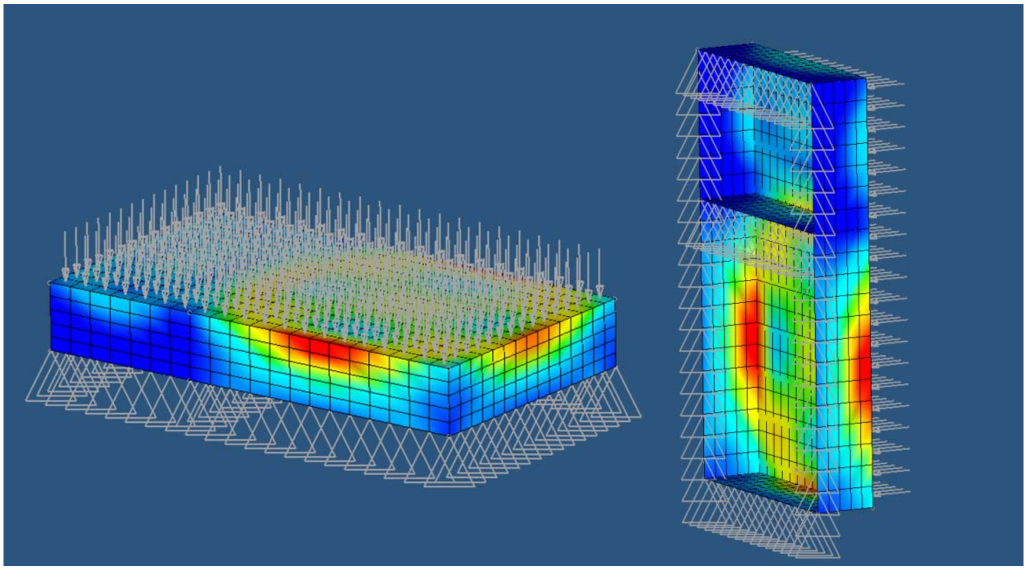


Figure 8.5: A Stress Contour Mesh of the Package Design

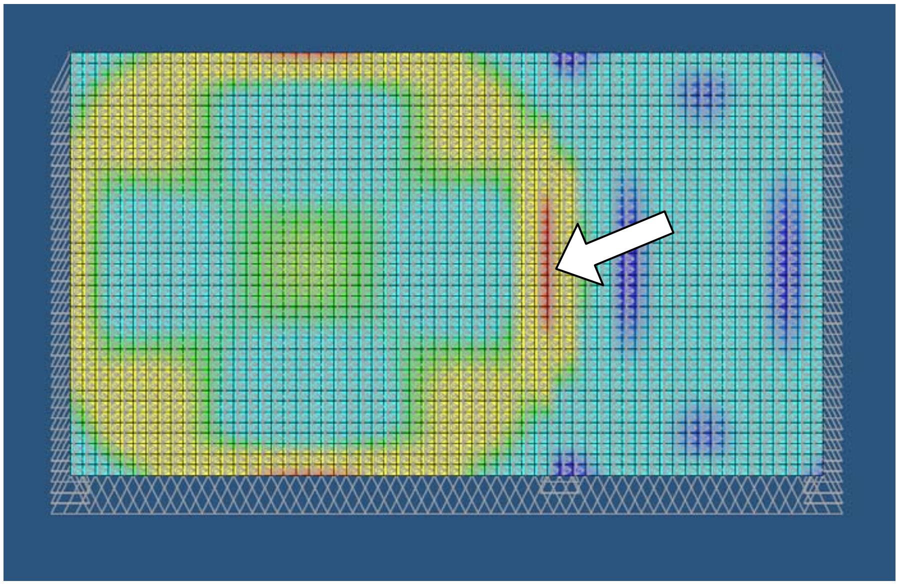
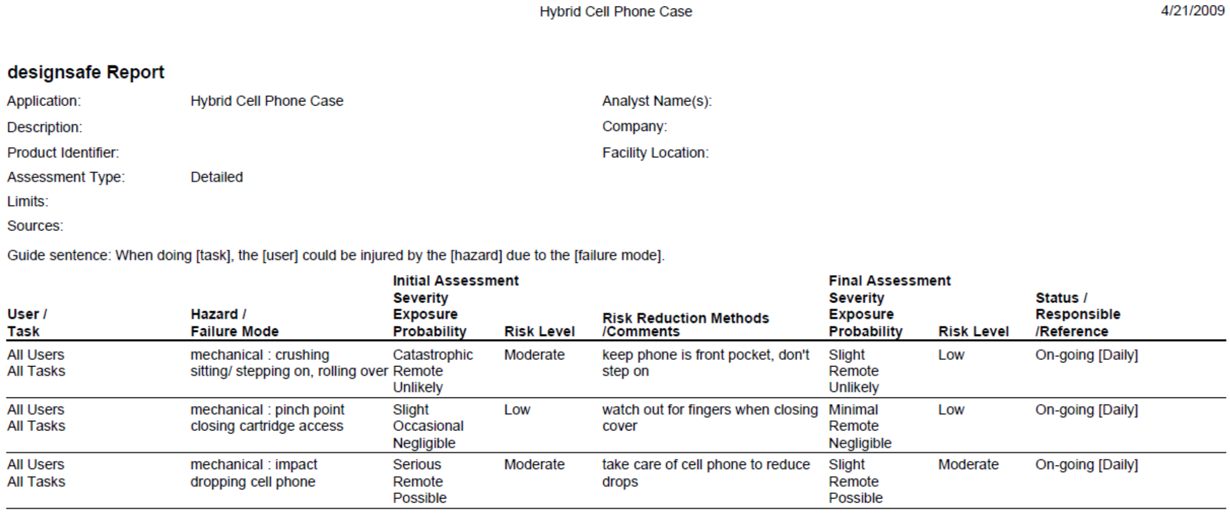


Figure 8.6: A Refined Mesh of the Upper Surface and the Maximum Stress Point

8.4.5. Parameter Analysis: Design for Safety

Our team used DesignSafe to figure out the mechanical risks of our Hybrid Cell Phone Case. Some risk considered were crushing the case, pinching one's finger from the case cover, or impact on the case from dropping. The Figure 8.7 below helps to show the assessment of each failure mode and the severity of each. Comments were included to explain how the failure could take place. Reduction of risk was then assessed with explanation comments. For further discussion on safety issues concern every aspect of our product, refer to Appendix D.



Hybrid Cell Phone Case 4/21/2009

designsafe Report

Application:	Hybrid Cell Phone Case	Analyst Name(s):	
Description:		Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	**Hazard / Failure Mode**	**Initial Assessment Severity Exposure Probability**	**Risk Level**	**Risk Reduction Methods /Comments**	**Final Assessment Severity Exposure Probability**	**Risk Level**	**Status / Responsible /Reference**
All Users All Tasks	mechanical : crushing sitting/ stepping on, rolling over	Catastrophic Remote Unlikely	Moderate	keep phone is front pocket, don't step on	Slight Remote Unlikely	Low	On-going [Daily]
All Users All Tasks	mechanical : pinch point closing cartridge access	Slight Occasional Negligible	Low	watch out for fingers when closing cover	Minimal Remote Negligible	Low	On-going [Daily]
All Users All Tasks	mechanical : impact dropping cell phone	Serious Remote Possible	Moderate	take care of cell phone to reduce drops	Slight Remote Possible	Moderate	On-going [Daily]

Figure 8.7: DesignSafe on Hybrid Cell Phone Packaging Case

8.5. Packaging: Prototype Description

The prototype for our hybrid cell phone case was produced out of polycarbonate for testing purposes. A 3D printed ABS plastic mock-up was produced for display and aesthetics purposes. Both were used to help our team to validate our final design approach.

8.5.1. Prototype Description: Final Design Mock-up

Though the two main deliverables of our project were to come up with a package which can handle the heat output from a DMFC and design circuitry to run the hybrid system, our team would also like to deliver a final prototype design of the entire system. The final design will be based off of our CAD models explained in Section 8.3. The final design prototype will include all components detailed in our final design, from the fuel cell assembly to the fuel cartridge and fuel cell case. To achieve a quick prototype of our final design, our team will rely on the 3D printers provided for students at the University of Michigan. The reason we would like to produce this final prototype, though not working, is to see where the future of this project could go and to give a visual and tactile sense as to size and shape of our system for the University's design expo.

8.5.2. Prototype Description: Heat Validation Prototype

The finished prototype has dimensions of 98 x 55 x 17mm and is separated into two chambers. The first chamber was created to represent the methanol fuel cartridge. This chamber is placed on the one end of the prototype where there are no vent holes. It was filled with 10 mL of water to simulate the expected solution thermal conductivity, which is predicted to be at 0.56 W/m*K for a 6% methanol solution (water has a thermal conductivity of 0.58 W/m*K). It was then sealed to prevent leaking of the liquid. The other chamber has holes in its side to simulate the vents that appear in our final design. An aluminum block of dimensions 50 x 54 x 13mm has a hole in its center and two 16 Ohm resistors placed inside of it, using shrink wrap to cover any exposed electrical leads. In theory, assuming all power supplied to the heater was converted to heat, our fuel cell heat output could be model accurately based on the supplied power to these two resistors. These resistors were then insulated within the aluminum block and the leads attached to a power source. The assembly was placed within our package model, with two small sides for the wiring. Finally, a top plate, 4.8 mm thick, was attached to the open surface of the model with electrical tape, to completely seal the aluminum block inside.

Our prototype design was made out of polycarbonate plastic. Polycarbonates are commonly used for cases of cell phone because these materials have high impact (0.8-6.4 J/cm), tensile (65-73 MPa), shear and flexural (83-97 MPa) strength, as well as having low deformations under loads and excellent creep resistance. Polycarbonates are easy to fabricate which helps to keep cost low for manufacturing of cell phones. For our application, a low coefficient of thermal expansion, high electrical resistance, and low thermal conductivity is desired. Polycarbonate serves these purposes well, with a coefficient of thermal expansion of 70-76 10^{-6}/°C, a thermal conductivity between 0.196-0.201 W/m-°C (comparable to polystyrene at 0.10 W/m-ºC), and excellent electrical insulation properties.[27] These high strength properties will help to protect the internals of the phone from impacts loading such as when the phone is dropped. The low thermal conductivity will protect the user from heat that the fuel cell will produce while keeping the internal temperature high to increase fuel cell performance. Ease of fabrication with these materials helps our team during prototyping and allows for faster testing setup. The prototype will be very simple compared to the ideas we have for a final design, so that modeling of the structure is more accurate for analysis. The drawings below with help to further explain our prototype case (Figure 8.8). A complete list of materials and equipment used for our package prototype can be found in Appendix A.

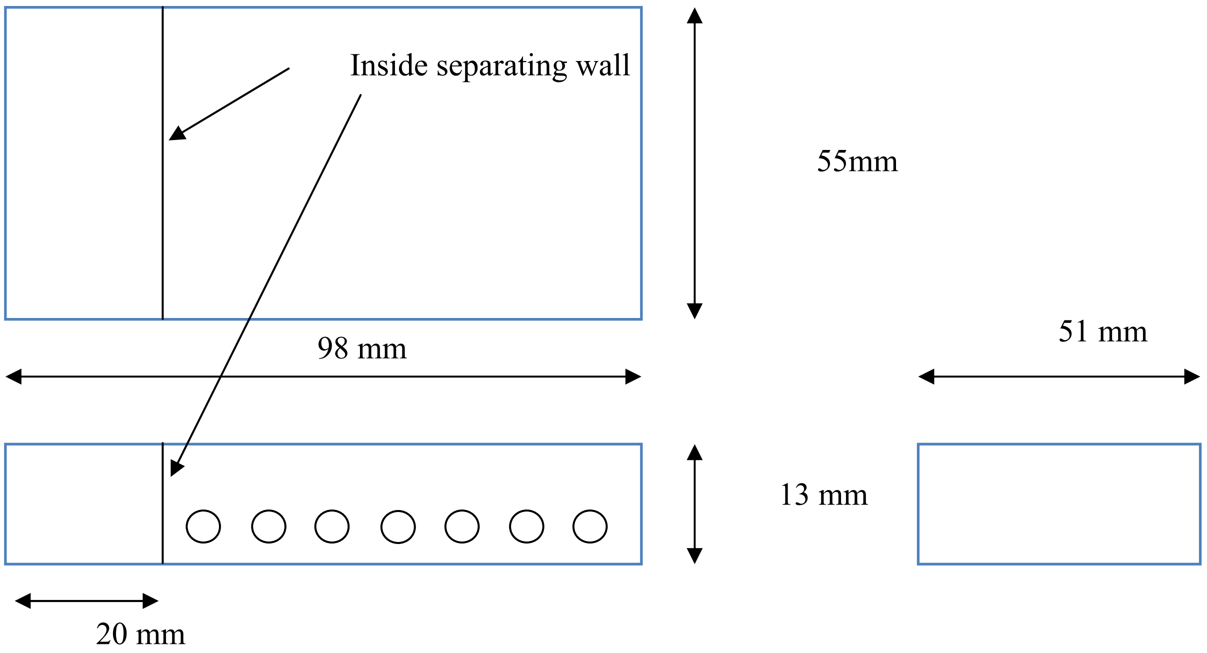


Figure 8.8: Polycarbonate Case Drawings for Prototype

We will need to mock a fake fuel cell so that the heat produced by a fuel cell can be properly tested. Using a resistor and an aluminum block, we will create a box with the same dimensions of our designed fuel cell (54x50x12.5 mm). A resistor should convert all of the supplied power directly into heat, allowing us to control specifically its heat output. Aluminum will be used because it has a high thermal conductivity and it will best characterize a fuel cell heat output in all directions. It will also heat to achieve faster testing results because it will heat up to the temperature of the fuel cell faster with a high thermal conductivity.

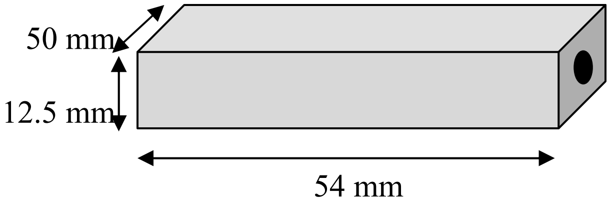


Figure 8.9: Fuel Cell Mock-up Made of Aluminum

8.6. Packaging: Fabrication

Our package fabrication was done both using the mechanical machine shop and the 3D printing resources at the Duderstadt Center. Both tasks of producing the testing prototype and display were done in parallel to save on time during testing and before our design expo. Both the testing prototype and 3D printed prototype turned out to work good and pictures are in the following sections.

8.6.1. Package Fabrication: Final Design Mock-up

In this prototype, some minor modifications were made to our final design CAD model to make it more useable in the real world. This including making the entire system capable of assembly without extra parts. The entire model therefore relied on snap fitting to hold the pieces together, which were added to both the cell phone and the external casing. Also added were four thin pegs extending from the thermal insulation, which were designed to hold the fuel cell system in place securely to the back casing. These modifications and the final prototype can be seen in Figure 8.10 on the next page.

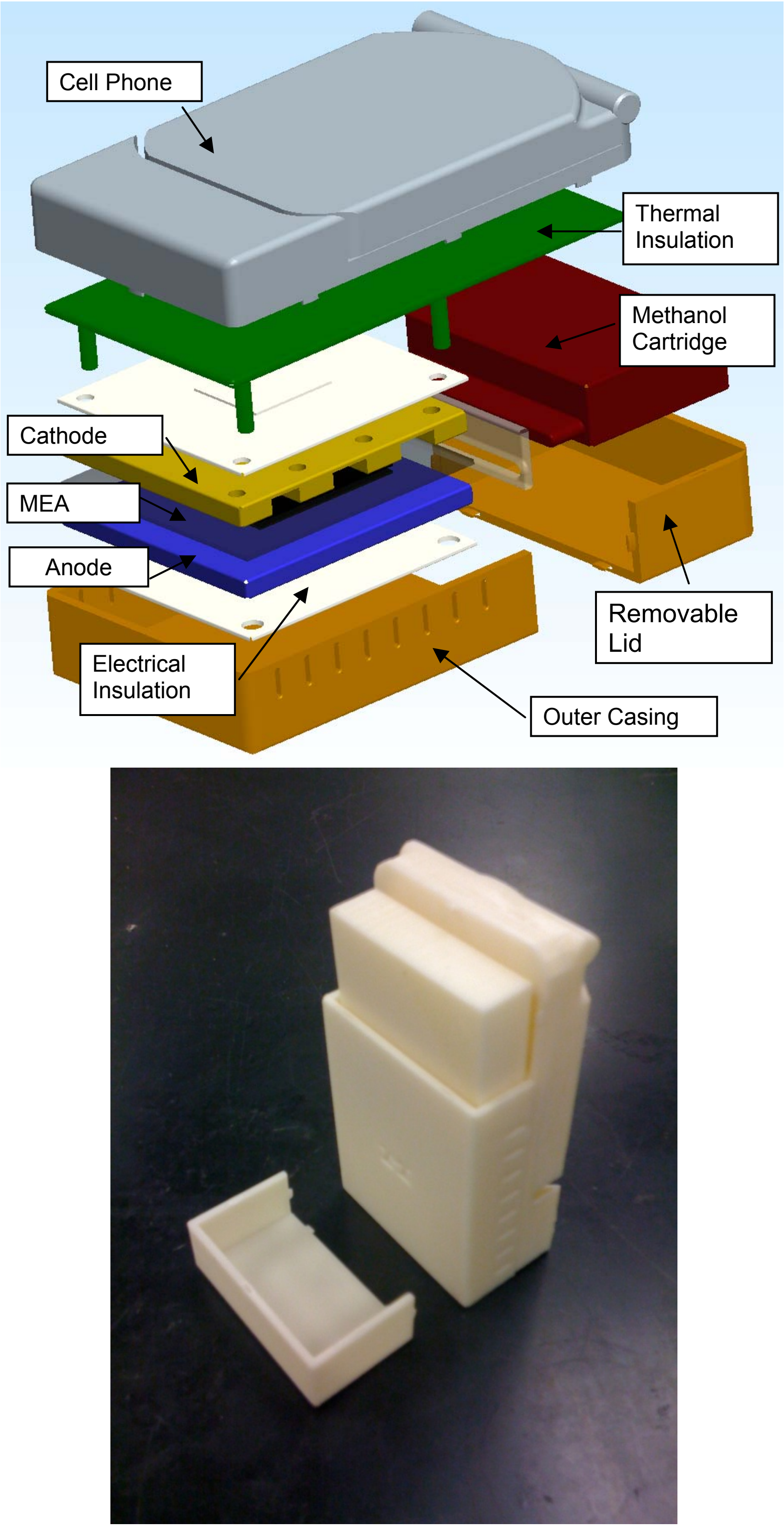


Figure 8.10: CAD Modeling and Rapid Prototype of the Maizr.

8.6.2. Package Fabrication: Heat Validation Prototype

Our heat package testing prototype is constructed out of polycarbonate plastic. Polycarbonate was chosen for this initial testing do to its low thermal conductance of 0.196 W/m*K and high electrical insulating properties ranging between 1E14 and 1E17 Ohm*cm. One 609.6 x 304.8 x 2.38 mm thick sheet of polycarbonate were purchased through McMaster-Carr. A band saw at 3400 RPM was used to cut the 8 pieces into their appropriate dimensions, as can be seen in Figure 8.8. For the two long side pieces, 7 holes approximately 2mm in diameter were drilled near one end, each 7mm apart and 4mm from the bottom edge. The pieces were then sanded down using 120 grit sandpaper to smooth the edges and surfaces. Each piece was than adhered together using two-part epoxy plastic welder.

8.7. Packaging: Validation

Package validation was performed by using our heat testing prototype. Temperatures measured during testing, as well as, touch sensitive testing helped to validate if the package would be able to handle a range of heat outputs.

8.7.1. Package Validation: Testing Methods

Based on our heat analysis done previously, we used power resistor capable of emitting a maximum of 10 Watts of heat. This will allow us to analyze a variable range of heat output potentials, including a factor of safety. By connecting this resistor to a voltage source and then placing it inside the box, we hope to accurately replicate the heat source of the fuel cell. A voltage source capable of outputting 10 Watts is needed to reach these heat output. We will keep the aluminum block from being exposed to the flowing current by placing heat shrink on the exposed wire. The voltage source can be varied, allowing us to use the resistor to mimic the heat produced by the fuel cell. A simple diagram below will help to further explain our test (Figure 8.11).

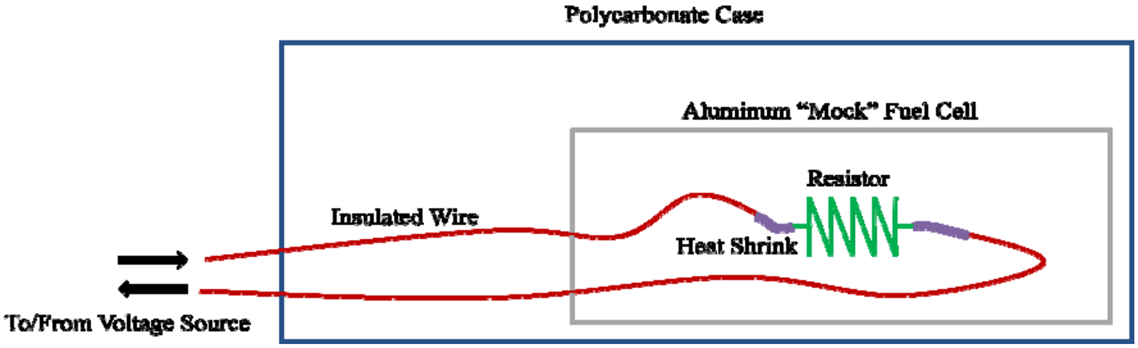


Figure 8.11: Prototyping Fuel Cell Case for Hybrid Cell Phone

While running the test, thermocouples will be used to measure the temperatures at the outside of the case, on the inside components, and the ambient temperature. The outside temperature will monitored to see if the polycarbonate has a low enough thermal conductivity to protect the user. The inside temperature determines if the polycarbonate can keep in enough heat to maximize the potential of the fuel cell. The inner temperature will also help our team test to make sure other components of the system will not be harmed by the fuel cell. If the inner temperatures become too high, insulation may be required to protect the components.

Following the fabrication of our heat package prototype, our team conducted several experiments to validate the heat characteristics of this system. Setup before our testing involved placing one thermal couple inside the casing next to, but not in contact with, the aluminum block, and a second thermal couple taped to the bottom (the side with a 2 mm thick casing) large surface to measure the temperature of the casing. The entire model was placed sitting bottom up on an insulated surface. This testing setup can be seen in Figure 8.12. For the case of insulated testing, a coat made of a cotton blend was wrapped around the package to cover all surfaces (thermal resistance 100 times order of magnitude higher than the casing). Our testing with an ambient temperature of 3°C required the model to be placed within a refrigerator set at this temperature so that a steady environment could be maintained. A small fan was also placed next to the package, creating an estimated air flow rate of 0.7 m/s over the casing. Both of these experiments were designed to simulate extreme environmental conditions. The power source was finally turned on and set to the appropriate power setting.

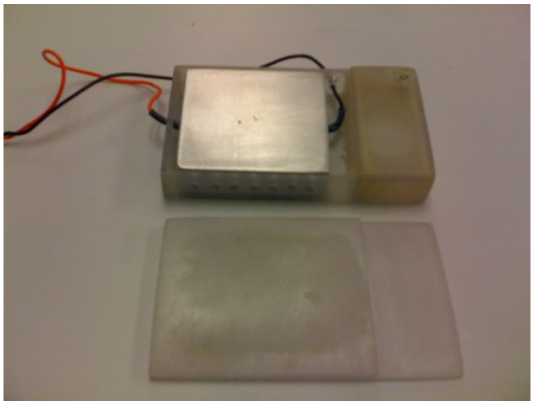


Figure 8.12: Heat Packaging Prototype Setup. Includes covering top, aluminum variable heater block, and sealed water chamber. Not shown: thermocouples (one taped to top and another between the block and water chamber), power source (connected to red and black wires)

We tested four power settings for the heater: 0.5W, 1.0W, 2.0W, and 3.0W. The two extreme conditions were both tested at 1W of power. Initially, the inside, outside, ambient temperatures were recorded before the power source was turned on. Then these measurements were taken in approximately five minute intervals until a steady state temperature was reached for each test. Hand touch tests were used to see in the outside case was too hot to the touch. Even during the 3 W test the case was never too hot to the touch were the user would be burned.

8.7.2. Package Validation: Thermal Modeling and Expected Results

Heat transfer tracking inside the packaging case requires several assumptions to be made as well as specifying key design parameters. First, we note that the fuel cell ideally operates at only the two different power outputs, stand-by and talk mode. These two modes have an associated heat transfer characterization which can change rapidly depending on the user demands. Results will therefore be for the maximum temperature and heat transfer rate values which are associated with talk mode, the mode that should produce the most drastic characteristics.

Between components within the casing, there are two major “chambers” which can be approximated for analysis; the fuel cell and the methanol. For simplicity, the fuel cell can be modeled as a heat source “box” whose surface temperature is a constant temperature for steady state conditions and which produces a variable heat output from 0.5 W to 5 W. For the purposes of this analysis, the points 0.5 W, 1 W, 2 W, and 3 W were considered, which were then later tested in our prototype validation experiments (see Section 8.7.3.).The methanol storage tank will be made of thin, highly conductive walls, meaning the thermal resistance of these parameters can be neglected, as well as any contact resistance. This leaves the thermal conductivity of the methanol solution, which is comparable to the thermal conductivity of water as stated in Section 8.5.2.

These assumptions then give various temperatures at the inside casing of the package design. Once again, contact resistances are neglected as their magnitude is much smaller than that of the material’s. The heat transfer to the phone is neglected as well due the highly insulating material between it and the fuel cell packaging. This then leaves eight surfaces to be evaluated (four for the bottom casing and four for the methanol tank removable casing), which setups up a model of eight resistances in parallel to each other between the fuel cell and the outside casing, as seen in Section 14.18 Appendix R.

Heat transfer from the external packaging to the ambient temperature is primarily accomplished by thermal buoyant flow when in still atmosphere. This flow works in two orientations; when a flat plate is vertical and when it is laying down horizontally. Assuming the cell phone is laying face down such that the bottom casing is facing upwards, this leaves two surfaces which are horizontal and six which are vertical (when standing, these orientations change, but the resultant heat differences are small). Each of these has its own thermal resistance based upon the temperature of the casing, which are then added in series to the thermal resistances found within the package. Finally, as there are several vents along the bottom side around the fuel cell, an additional thermal resistance must be added to include the associated heat losses.

The second mode of heat transfer of this system is caused by an air flow induced within the fuel cell, as it requires oxygen to operate. This flow is difficult to model without a computational fluid dynamics computer program, which can take into account pressure losses caused by sharp corners and flow inlets. However, an estimated flow rate can be made based on the methanol consumption rate, which is directly proportional to the air consumption rate. The result is translated into a steady flow rate passing through the system, which can be modeled as a long plate dissipating heat to laminar flow.

From all of this analysis, a final maximum internal temperature of approximately 30.1ºC is expected for the 1W case, which will result in a case temperature maximum of 30ºC (~86ºF). On top of this, the methanol concentration should reach a pre-heated temperature of 30ºC. All of these calculations are for steady state heat transfer rates, and will generally be smaller than the real world values due to environmental conditions. The final calculations can be found in Appendix S.

8.7.3. Package Validation: Results

The results for our 1 W testing can be seen in Figure 8.12.

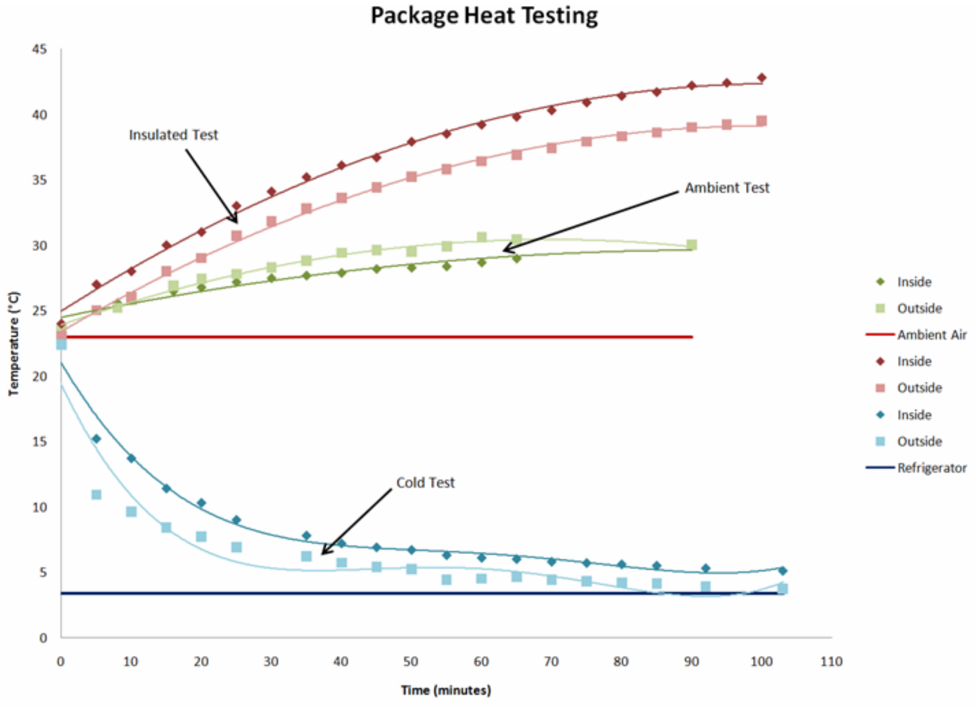


Figure 8.12: Results for Package Heat Testing for 1W Heat Output

The results show that at our expected heat output of 1W, a maximum temperature of 30˚C will be reached for both at the surface and inside the casing. This we believe is reasonable, as compared to our calculated model of 30.1˚C (see Appendix P). For the insulated experiment, a maximum temperature of 43.5˚C for the inside and 40.2˚C for the outside is expected. The results from the other experiments can be found in Appendix Q.

We did notice a discrepancy in the 1 W and 2W experiments from the others. These showed an inside temperature lower than that of the outside casing. We believe this is most likely due to the thermocouple being placed farther away from the aluminum block than for the other experiments, causing a higher resistance (due to the air gap) and a slightly lower temperature inside. In general, we predict that the fuel cell temperature, which is the main source of heat inside the casing, to be hotter than the outside casing. However, these numbers can still be used as approximations of what to expect from a final design.

8.7.4. Package Validation: Discussion

The main objective of our heat package testing was to verify that our proposed design would not harm potential users, that is, cause an external temperature greater than the threshold of pain at

44˚C. At a heat output rating of 3W, our experimentation resulted in an external casing temperature of 47˚C after about 95 minutes, which is outside of the range of acceptable temperatures. However, for the expected output of 1W of heat, our packaging design does fall within acceptable temperature ranges, at about 30˚C. Even if the case were to be insulated while recharging (and thus at maximum power output), a maximum temperature of about 40˚C is predicted, which still falls within design limits, making our prototype a viable option. This configuration provides an estimated factor of safety of 2.7 based on these testing measurements.

We believe these numbers represent close ranges to what the final product will have to undergo should the current parameters remain the same. One aspect which provides this certainty comes from our matching dimensions and material characteristics (less than 5% differences) which will be used for our final design with those of our prototype. Another factor is our strong correlation between our theoretical temperatures and our experimental results. For all except the 3W testing, our predicted temperatures fell within a 98% confidence range from our measured temperatures. While the 3W model is several degrees less than the experimental results, these temperatures fall outside the normal operating ranges of our final design, and most likely require a more accurate model for the air flow and heat transfer.

These results fall within design specifications and therefore most parameters will likely only need to be refined rather than redesigned. As expected, some heat was contained within the casing while still maintaining acceptable temperatures for a user to handle. Our testing also sets a benchmark for future test procedures involving different materials, thicknesses of packaging, and overall dimensions.

In addition to this proof of concept, our design intent was to increase the fuel cell power output by increasing the temperature inside the package. If the phone was allowed to reach steady state conditions for 1W heat output, this would result in an expected amplified power output at 50.6mW, an increase of about 12%. Furthermore, if the phone were insulated while recharging (say, by placing it inside a pocket or purse), the maximum power output would further increase to 52.6mW, a 17% improvement from ambient conditions. With the average cell phone talk time at approximately 15 minutes while driving (where the cell phone is most frequently used) [32], four hours of recharging time would be needed for the battery to return to full state of charge under these conditions, a full hour less than at room temperature.

However, some improvement could be made in finding an ideal temperature operating range which would give the fuel cell a higher power output. One possible way of controlling the heat conduction paths is to reduce the contact area between the fuel cell and the inside casing. Based on our heat modeling, decreasing this area to 5% of what it currently is should result in an increase in the maximum possible temperature by 5˚C. In addition to this, thicker packaging could be utilized to contain heat better over shorter time intervals, as well as increase protection for the fuel cell and other components. This must of course be weighed against the added size, weight, and cost of the product this would require.

Finally, if this package were subjected to extreme cold environmental conditions over a prolonged period, our testing suggests that the fuel cell power output would also decrease appreciably. An estimated power output of 42.9mW is predicted for the fuel cell if the package was allowed to reach steady state at a temperature of 5.1°C. This is a 5% loss in maximum normal power capabilities. Such a problem could potentially reduce the maximum power capability so as to make the phone inoperable. Therefore, solutions include ideas similar to the above proposed designs used to contain the heat and increase thermal resistance. Others could include an internal temperature sensor and heating plate to prevent these conditions from happening. Further testing will need to be conducted to better understand and address this issue. However, the current model should still be applicable, as it can use the onboard battery to operate the phone without the improved characteristics.

Finally, the model designed here assumes an ideal insulating material separating the phone from the fuel cell, which in reality will not exist (though its resistance will be larger than the surrounding material). Measurements of the heat interaction of these two components will need to be included in a more refined test bed. Potentially, the phone could generate up to 1W of heat output during peak operation, which could result in a system closer to our 2W test findings. While this still should meet design requirements, more accurate modeling of this setup will have to be conducted to verify these predictions.

9. Final Design Discussion

9.1. Discussion: Design Critique

There are several design drawbacks to our final design which would have to be addressed in future models. The two major sections of this report (heat and power) provide an in depth analysis on to the specific advantages and areas of improvement (Sections 6.2.4. and 6.3.4.) for each subtask. However, there are in existence other design problems which do not fit into other sections, which must be tackled for a viable final design and are discussed here.

The most limiting factor for this design is that a final complete prototype was never able to be completed as was originally intended. Size factors, restrictions on our resources, limited in-depth knowledge on the relevant fields investigated, and time constraints all contributed to us not being able to integrate the power, heat, and packaging aspects into one complete product. While disappointing, we do realize that the scope of the project had to change as relevant information was presented. However, this does not mean that this goal is not possible, as our various testing procedures demonstrated. Rather, we hope that with the help of this document, future generations will reach this accomplishment.

One of these involves handling the small (though non-negligible, as originally believed) amount of water produced by the fuel cell. While originally it was our intent to handle this effectively, time constraints and other design critical issues left this part of the project incomplete. While the water would act differently in our planned fuel cell geometry, it would still most likely produce a small concentration of hydrogen on the cathode side as experienced in our lab testing.

A serious potential flaw which our team was unable to adequately solve is in providing enough air supply to the fuel cell during use. While more ventilation throughout the cell phone, such as at the bottom of the phone or across its back, may help to alleviate this problem, additional problems can arise due to these factors. An example of this would include the resultant air flow and fuel cell requirements needed to introduce a cross hatch pattern for the cathode side, optimization problems which are beyond the scope of this project. Also, this choose would cause more heat to be exhausted into the environment instead of being trapped into the package. Lastly, normal use of a cell phone may vary drastically from person to person, making actual usage sporadic and difficult to prevent at least some blockage of air flow. Nevertheless, improvements like this could be proposed and then evaluated, as well as other design possibilities, such as comfort grooves along the side casing which guide the user's hand to not block air vents.

Another potential problem this final model faces is the connection between the fuel cell and the methanol cartridge. From our alpha design, we intended to have a push cartridge capability to ensure smooth connections. However, as building and testing this exceeded our resources and increased size demands, the idea was abandoned for a more practical shape. A connector was instead inserted into between the fuel cell and cartridge, but this was never fully formed as to where and how it would properly function.

Coupled along with this obstacle is the restriction that this design will only ideally work in two orientations due to its gravity feed system. While this saves on space, power requirements, and overall structure stability, it still is not practical as a consumer end product. Future work will have to investigate further as to how a delivery subsystem will work to move the methanol from the cartridge to the fuel cell. Some potential ideas include those discussed in our research sections, such as micro-pumping (Section 8.1.3.).

Finally, our end prototype relied on no additional parts to attach to each other. This is something we feel should be kept in the future designs, as it reduces assembly time, costs, and makes the structure less likely to fail or lose pieces. However, the design as it currently stands could benefit from further refinement of the various snap fittings and connection rods. This would include controlling where and how they fit into each other, so as to optimize ease of use, and also to improve durability by making them thicker and stronger. In addition to this, overall optimization of structural integrity and smoothness of design would help increase consumer appeal, the safety of all components, and component durability. Examples of this would include installing ridges and using varying thicknesses of material.

9.2. Discussion: Environmental Sustainability

Consumer electronics is not exactly a market that is known for its environmental sustainability. Toxic materials are common in electronic components and computers and gadgets are often discarded in landfills. However, fuel cells are often billed as "green" technology because they create electricity without burning fossil fuels and with low- or no-emissions. In the following sections, we will examine whether the hybrid product we have developed makes a positive or negative impact on the environment relative to current technology.

9.2.1. Sustainability: Energy Consumption During Use

It must first be understood how much power is consumed by the phone when in use so that a comparison may be made between emissions created by using methanol as a fuel versus using electricity from the grid. Recent data shows that the average American talks for 819 minutes every month [33] and sends about 200 text messages (averaging 30 seconds of typing time) each month [34] for a total "talk time" use of 15.3 hours per month or 183.8 hours per year. With a cell phone that draws 1W or 275mA for talk mode, that translates into 183.8Wh of power per year. Assuming a user never turns off his cell phone, the rest of the time every year is considered standby time. At a power draw of 8.4mW or 5mA, this adds another 73.6Wh to the power consumed in one year by the cell phone, which totals 257.4Wh. The cell phone, thus, consumes about 29.4mW on average throughout the year.

9.2.2. Sustainability: Emissions from Energy Consumption

To understand what this means in terms of methanol consumption, we must consider how methanol is converted into electrical energy, because its effective energy density is not the same as its Higher Heating Value when used as a fuel in a fuel cell. The process is described in Section 4.2., and essentially each molecule of methanol carries six electrons that can be harnessed for electrical power. We then use the conversion below to find the theoretical methanol consumption rate, given that 1 amp is equal to one coulomb per second.

Eq. 9.1

$$\frac{6.24x10^{18} electrons}{1\,coulomb} * \frac{1\,molecule\ methanol}{6\,electrons} * \frac{1\,mol\ methanol}{6.02x10^{23} molecules} * \frac{32g}{1\,mol\ methanol} * \frac{0.029C}{sec} = 1.6x10^{-6}\frac{g}{sec}$$

This is equivalent to 50.6g methanol per year. One mole of methanol can produce one mole of CO_2, so this mass of methanol can produce 69.6g of CO_2 when used in a DMFC. Normalized to pounds of CO_2 per megawatt, this ends up being 595lb/MWh.

In the state of Michigan, electricity is generated from a number of sources, primarily coal, but also nuclear, natural gas, and some other renewable [35]. The average CO_2 emissions for electricity generated is 1,418lb/MWh. This means that our design could reduce carbon emissions associated with cell phone use by 58%. Sulfur and nitrogen oxides are also completely eliminated with the fuel cell. While this sounds exciting, it is important to note that this is with an ideally efficient DMFC. Right now, DMFC technology is around 25% efficient, where much of the methanol diffuses through the membrane and reacts with air on the other side. This entirely offsets the potential gains; however, as fuel cell technology continues to progress, new membrane compositions may be discovered that allow for greater efficiency, in which case this technology may begin to have a positive impact.

9.2.3. Sustainability: Product Waste

The average lifetime for a cellular phone in the United States is 18 months, and every year, Americans discard nearly 125 million cell phones [36], most of which end up in landfills along with their batteries. Designing an actual cell phone was not a part of this project, but we took steps in order to minimize the impact of the fuel cell and packaging on the environment.

Foremost, we hope that the product's increased utility thanks to the hybrid system will encourage users to keep it longer. Further, the fuel cell and packaging will likely outlive the phone components themselves, and the packaging should be designed to interface with each new model of cell phone produced.

Section 14.3.3. discusses the environmental impact of the packaging material, which is admittedly high because it is a plastic, and the use of interchangeable cartridges could potentially be a large consumer waste problem (as discussed in Section 14.3.8., there could be millions of units produced every year.) However, the PVC chosen for the package and the nylon chosen for the cartridge are recyclable, and we think steps can be taken to minimize assembly complexity to facilitate recycling. Companies exist, such as local Ann Arbor-area Recellular, which specialize in recycling and reuse of cell phone components and it could benefit Harris Corporation to make such an effort in a number of ways. Many components associated with the cell phone and the fuel cell will not fail in the short lifetime of the product and could be harvested for use in remanufactured products or other products in Harris' line. Most plastics, metals, rubbers, etc can be very easily recycled and there is a surprising amount of precious metals in cell phones as well. It is estimated that each cell phone contains about $1.59 in rare metals, and current recycling programs recover about $630,000 in such metals every year in the United States [37].

Another consideration with using a fuel cartridge is that once the cartridge is effectively depleted of methanol, it will still contain water and traces of the fuel. This contaminated water could potential total 350mL per user, per year. This very dilute liquid must still be treated properly, which consists of processing the solution in a treatment center which meets specifications as laid out in the Resource Conservation and Recovery Act [38].

10. Recommendations

As stated in Section 9.1., concerning our design critique, there are several ways in which we feel this project could be greatly improved with further work and research. This section provides a summary of the high level technical and practical aspects which are discussed in greater detail in their relevant sections.

For characterizing the power and heat output of the fuel cell (Sections 6.2.4 and 6.2.3), more tests can be conducted to gain a refined analysis of how the stack reacts to different parameter changes, such as different methanol and air flow rates. A more refined method of testing the heat output could also be undertaken, one which uses an effective thermally insulating cooler and has a higher resolution of precision and control. Finally, as our final design used a passive fuel cell with no air pumps to supply oxygen, testing an air-breathing cell would give a clearer understanding of the performance under final operating conditions.

For the hybrid circuitry (Section 7.5.2), it is recommended that further testing with a fuel cell outputting higher power levels be preformed to verify that this configuration will work under non-ideal conditions, such as when cycling between standby and talk mode. Also, as the circuitry performed several operations which were not desired in our final design, such as drawing current from the battery in when standby mode was simulated, further refinement of the demo boards could be made to make them match our design specifications. Finally, testing on these refinements could be done to verify theoretical values of how long the battery would take to recharge the battery.

For the heat packaging design (Section 8.7.4), a variety of improvements could be made to both increase the thermal insulation for the fuel cell and to ensure that the user is not harmed by an excess in temperatures. As the prototype was not constructed out of the material chosen for the final design, retesting which replaces this parameter with the desired characteristics could be completed to check results and verify improvements/drawbacks. Also, further testing could be done to see the effective of reducing contact paths from the fuel cell to the casing, which was never fully explored. Moreover, as our final prototype was merely a test bed which did not actually use a fuel cell as a heat source, testing could be done to ensure that our modeling was consistent with actual real world scenarios.

Lastly, from our design critique (Section 9.1), it was noted that while we did not attain our final design objective of combining the three different aspects of our project into a final product, significant advancements were made and groundwork was laid for further generations. It also discussed several flaws unaccounted for in our final design not associated with the three general areas of this report. This includes aspects such as air flow rates and blocked air paths for the fuel cell, methanol cartridge proper packaging, and potential solutions in controlling the resultant water produced by the fuel cell. Refinement of these ideas coupled with testing would be required so as to demonstrate these problems have been dealt with effectively.

11. Conclusions

The creation of a hybrid fuel cell system to power a cellular phone can greatly extend the operational life of the product and alleviate the need for constantly recharging the battery. A small Direct Methanol Fuel Cell can provide constant power delivery over a long period of time, while the battery will be able to supply large amounts of power when the cell phone is operating in a mode that requires high electrical current. Harris Corporation is interested in pursuing such a technology and has requested the help of a small group of University of Michigan students in order to advance the project. The task set before us was to design a fuel cell system using off-the-shelf components and to package it with a cell phone, while considering safety issues related to managing the heat generated by the fuel cell and the on-board storage of methanol. We have completed an exhaustive literature review on the relevant topics, including fuel cell and battery technologies, heat management techniques, and structural packaging. From this, we were able to compile a complete list of customer requirements, and begin to determine the engineering specifications that a prototype must meet. Once specifications are determined, we purchased the necessary components needed to validate our various design aspects. Testing then provided feedback as to the effectiveness of this design and allowed us to show such a device is feasible in each subsystem. This included testing the fuel cell power output characteristics, the heat output responses, the hybrid circuitry efficiency, and the heat packaging validation. Ultimately, we would have liked to incorporate the hybrid system into a final product which extended the operation life of the cell phone while maintaining a compact, safe, reliable and attractive device. Though this ultimate goal was not achieved, these final designs and prototypes presented within this report set a cornerstone for future generations' work. Sizing the fuel cell and battery will require that future teams strike a balance between maximum power delivery and size, weight and cost. Care must also be taken to ensure that external temperatures are comfortable for the user and internal temperatures do not damage components. The prototype should further be required to pass tough military standard methods for testing electronic equipment to ensure the product's reliability and safety under abuse. The test beds generated by this design project allow for these standards to be evaluated for any final product. While this does not mean we have addressed effectively all issues and potential stumbling blocks within this venture, the processes stated here are a rigorous first attempt toward a final concept. With any luck, after several more iterations of testing and analysis, a final product will be manufactured and put on store shelves across the country. As with any idea, the process from day dreaming to completion is a challenging road, but it is our hope that this report's findings demonstrate this road is a worth taking.

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14. Appendices

14.1. Appendix A: Bill of Materials and Equipment Used

All these materials and equipment were used to formulate experiments and testing with the exception of the 3D printer which helped us have a non-functioning prototype for the design expo.

Table A.1: Bill of Materials

Parts	Quantity	Supplier	Price
Polycarbonate plastic 12x12in sheet 3/32" thick	1	McMaster-Carr	$6.66
Polycarbonate glue	1	Carpenter Bros. Hardware	$5.29
Aluminum block	1	UM Machine Shop	Scrap, free
TPS61201EVM-179	1	Texas Instruments	$49.00
bq240301EVM	1	Texas Instruments	$49.00
NiMH Battery w/Charger	1	Batteries Plus	$14.99
Ultralast Li-Ion Battery	1	Batteries Plus	$9.89
AA Battery Cradle	1	Radio Shack	$0.99
Perf. Circuit Board	1	Radio Shack	$4.49
20ga Solid Core Wire	3 rolls	Radio Shack	$7.99
Heat Shrink	1 pkg	Radio Shack	$3.99
Var. Potentiometers and Resistors	3	UM X50 Lab	<$10.00
Parker TekStak DMFC	1	TesSol	$199.00
Air Pump	1	Fuel Cell Store	$149.95
Fuel Pump	1	Fuel Cell Store	$155.00
99% Methanol	1 Quart	McMaster-Carr	$13.42
Deionized Water	1500mL	UM Lab EWRE17	Free
Cooler	1	Kroger	$3.99

Table A.2: Equipment List

Equipment	Quantity	Provided by
DC Voltage Source	2	UM X50 Lab/ UM 2190 GG Brown Lab
Heating Plate/ Mixer	2	UM 2190 GG Brown Lab
Multimeter	3	UM X50 Lab
Thermocouple	2	UM Auto Lab-Tom Bress
Thermometer	1	UM Auto Lab-Tom Bress
Graduated Cylinder	2	UM 2190 GG Brown Lab
Flask	6	UM 2190 GG Brown Lab
Bread Board	3	UM X50 Lab

Drill Press	1	UM ME Machine Shop
Band Saw	1	UM ME Machine Shop
Sand Paper	4 sheets	UM ME Machine Shop
3D Printer	1	Duderstadt Center
Soldering Iron and Stand	1	UM 2190 GG Brown Lab

14.2. Appendix B: Description of Engineering Changes from DR#3

There were few design changes after Design Review #3. Our design itself was fairly set; our goal after DR3 was to conduct our validation experiments in order to determine how future designs may be changed. At that point, we had a clear testing plan, detailed on a daily basis, and we focused on executing our plan. We felt this time was better spent performing the validation and considering the results rather than trying to squeeze changes into our design at the last moment. Instead, we have clearly laid out in this paper how we modified our testing methods along the way, how we could better conduct our tests, and what steps could be taken to improve the design in the future. See the discussion sections under Section 6: Fuel Cell Testing and Verification, Section 7: Hybrid Circuitry Design, Section 8: Packaging Design, as well as thorough commentary provided in the Section 9: Final Design Discussion.

14.3. Appendix C: Design Analysis

14.3.1. Material Selection for Cell Phone Casing

The cell phone package is designed to protect the internal components of the phone including sensitive circuitry and, in the case of our design, a fuel cell and a potentially hazardous container of methanol. The package must be able to withstand typical forces that such a product may encounter. In order to determine a suitable material for the design, we used the Cambridge Engineering Selector (CES) computer program, which contains a database of engineering materials and methods for narrowing down a list of materials based on quantitative and qualitative property limits and cost.

There are a number of qualitative properties that help narrow the field of materials by selecting boxes that range from “very poor” to “average” to “very good” for the property. As has been described, a material is desired that has a low thermal conductivity in order to retain some of the generated heat inside the package. To avoid any possibility for electrical shorts from the fuel cell or circuitry to the package, an electrical insulator is preferable as well. The case could potentially come into contact with the slightly acidic methanol fuel, and thus should remain durable when in contact with water and weak acids. Typical cell phone use may take place outdoors, so the material should be very resistant to damage from UV rays as well. The group of materials that passes these qualitative requirements is mostly plastics, with a few elastomers.

Mechanical property limits were calculated for using two common loading scenarios. First, as described in the specifications, the phone must be able to survive a drop from 1.5m onto the phone’s smallest face. The resulting 1000N force from the drop must be transmitted through a cross section of $280mm^2$, as shown in Fig C.1(a). This requires the material to have a compressive strength of at least 3.6MPa.The other loading scenario is if the phone were to be crushed under the weight of the user; such as if it were directly sat or stepped on. As an extreme case, we calculated the required strength if a 250lb user applied all of his weight to the phone. The resulting 1113N load is distributed across the broad section of the cell phone and transmitted through a $698mm^2$ cross section as shown in Fig C.l(b). This requires a compressive strength of 1.6MPa, but because this is a smaller value than for the drop test, the property limit will be set at 3.6MPa. A more thorough physical analysis using FEA is described in Section 8.4.4. Additionally, because the operating temperatures may become elevated inside the cell phone, the material has to be able to withstand 60^oC.

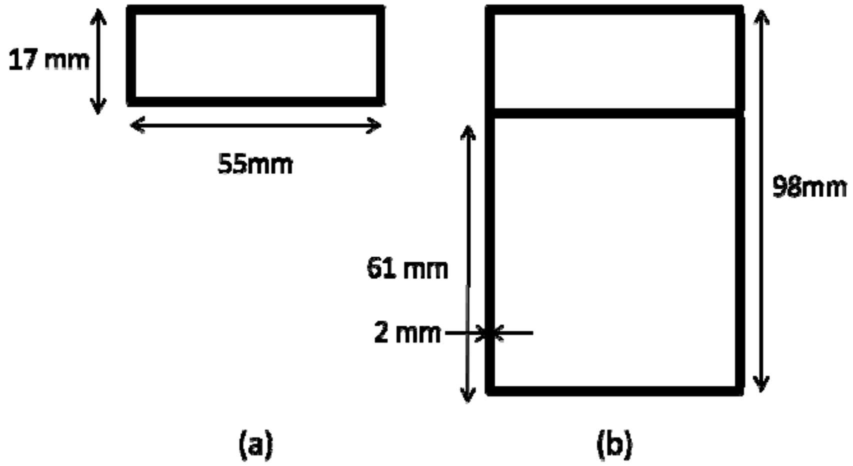


Figure A.1: Package cross sectional areas which experience compressive loading

There are five remaining materials that meet all of the qualitative and quantitative properties required for our design. They are; Polyetheretherketone (PEEK), Cellulose polymers, Polycarbonate, Polyethylene tetraphthalate (PET), and Polyvinylchloride (PVC). Our package is comparable to a column in that it will sustain primarily compressive loading (as described above) and the package will be widely mass produced on for what will be a relatively inexpensive product. Thus, the proper material index for ranking the candidates is the index for a cheap column with a prescribed strength, given in Equation C.1 below

$$M = \frac{E^{1/2}}{C_m \rho} \quad \text{(Eq C.1)}$$

where E is Young's modulus, C_m is material cost per unit weight, and ρ is the material density. In order to produce the strongest and cheapest product, we need to maximize this index. Because the five materials have similar density, the best way to compare these materials in terms of modulus and cost is with a graph, which is given in Figure A.2 below.

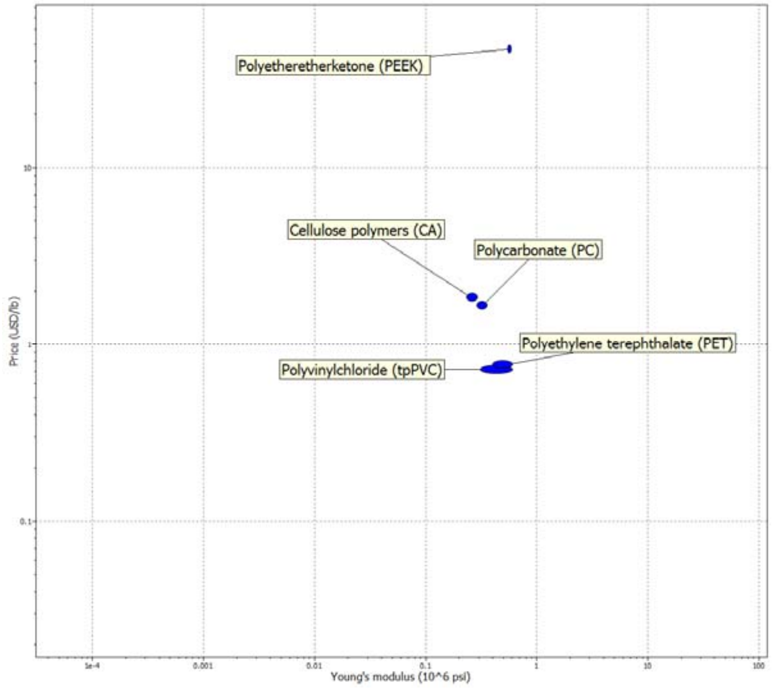


Figure C.2: Cost vs Young's Modulus for Package Material Candidates

Examination of the figure allows us to quickly eliminate the prohibitively expensive PEEK material, and leaves no reason to further consider cellulose polymers or polycarbonate. An interesting note is that we built our heat testing package prototype (as described in Section 8.5.2.) with polycarbonate because of its strength, thermal insulating capabilities and availability in sheet stock. However, both PVC and PET plastics have similar properties and are considerably cheaper than polycarbonate. As the figure shows, the two plastics can have identical Young's Modulus', while PET is very slightly more expensive. Further examination of the materials shows that PET has marginally lower thermal conductivity, but has a significantly lower compressive strength when compared to some types of PVC. Additionally, PET, which is used in drinking bottles, is very easily recyclable while PVC is slightly more difficult; Section 14.3.2. has a more in-depth look at the ecological aspects. Considering all properties, we have selected PVC for our final design. Its lower cost and higher strength were the largest determining factors. The higher thermal conductivity is almost negligible and the difference can be accounted for in our design by adjusting conduction paths.

Table C.1: Material Properties for Package Candidates

	PET	**PVC**
Young's Modulus (Mpsi)	0.40-0.60	0.31-0.60
Compressive Strength (ksi)	9.01-9.94	6.16-13.0
Thermal Conductivity (BTU-ft/h-ft^2-F)	0.080-0.0872	0.085-0.169
Price (USD/lb)	0.74-0.81	0.69-0.76
Recycling Number	1	3

14.3.2. Material Selection for Methanol Cartridge

The process of selecting the material for the methanol cartridge was a little less straight forward than for the package casing because methanol can degrade many materials, including aluminum, copper, magnesium, platinum, zincs, and most plastics.[39] In long-term situations, methanol is typically stored and transported in steel containers. Many resins, nylons, rubbers, Teflon, ethylene propylene rubber, and Neoprene can be used to store methanol as well.

In addition to simply containing the methanol, the cartridge must be able to withstand crushing and impact forces. While the cartridge is inside the exterior packaging and therefore protected from much of the extreme loading, it will still be subjected to shock if dropped and must be strong enough to resist crushing if the exterior case fails. For these reasons the cartridge is must be held to the same mechanical property limits as the exterior packaging.

The cartridge is something that will be mass produced in much higher quantities than the actual cell phone package, because it is an item that is consumed in use (i.e. its contents is depleted.) It thus needs to be cheap to manufacture and easy to recycle in one of two ways; either returned to the manufacturer for refilling or melted down and reformed. Because methanol will eventually break down materials, the refilling option may lead to recirculation of unsafe cartridges, thus we would like to choose a material that can be melted down after each use to avoid material breakdown from prolonged exposure to methanol.

We examined a number of materials which were compatible with methanol exposure, and the relevant properties are given in Table C.2 below.

Table C.2: Material Properties for Methanol Cartridge

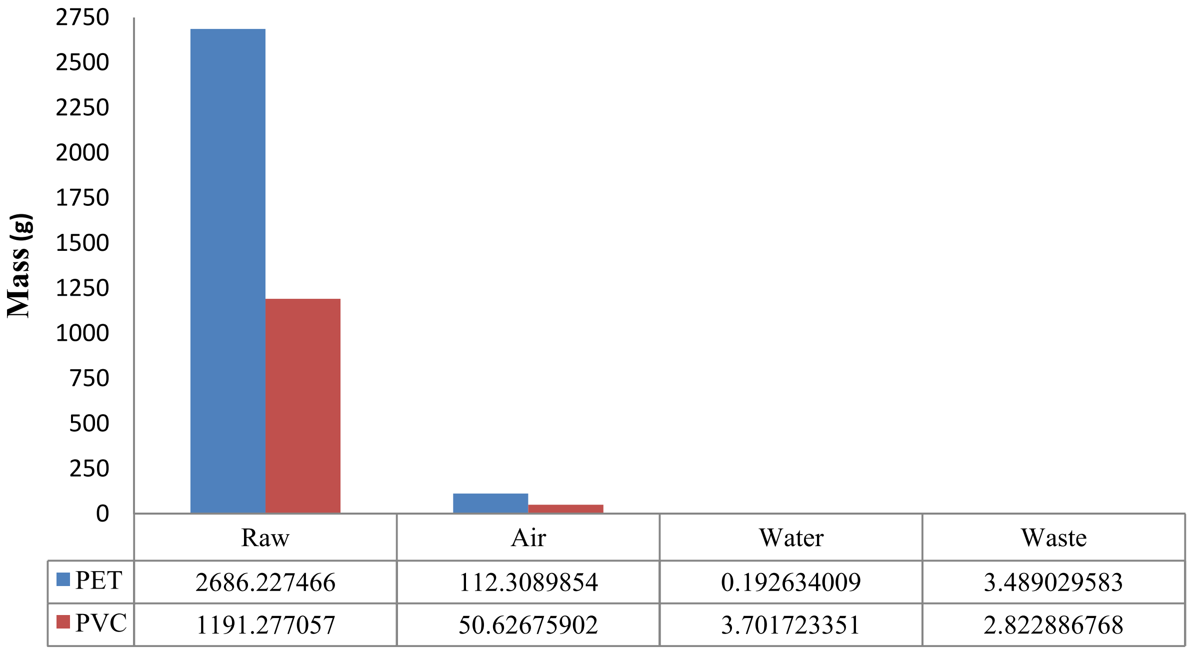
	Mild Steel	Nylon	Teflon	Butyl Rubber	Neoprene
Young's Modulus (Mpsi)	29.0-32.1	0.38-0.46	0.058-0.080	~2x10^{-4}	~2x10^{-4}
Compressive Strength (ksi)	36.3-57.3	7.98-15.1	2.39-3.99	0.319-0.479	0.54-4.18
Thermal Conductivity (BTU-ft/h-ft^2-F)	28.3-31.2	0.14-0.15	0.14-0.15	0.046-0.058	0.058-0.069
Price (USD/lb)	0.36-0.40	1.61-1.77	6.70-7.64	1.78-1.96	2.42-2.66
Recycling	Recyclable	#7	#7	Not Recyclable	Not Recyclable

As you can see, only steel, nylon, and Teflon are strong enough to meet the requirements of the cartridge design on their own. Butyl rubber and Neoprene could act as liners or coatings for the interior of the cartridge, which could then be made out of a common plastic. Teflon has enough strength to be used in our design, but its cost is prohibitively expensive. Because it is also used as a coating, however, it could be used in small amounts to line the interior of the cartridge in the same way as rubber or Neoprene. We decided against using any type of coating or liner for three reasons; first, a coating would add complexity to the manufacturing process and thus increase costs. Second, if the coating did not perfectly cover every part of the cartridge that could come into contact with the methanol, there would be weak areas where degradation could begin and then spread. Finally, a coating could add difficulty to recycling because the material would have to be separated from the primary cartridge material, and in the case of Neoprene and butyl rubber the coating would not be recyclable.

The remaining options, then, are mild steel and nylon. Steel is cheap, strong, and easily recycled, however it would be very expensive to manufacture a geometry that has an interior volume and must have an interlocking valve interface, as has been described in Section 8.3. This type of geometry would be much easier to injection mold with a substance like Nylon. Nylon is much more expensive than steel but still on the cheaper end of high performance polymers. It can also be recycled, though with a recycling number of 7 it is likely to require a less common and more expensive recycling process than a plastic with a lower number. Nylon will be a good fit for our design.

14.3.3. Material Selection Assignment (Environmental Performance)

Polyethylene terephthalate (PET) plastic has more emissions than polyvinyl chloride (PVC). This is made clear in Figure C.3 shown below. The actual mass in grams is shown at the bottom of the bar graph. This graph was produced by combining the emission calculation of the two plastics using SimaPro 7 and Microsoft Excel. SimaPro needed the mass of both plastics needed to produce our hybrid cell phone case. The mass for PET and PVC were 0.0377 and 0.0404 kg, respectively. From this emission, PVC would be a more eco-friendly material to choose for our case.



	Raw	Air	Water	Waste
🟦 PET	2686.227466	112.3089854	0.192634009	3.489029583
🟥 PVC	1191.277057	50.62675902	3.701723351	2.822886768

Figure C.3: Total Emissions Bar Graph for PET and PVC plastics

From the graph below it is hard to say whether or not there is a concise winner in which material has less of an impact. PVC has a lower impact on respitory organics, respitory inorganics, climate change and acidification. PET has a lower impact on carcinogins, ecotoxicity, and minerals. They both have low impact on radiation, ozone layer and land use. PVC seems to have an edge on a lower impact on the enviroment and others than PET.

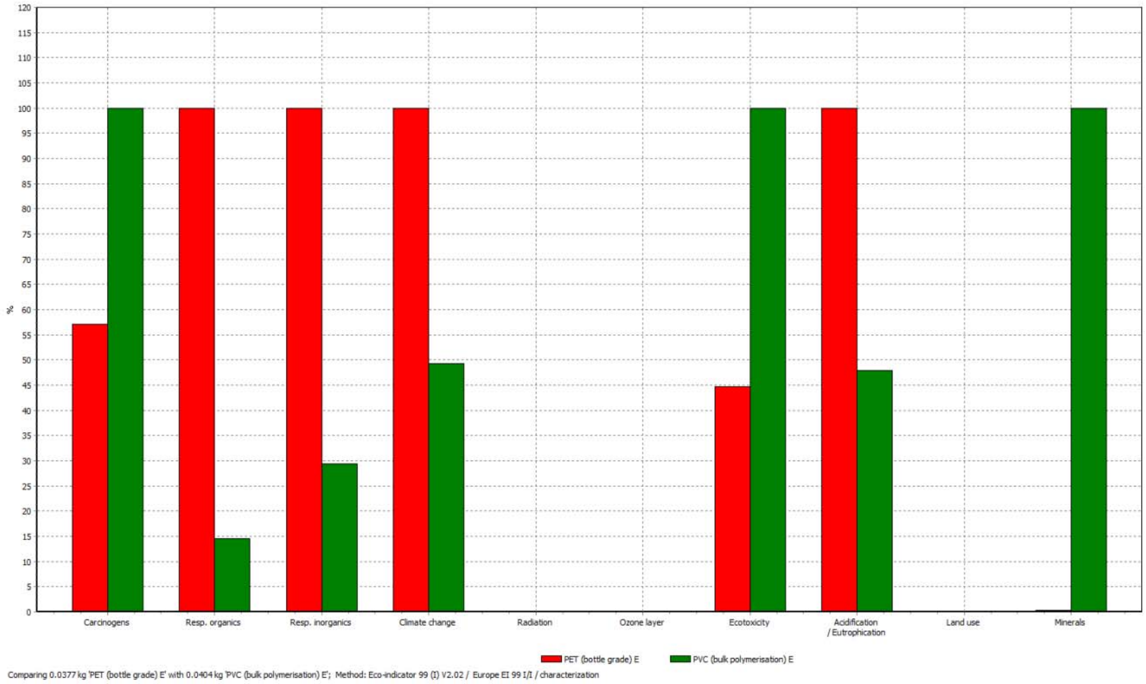
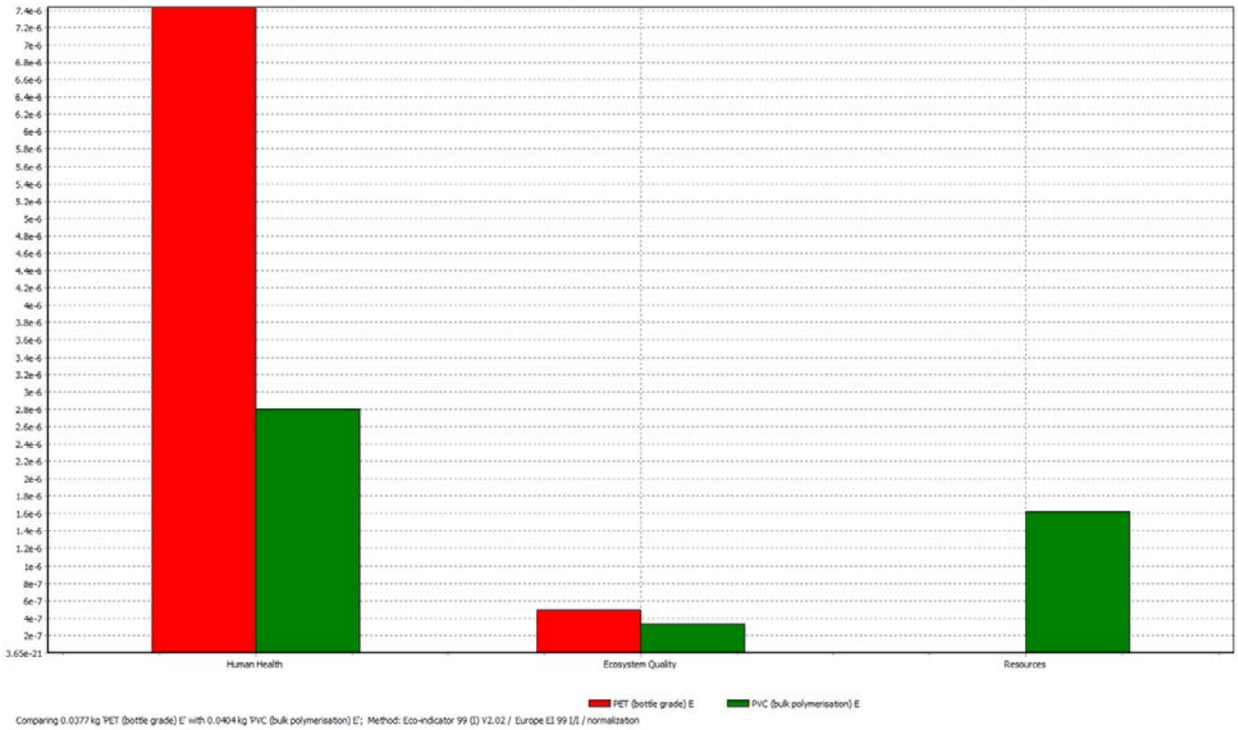


Figure C.4: Relative Impacts in Disaggregated Damage Categories Graph

PET's have more of an affect on human health and the ecosystem quality, but less affect on resources than PVC. PVC seems to be a better material to use for our hybrid cell phone case, however if it is easier to mass produced, the potential to use PET is still there.



Comparing 0.0377 kg 'PET (bottle grade) E' with 0.0404 kg 'PVC (bulk polymerisation) E'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Figure C.5: Normalized Score in Human Health, Eco-Toxicity, and Resource Categories Graph

The total points against PET stack up more than do the points against PVC. This even being that PET doesn't seem to affect the resources, which my be due because of the great recycling program in the country for PET. From an enviromental stand point, PVC should be used for the production of our hybrid cell phone case.

Figure C.6: Single Score in SimaPro "Point" to Compare Materials

14.3.4. Manufacturing Process Selection

14.3.4.1. Production Batch Size: Package Casing

Target customers for this product are people, corporations, or government agencies that are willing to pay a premium for the extended operating lifetime that our product offers. Such people are likely to spend a lot of time traveling or in situations where access to an electricity grid is unavailable. The most likely early adopter could be the U.S. military, especially considering Harris Corporation's experience with defense contracts. Some reports show estimate that tactical communications spending will increase to $5.7 billion by 2010. [43] With 2.5 million servicemen and women around the world (not counting employees of other governmental agencies stationed overseas) [40], the market for a military application of this product is enormous.

Another market to compare with is the satellite phone industry, because satellite phones are typically operated in remote areas away from the grid, and would benefit from this hybrid technology. With each of the two major satellite providers having more than 100,000 subscribers each, [41] this represents another significant market.

A third market is business owners or employees who spend time traveling and manage a lot of information with their cell phones. Such users may own Blackberries, which sold 7.8 million units last year [http://www.roughlydrafted.com/2009/04/02/rim-shares-surge-as-blackberry-sales-hit-record-78-million/] or Apple iPhones, which sold over 11 million units in 2008 [http://apple20.blogs.fortune.cnn.com/2009/03/12/iphone-sales-grew-245-in-2008-gartner/]. Additionally, a total of 1.1 billion cell phones were sold worldwide in 2007. [42]

Everything considered the market for this product is gigantic and still growing. It is safe to assume a six-figure production number, which we will estimate at 250,000 units for the first production run.

14.3.4.2. Production Batch Size: Package Casing

Based on the product productions numbers given in the above section, it is easy to estimate the number of cartridges that need to be produced to meet demand. If a cartridge can supply 30 days of standby time, we can conservatively estimate that a user may run out of methanol every two weeks if he uses his cell phone heavily. This means that production for the methanol cartridge will be 24 times the number of phones produced, or 6 million units.

14.3.4.3. Manufacturing Process Selection: Package Casing

To select a manufacturing process for the cell phone package we again used the CES software. The product will be a high production volume, 3D shape with fine dimensions and tolerances. The properties entered into CES for this component are given in Table C.3 below.

Table C.3: Manufacturing Process Data for Package Casing

Process	Primary Shaping	
Geometry	3D Solid	
	Minimum	**Maximum**
Weight (lb)		0.11
Section Thickness (mil)	19.0	119.0
Tolerance (mil)		5.0
Batch Size (units)	250,000	

There were only a few process options that were able to meet these specifications. Bulk molding or “dough” molding was an option, however it is incompatible with the PVC material we have selected. Powder injection molding and pressing and sintering were also options, however these processes are only suitable for metals, ceramics, and certain composites. The only process which can meet these requirements for PVC material is injection molding. This process is commonly used with PVC and is best suited for high volume applications such as our product.

14.3.4.4. Manufacturing Process Selection: Fuel Cartridge

The methanol cartridge is a hollow shape with thin walls and an intricate interface. Using the CES software, we entered in the following property information, as given in Table C.4.

Table C.4: Manufacturing Process Data for Fuel Cartridge

Process	Primary Shaping	
Geometry	3D Hollow	
	Minimum	**Maximum**
Weight (lb)		0.05
Section Thickness (mil)	19.0	80.0
Tolerance (mil)		5.0
Batch Size (units)	6,000,000	

Again, only a few options remained; injection molding, investment casting, powder injection molding and pressing and sintering. Investment casting is typically used for metals and alloys, so only injection molding is suitable for this part.

The manufacturing processes selection results for each of these parts is not surprising. Cell phone packages, as well as many other common polymer parts, are typically injection molded whenever a large batch size is necessary. Cost of the tooling is very high because precise and complex dies are required, but the relative cost per unit decreases dramatically with production volume, especially for batch sizes greater than 10^6.

14.4. Appendix D: Safety

When tasked to fill out a safety report (14.4.2.), our team went into great depth to discuss the hazards that exist within our project and how to avoid those hazards. The safety report was filled out before testing began so our team was prepared for potential dangers. The best way to prevent a problem is knowing there is a potential for one. There were three main factors that our team had to deal with in terms of safety. Those factors were the handling of methanol (toxic material), the heat that would be produced by our fuel cell and components, and the electrical components. Greater detail on the methanol fuel and electrical components and more can be read in Section 3 of our safety report for our project. The heat output of our system and test is discussed in Section 14.4.1. and in Section 6 of our Final Report. Much attention to detail was used when dealing with safety and our project.

14.4.1. Heat Output

Heat was a main safety concern so that the user and ourselves were never affected by too high of temperatures from the fuel cell, packaging, and hybrid cell phone package testing. Much precaution was taken when dealing with the heat testing and temperatures were monitored extensively to make sure no one or device was harmed.

Heat may also impair the safety, performance, and reliability of a cell phone. An electric system has the potential to emit smoke or catch fire if the device generates more heat than anticipated. Excessive heat may also degrade the performance of the device by lowering its operating speed, and in the worst case, damage the cell phone. Of course, high temperatures can be harmful if the user is not protected from direct contact as well.

14.4.2. Safety Report (given in entirety, pg 75-89)

ME 450 Safety Reporting: Winter 2009

Project #: ___26_____ **Date:** ______10 March 2009_____________
Report Version #: ___2.0______
Project Title: ____Maizr- DMFC Hybrid Cell Phone____________
Team Member Names: Cameron Graybeal, Chad Neumann, Matt Putz, Dianyun Zhang
Team Member Uniquenames:__camrg, cmnmich, mpputz, dianyun

Attach your Safety Report to this cover page and instructions found on Pages 2 and 3.
The Safety Report is to be completed by your team and must be approved by your section instructor (or approved substitute) prior to any hands-on experimentation, manufacturing or testing of your prototype.

The safety hazards inherent in your experimental plans, component selection, manufacturing methods, assembly techniques, and testing must be expressed and evaluated before any hands-on work with safety consequences will be allowed to proceed.

The purpose of this safety report is to assure that you have thought through your hands-on work before it begins, and that you have shared your plans with your Section Instructor. You may submit more than one version. This will likely be necessary as your project evolves.

APPROVAL:
Name: __________________________
Signature: __________________________
Date: __________________________

1. Introduction

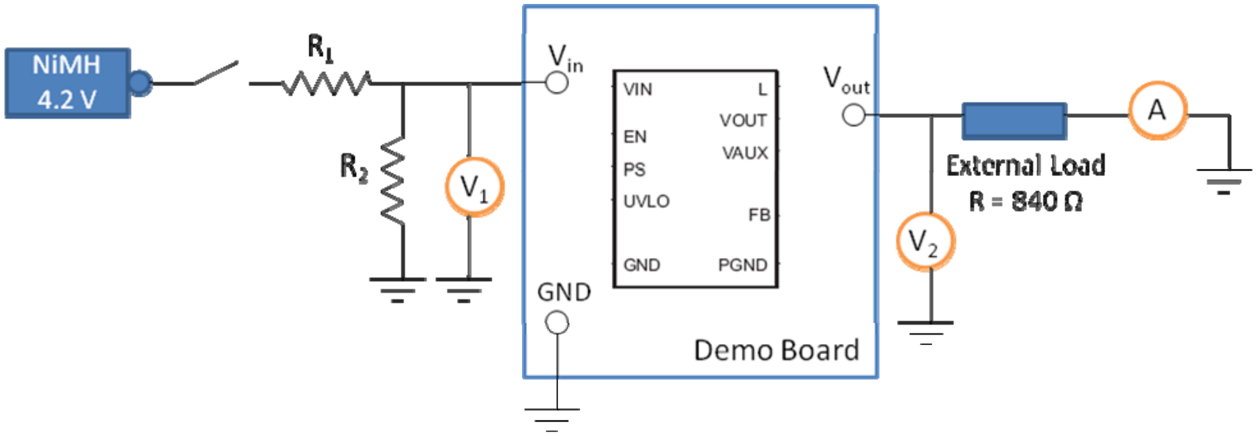
The safety report was filled out before our testing was performed on our major components of our project being the fuel cell and circuitry. Precautions were taken to the fullest extent even though many of the situations that were thought out using DesignSafe, never came into action.

2. Experimentation Plans

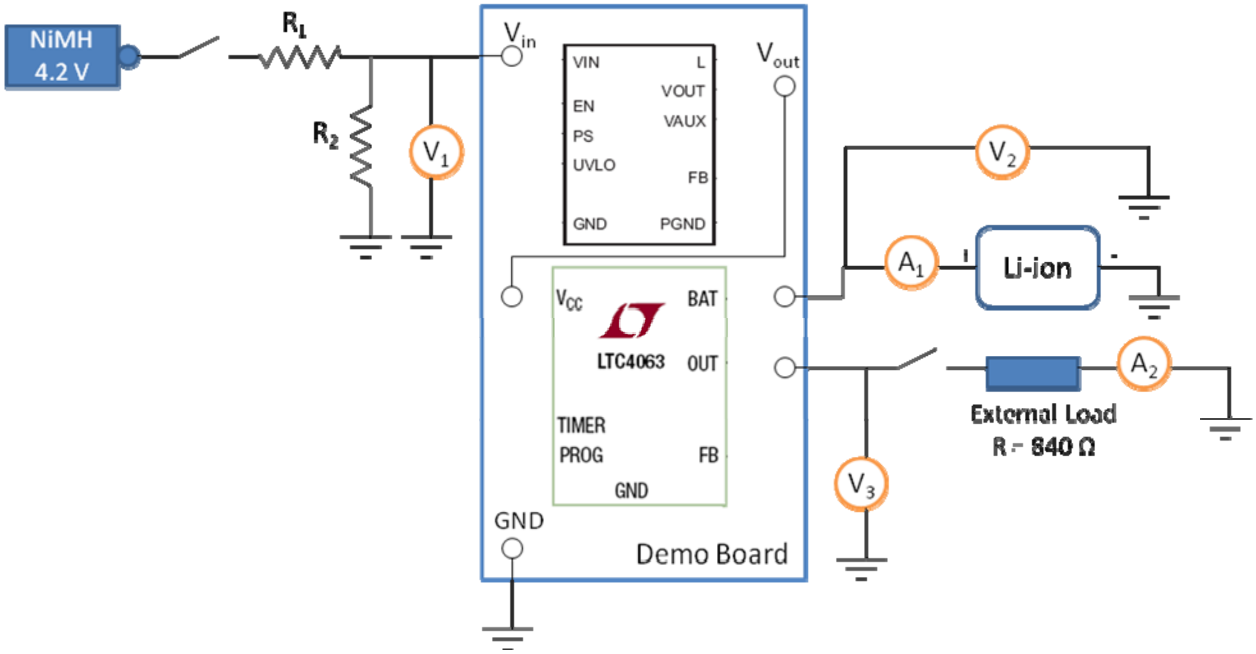
2.1. Test 1: Hybrid System Power Integration

Our goal is to verify a proof-of-concept design for hybrid integration of a fuel cell and battery combination, to find optimal working conditions, and to determine safe operating parameters of the circuit. This will happen in four phases. First, testing the voltage booster chip using a battery for input power (used with a voltage divider to simulate a fuel cell) and a load to simulate a cell phone. Second, the voltage booster will be combined with a battery charging chip and the simulated fuel cell will be used to charge a lithium ion battery. Third, the simulated fuel cell will be connected in parallel with the battery to power a load to simulate talk mode, and finally the simulated fuel cell will be used to recharge the battery while also powering a load to simulate the phone in standby mode.

Diagrams are given for the described configurations below, including where voltage and current readings will be collected. Configuration 1 shows the simulated fuel cell powering a voltage booster chip, which is then used to power a resistive load. The 'Demo Board' includes the chip as well as the necessary circuit components to set the boosting ratio. Configuration 2, 3 and 4 shows the simulated fuel cell used to power a voltage booster chip and a battery charger chip, which can then charge the battery, power the load, or do both at the same time. The written procedure can be found in the appendix.



Configuration 1



Configurations 2, 3 and 4 (switchable)

2.2. Test 2: Direct Methanol Fuel Cell Power Characterization

Our second test is designed to determine the fuel cell power output characteristics for different configurations of methanol fuel and fuel cell components, as well as to validate the original manufacturer's specifications. This will allow us to find the optimal operating power configuration for powering the cell phone. Testing will consist of measuring the voltage and current output of the fuel cell when an external load is applied under various input parameter conditions. Specifically, we wish to characterize the effects of changing the methanol solution concentration, changing the temperature of the input methanol, not using an air pump to supply oxygen to the fuel cell, and a direct gravity feed (no fuel pump) of the methanol solution.

A diagram of this setup is shown in Configurations 5 and 6. For Configuration 6, the needed components are shown as they will be setup. A heating plate/cooling chamber will be used to control the input methanol temperature. Solutions will be created in an external beaker using the proper combinations of methanol and distilled water. Different molar solutions will be used from 1-4 Mol or 4-16 milliliters of methanol. Both pumps require external power supplies not shown in the diagram of 12V for the liquid pump and 6V for the air one. A full procedure can be found in the Appendix of this report.

Configuration 5

Configuration 6

2.3. Test 3: Fuel Cell Heat Characterization

Our third test's goal is to determine the heat flux characteristics of the DMFC per unit of area established by the various input parameters. This will be conducted alongside Test 1, as the same experimental parameters are changed. We will use this information to model our fuel cell heat output rate to find the most effective and safe way to dissipate the heat. This involves the same main risks as Test 1.

Configuration 6 also shows this test setup. One thermal couple will be placed on the fuel cell to determine its operating temperature, followed by a thin sheet of glass cut to the necessary dimensions, followed by another thermal couple which will be placed on the outside center of the glass. In this respect, we will be able to determine the temperature difference across the glass and calculate the heat output based on the glass resistance. A final thermal couple or thermometer will be used to measure the external room temperature to maintain testing consistency. The procedure for this test is written out in the appendix.

3. Purchased Component and Material Inventory

3.1. Batteries and Voltage Sources

Batteries will be used for two applications in our experimentation. A Lithium Ion battery is a necessary component of our hybrid system to provide the power needs of the cell phone during talk mode. Another battery will be used to simulate the fuel cell for this series of tests, as described in Section 2 above. Batteries carry the potential risk to shock someone who may touch the circuit in a way that causes a short. Failure of the battery will depend on the quality of the connection made in the circuit. Poor connection could cause damage to the battery and cause the circuit to fail. The potential for the battery to overheat and catch on fire has been reported with other products that use Li-Ion batteries.

3.2. Voltage Booster

The voltage booster is used to boost a small voltage to a larger one to power a load. Because our one cell fuel cell only outputs 0.75 Volts, the voltage needs to be increased to achieve the necessary voltage to power the cell phone and charge the battery. Mishandling of the chip when power is being supplied could shock a user or damage the chip, and overheating during soldering could cause the pins to loosen from the chip. Failure could happen if there was a surge in power supply from the simulated fuel cell to the booster.

3.3. Battery Charging Chip

This chip is necessary to charge the Li-ion battery and it is programmed so that the battery is not over charged. Just as with the voltage booster, mishandling could cause shock or damage to the chip, and poor soldering could damage the pins. A surge of power could also potentially damage the charger.

3.4. Other Electrical Components

Our circuit design requires a number of standard electrical components, such as resistors, capacitors and switches. Circuit components may have sharp wire leads that could potentially break skin if mishandled. Each of these elements can be damaged by a power surge and must be properly soldered or attached with other secure connections or the circuit will not work. We will be using a ‘breadboard’ type circuit board for prototyping, and must be careful to make connections properly because it is easy to make mistakes with component layout or make faulty connections on this type of board, both of which could damage the circuit. We may also be using standard perforated circuit board, which may have sharp edges when cut and which can melt if overheated with a soldering iron.

3.5. Data Acquisition Hardware

A method to measure voltages and currents over time is necessary to evaluate the power output characteristics of our fuel cell. An oscilloscope with data logging capabilities should be sufficient for our tests. We will need to measure the voltages and currents at multiple places, but for most of our tests we do not need to take all of these measurements at the same instant, so the one or two channels provided by an oscilloscope can be moved to each point when necessary. Oscilloscopes are precision instruments that can be damaged by electrical surges or by impacts if dropped. We will not be working with voltages high enough to damage the equipment but we will handle the oscilloscopes (and any other precision instruments we may end up using) with care as to not drop or bump them.

3.6. Safety Equipment

Certain safety procedures must be in place in order to protect ourselves and our circuit from damage. None of the components we are using at this point are inherently dangerous, but as stated in previous subsections it is possible to get slight shocks or damage components with mishandling. We will work on an anti-static pad to avoid instances of static build-up and arcs. We will use proper circuitry tools such as wire strippers and special pliers to handle the chips to avoid damage or injury. When soldering, we will be mindful of the heated iron and use an iron stand to keep the tip up off of the table and away from things that could be melted. Other safety equipment should not be necessary at this stage in our experimentation.

3.7. Direct Methanol Fuel Cell

The Parker TekStak DMFC is our chosen fuel cell for this project. We are designing a circuit which will charge a battery and power a cell phone based on the power output characteristics of this cell. While the power specifications can be modeled using theoretical results and then imitated with a battery or other voltage source, the cell is necessary to evaluate the theoretical model. Because heat management is also a large issue in our project, we also need the cell to empirically determine the heat output of the cell, which can only be very roughly calculated theoretically.

The TekStak is composed of 41 parts. Most of these parts are made out of common plastics, metals and rubbers, as well as two graphite plates. One component, the Membrane Electrode Assembly (MEA) has a couple of safety concerns. It contains carbon cloth and Ruthenium black, which can be flammable and eye irritant. It also contains Platinum black, which is highly flammable, eye and skin irritant, and harmful if ingested or swallowed. These materials are more dangerous to handle when in powder form, because the dust can be more easily transported to the eyes, mouth, nose and skin, but in the MEA they are formed into a solid. We will need to handle this component carefully with gloves and eye protection, taking care to keep it away from open flame. This component will be contained within the fuel cell after assembly, i.e. it will not be exposed during operation. Material Safety Data Sheets are attached in the appendix.

The geometries of the components that make up the TekStak are benign. The kit was designed to be assembled and disassembled multiple times in an educational setting, so there are no dangerous sharp edges or moving parts.

The TekStak poses some dangers while in operation. First, it requires the use of liquid methanol fuel, the hazards of which are described in the next section. Also, the fuel cell will generate heat and may require heated fuel for operation, so we will need to take care to avoid touching it while it is hot and use gloves for handling during or immediately following operation. Finally, the fuel cell generates electricity and could cause a shock. The voltages and currents of the cell are sufficiently low as to not pose the risk of harm to humans; however we will be careful as to not touch charged components during operation.

The fuel cell could fail in a number of ways. The most catastrophic failures are the events that would cause methanol to leak and spill onto other components or the user. The fittings between the fuel lines and the fuel cell could break or strip, or the flexible fuel line could split or stretch, all of which would cause leaks. If the bolts and nuts holding the stack together creep, crack or otherwise fatigue, the stack components could separate and fuel could spill out of the cell. This is unlikely because the bolts are supposed to be very lightly tightened. Over-tightening can crack the graphite plates, which would also cause methanol to leak. The worst case would be a crack in the MEA, caused by over-tightening or over-pressurizing. This would not only cause methanol to cross the MEA boundary and flow out of the cell, but the fuel may carry some of the toxic membrane material with it, potentially harming the user. Electrical connections also have the potential to wear out or break, resulting the lost ability to deliver power.

3.8. Liquid Methanol

Methanol is supplied to the fuel cell, where it is broken down in a chemical reaction that releases electrons. Methanol is a toxic and flammable substance. It can cause eye irritation, digestive tract damage, blindness and death. Prolonged skin contact can cause irritation and dermatitis. We will take care to handle it cautiously using gloves and protective eyewear, and work in a ventilated room or under a fume hood. As mentioned above, methanol could possibly leak at a number of places from the fuel cell, or potentially from any component or fitting in the fuel storage and delivery system. We will avoid heating it past its boiling point ($65^{o}C$) to reduce fumes and we must keep it away from open flame. If any component of the system becomes excessively hot during use, we must be cautious to ensure that the methanol is properly protected from that area. The MSDS is attached in the appendix.

3.9. Fuel Pump

A diaphragm-type liquid pump is required to circulate fuel to the cell throughout operation. The pump could leak methanol if the intake and output hose fittings were to strip or break or the line was to split or stretch at the fitting. Leaking could also occur if the casing sustained an impact and split. The pump could cease functioning if the diaphragm became worn through use and ripped or broke its seal, the actuator wore out or seized, the check valves broke or seized or the electrical connections snapped.

3.10. Air Pump

A diaphragm-type air pump is required to force pressurized air past one side of the fuel cell. If the pump were to cease functioning, there is no danger to the user, but the cell's efficiency would be negatively impacted. This pump is similar to the fuel pump and can fail in the same ways; the pump will stop if the diaphragm became worn through use and ripped or broke its seal, the actuator wore out or seized, the check valves broke or seized or the electrical connections snapped.

3.11. Heating Plate

The use of a heating plate will be necessary to heat the methanol fuel; we will be testing the impact of fuel temperature on cell efficiency. The potential for high temperatures is an obvious concern. We will be careful not to touch the hot surface with bare skin and not to place flammable or easily melted materials on it. We will also monitor the methanol temperature so we do not boil it and produce a large amount of fumes. The plate should be internally regulated as to not heat up to temperatures that would damage itself, but internal components could be damaged by electrical surge or weakened by thermal cycling.

4. DesignSafe Anaylsis

The DesignSafe analysis for circuitry and the fuel cell can be read following the end of the safety report.

5. Manufacturing and Assembly

There is basically no manufacturing involved in this stage, aside from cutting and bending operations required to form circuit component leads and solid core wire. This will require a wire stripper and a pair of needle nose pliers.

Assembly will consist of straightforward circuit building techniques. The resistors for the voltage divider and external load will be inserted into a breadboard, as will lead wires from the simulated fuel cell and the battery to be charged. Solid core wire will be used to make the proper connections and wire elements to a common ground. The 'Demo Boards' shown in the circuit contain the two chips and the other necessary circuit elements to adjust output. They will have wire leads that will be inserted into the breadboard to be integrated with the other elements. The oscilloscope will be attached to the circuit at the proper places using spring-loaded prongs.

The circuit will be assembled and tested in Professor Skerlos's lab.

6. Safety Report Appendices

Test 1: Procedure for Hybrid Cell Phone Powering System:

1) Produce accurate setup for Configuration 1, which consists of a fuel cell, booster chip, and model load. Double check all connections and parameters for correct assignment.
2) Turn on all measuring devices and set to zero offset.

3) Measure voltage and current of the simulated fuel cell and the cell phone load
4) Decrease load until desired current of 5 mA is drawn. This should occur within a resistance range of 0.75kΩ and 1kΩ, at ideally a calculated value of 0.84 kΩ.
5) Record battery voltage output and load current and voltage settings. Verify that these are within desired specifications.
6) Disconnect circuit, reconnect, and then repeat steps 3 through 5 four more times to verify test setup and analyze uncertainty factors.
7) Turn off and disconnect all relevant pieces which will not be used for Configuration 2.
8) Setup Configuration 2, which includes simulated fuel cell, booster chip, charger, and lithium ion battery. Battery will initially be uncharged.
9) Repeat step 2.
10) Measure voltage and current both across the battery and after the voltage divider with the oscilloscope program at a measurement rate of 10 Hz. Will record these findings for 30 minutes.
11) Measure the voltage between battery and charging chip periodically (every 3 minutes for ten data points).
12) Measure periodically ambient external temperature for verification with other findings (minimum five measurements).
13) Disconnect lithium battery and simulated cell from the circuit, reconnect, and repeat steps 10 through 14 once to verify charging parameters.
14) Repeat steps 10 through 15 two more times; once with the battery at half capacity, and once when the battery is nearly recharged initially. This is used to characterize the recharging rate of the lithium battery.
15) Turn off and disconnect all parts before continuing to step 17.
16) Setup Configuration 3, which includes the fuel cell, booster chip, battery, and high power talk mode load. Battery is initially charged.
17) Turn on all accessories and repeat step 2.
18) Measure the voltage across the load and the input battery, as well as the current through the lithium battery and the load.
19) Adjust load size as needed to achieve correct voltage and current required. This should be around 275 mA for the maximum and 190 mA for average current draw, which equates to a range between 5Ω and 20Ω (theoretical ~10Ω).
20) Measure the voltage again across the input battery and the load, as well as the current through the battery and the load.
21) Disconnect the two batteries, reconnect these, and measure the system at least four more times for data analysis.
22) Turn off and disconnect all parts before continuing to step 25.
23) Setup Configuration 4, which includes the fuel cell, battery, booster chip, charging chips, switches, and two talk mode loads. Battery is initially uncharged.
24) Switch off both the load and battery components (or switch to the highest load) and connect the simulated battery.
25) Repeat step 2.
26) Flip switch for first the highest load and then the lithium battery.
27) Measure and record the voltage across the load resistor and adjust so that the current is at 5mA (~0.84kΩ).

28) Measure the voltage and the current of the input battery, the lithium ion battery, and the load.
29) Disconnect these three components and reconnect them, and then measure the voltage and current of each component again.
30) Repeat step 31 three more times minimum to completely characterize the circuit.
31) Repeat steps 26 through 32 with the smaller load, setting the resistor between the rang of 5-20Ω.
32) Disconnect and store all components as required for safety and maintenance.

Test 2: Procedure for Methanol Fuel Cell Power Characterization

1) Verify that a proper setup has been achieved. Double check all wires, connections, fittings, and safety protections for proper placement.
2) Apply proper mixture and temperature of methanol (See step 9)
3) Turn on all recording devices and set to zero.
4) Turn on liquid fuel pump and air pump. Verify methanol solution is at correct operating temperature (initial test setup is for room temperature).
5) Stack must be "broken in" if this is the first time for operation. Therefore, a small load should be placed on the stack while it runs for several hours (? This is recommended by parker).
6) Once membranes become fully saturated, connect largest load to stack and record stack voltage, current output, load resistance, the fuel cell external temperature, and methanol fuel temperature.
7) Decrease load size to next target resistance (~5kΩ less increments) and repeat recordings of step 6.
8) Continue decreasing load resistance until minimum load (or a stack voltage of 0.3 V) is reached while recording the above characteristics. This should result in approximately 20 data points and a final resistance of 5Ω.
9) Repeat steps 6 through 8 while changing the following parameters one at a time. For each factor, the optimal condition is chosen and used for the next parameter testing (i.e. if 10% methanol is found to produce the optimal power, then it will be used for all the testing configurations concerning the methanol temperature and for the no fuel pump and no air pump tests).
a. Methanol Solution
    i. 1 – 4 Mol
b. Methanol Temperature
    i. 0ºC
    ii. 25ºC (room temperature)
    iii. 40ºC

c. No fuel pump (direct gravity feed)
d. No air pump (air convection)
10) Disassemble each component and ensure safe containment of all dangerous materials (methanol specifically – also have safe protection of fuel cell so that it won't break). Includes flushing out of fuel cells with water and then possibly air drying the inside of the MEA with the air pump.

Test 3: Procedure for Fuel Cell Heat Characterization

1) Verify test setup.
2) Turn on and zero voltmeter and ensure that each all thermal couples read a consistent temperature. Record these and try to fix discrepancies or include these in analysis of the temperature of the various parts.
3) Turn on fuel pump and any other required conditions (air pump, heated methanol, etc.).
4) Set maximum resistance of load (~100kΩ).
5) Allow temperatures to stabilize to ensure steady state conditions.
6) Record temperature of side not facing fuel cell on the conductive material, in between fuel cell and conductive material, ambient room temperature, current output, and stack voltage.
7) Decrease load resistance to next increment and record the measurements of step 4.
8) Continue decreasing load resistance in 5kΩ increments to obtain approximately 20 data points, stopping at the minimum resistance of ~5Ω. Record at each point the desired measurements of step 4.
9) Repeat steps 4 through 8 while changing the following parameters one at a time.
    a. Methanol Solution
        i. 1 – 4 Mol
    b. Methanol Temperature
        i. 0ºC
        ii. 25ºC (room temperature)
        iii. 40ºC

    c. No fuel pump (direct gravity feed)
    d. No air pump (air convection)

For each factor, the optimal condition is chosen and used for the next parameter testing (i.e. if 10% methanol is found to produce the optimal power, then it will be used for all the testing configurations concerning the methanol temperature and for the no fuel pump and no air pump tests).

10) Repeat testing steps 4 through 8 as needed to verify these findings. Suggested testing times is a minimum of five, but may change depending on time constraints.
11) Disassemble and store all components as necessary.

designsafe Report

Application: Circuitry for Fuel Cell System

Analyst Name(s): Cameron Graybeal, Dianyun Zhang, Matthew Putz, Chad Neumann

Description:

Company:

Product Identifier:

Facility Location:

Assessment Type: Detailed

Limits:

Sources:

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	electrical / electronic : energized equipment / live parts working with electricity that will be charged for testing	Serious Frequent Unlikely	High	cannot reduce risk, take precaution when testing	Serious Frequent Possible	High	On-going [Daily] Team 26
All Users All Tasks	electrical / electronic : lack of grounding (earthing or neutral) improper wiring could lead to no grounding	Slight Remote Unlikely	Low	check wiring to make sure circuit is grouded	Slight Occasional Unlikely	Moderate	In-process Team 26
All Users All Tasks	electrical / electronic : insulation failure stripping wires could limit the amount of insulation exposing user	Slight Remote Possible	Moderate	do not be careless when wiring	Slight Remote Unlikely	Low	In-process Team 26
All Users All Tasks	electrical / electronic : shorts / arcing / sparking crossed wires/components could cause a short	Slight Remote Possible	Moderate	check wiring to make sure there are no shorts	Slight Occasional Possible	Moderate	In-process Team 26
All Users All Tasks	electrical / electronic : improper wiring not following circuit diagrams correctly	Serious Remote Possible	Moderate	do not be careless when wiring	Slight Occasional Possible	Moderate	In-process Team 26
All Users All Tasks	electrical / electronic : overloading surge in input voltages/currents	Serious Remote Unlikely	Moderate		Slight Remote Unlikely	Low	TBD Team 26
All Users All Tasks	electrical / electronic : contaminants methanol or water could be a contaminant	Serious Remote Negligible	Low	make sure work table is clean at all times	Minimal Remote Negligible	Low	On-going [Daily] Team 26

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	electrical / electronic : water / wet locations water is created in the process when fuel cell is used	Minimal Occasional Possible	Moderate	make sure work table is clean at all times	Minimal Occasional Negligible	Low	On-going [Daily] Team 26
All Users All Tasks	electrical / electronic : software errors chip malfunction	Slight Remote Unlikely	Low		Slight Remote Negligible	Low	TBD Team 26
All Users All Tasks	electrical / electronic : overvoltage /overcurrent if there was a spike in input or outputs	Minimal Remote Unlikely	Low		Slight Remote Unlikely	Low	TBD Team 26
All Users All Tasks	electrical / electronic : power supply interruption when using fuel cell, if methanol fuel runs out	Minimal Remote Negligible	Low	keep fuel cell fully fueled	Minimal None Negligible	Low	On-going [Daily] Team 26
All Users All Tasks	electrical / electronic : electrostatic discharge we produce static electricity, may cause chips to malfunction	Slight Occasional Unlikely	Moderate	use grounded wrist bands	Minimal Occasional Negligible	Low	In-process Team 26

designsafe Report

Application:	DMFC	Analyst Name(s):	Cameron Graybeal, Dianyun Zhang, Matthew Putz, Chad Neumann
Description:		Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	electrical / electronic : energized equipment / live parts DMFC produces power	Slight Occasional Unlikely	Moderate	Be aware of live parts	Slight Occasional Negligible	Low	
All Users All Tasks	electrical / electronic : shorts / arcing / sparking Improper wiring	Slight Remote Unlikely	Low	Check connections	Slight Occasional Negligible	Low	
All Users All Tasks	electrical / electronic : improper wiring Not checking connection before supplying power	Slight Remote Unlikely	Low	Check connections	Slight Occasional Negligible	Low	
All Users All Tasks	electrical / electronic : contaminants Dealing with methanol and water	Serious Remote Possible	Moderate	Keep work areas clean	Minimal Occasional Negligible	Low	
All Users All Tasks	electrical / electronic : water / wet locations DMFC produces water	Slight Occasional Probable	High	Keep work areas clean	Minimal Occasional Negligible	Low	
All Users All Tasks	fire and explosions : flammable liquid / vapor Spark could ignite methanol	Serious Remote Possible	Moderate	Check connections	Serious Remote Unlikely	Moderate	
All Users All Tasks	fire and explosions : exposed electrical arcs Faulty wiring	Serious Remote Possible	Moderate	Check for not shorts	Slight Remote Unlikely	Low	
All Users All Tasks	fire and explosions : static electricity Humans	Slight Remote Unlikely	Low	Wear static discharging wrist bands	Minimal None Negligible	Low	
All Users All Tasks	heat / temperature : burns / scalds DMFC produces heat	Serious Frequent Possible	High	Don't touch DMFC when hot	Minimal Remote Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	heat / temperature : severe heat DMFC produces heat	Serious Frequent Possible	High	Will not heat up work area enough to cause discomfort	Minimal Remote Negligible	Low	
All Users All Tasks	ventilation : loss of exhaust Not using ventilation system	Serious Remote Unlikely	Moderate	Use fume hood when using methanol	Minimal Occasional Unlikely	Low	
All Users All Tasks	ventilation : lack of fresh air Lab not properly vented	Serious Remote Negligible	Low	Lab will be properly vented	Minimal None Negligible	Low	
All Users All Tasks	chemical : reaction to / with chemicals Not properly cleaned equipement	Serious Remote Possible	Moderate	Clean equipement before/after use	Slight Remote Unlikely	Low	
All Users All Tasks	chemical : skin exposed to toxic chemcial Methanol exposed to skin	Serious Remote Possible	Moderate	Use proper PPE	Slight Occasional Unlikely	Moderate	
All Users All Tasks	chemicals and gases : methanol Methanol is toxic	Serious Frequent Possible	High	Use proper PPe	Slight Remote Unlikely	Low	

14.5. Appendix E: Power Consumption Map of a 2nd Generation GSM Phone

Table E.1: Typical Power Consumption in a GSM Handset. [28]

Sub-circuit	Peak Current Consumption in Talk Mode (mA)	Average Current Consumption in Standby Mode (mA)
Digital Base Band + Memory	19+6	0.3+0.04
Analog Base Band	9	0.15
SIM	1	0.06
RF	32	0.05
PA	200	0.77
PM(Housekeeping)	3	0.22
Misc. Other	5	0.67
Total Peak Current Consumption	**275**	**2.26**

14.6. Appendix F: DMFC Open Circuit Voltage Calculation Methodology

In a direct methanol fuel cell, the following reactions take place:

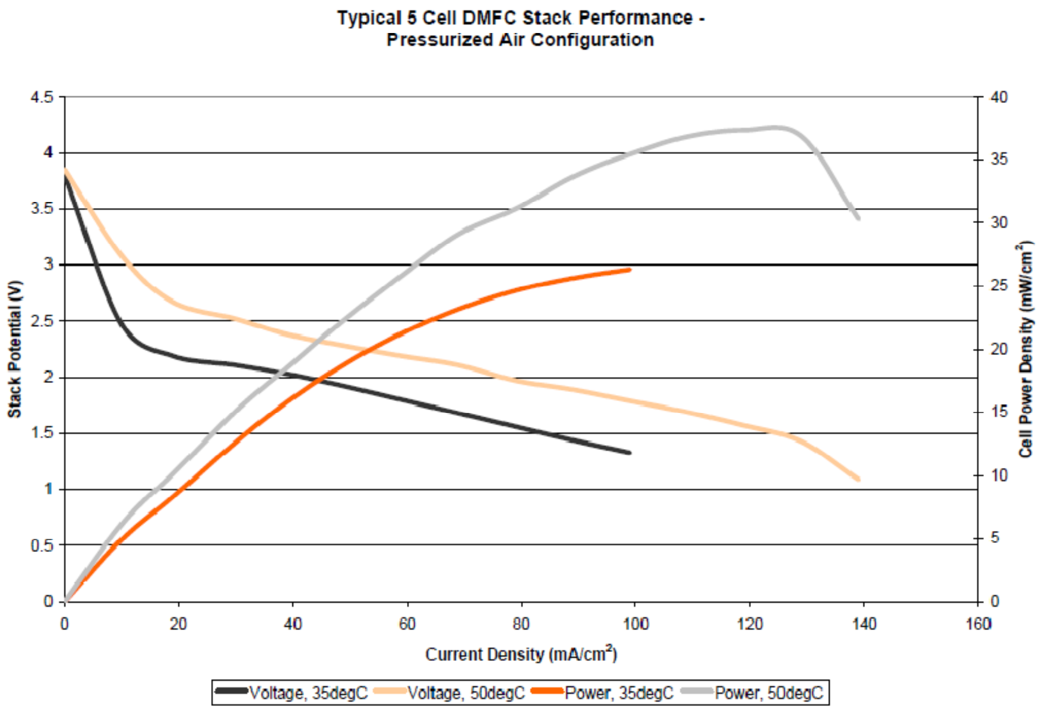
Anode: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$
Cathode: $6H^+ + 6e^- + 1.5O_2 \rightarrow 3H_2O$
Overall reaction: $CH_3OH + 1.5O_2 \rightarrow CO_2 + 2H_2O$

The theoretical open circuit voltage (V_{oc}) of a DMFC is calculated based on the free Gibbs enthalpy of the overall reaction (ΔG), the number of electrons transferred during the reaction and the following equation [13]:

$$V_{oc} = \frac{-\Delta G}{nF}$$

where F is the Faraday constant which is equal to 96485 A·s/mol. Based on the reaction formula, n is equal to 6 and ΔG is equal to -702.4 KJ/mol. Therefore, the theoretical open circuit voltage of a single methanol fuel cell is 1.21 V.

14.7. Appendix G: TekStack Direct Methanol Power Curves



14.8. Appendix H: Force Analysis

$$F = \frac{d}{dt}(mv) \qquad \text{Eq. D.1}$$

$$v = \sqrt{2g\Delta h} \qquad \text{Eq. D.2}$$

$$\Delta t = {}^{2L}\!/_{\sigma} \qquad \text{Eq. D.3}$$

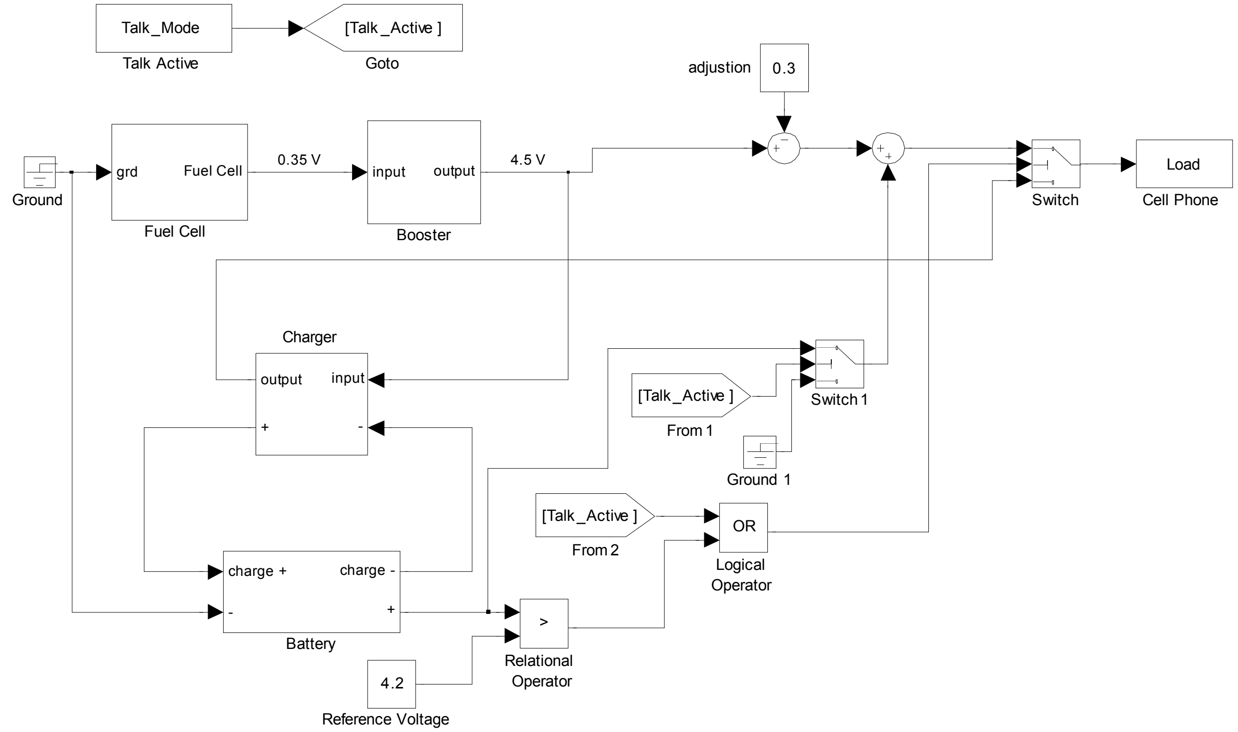
$$\sigma = \sqrt{{}^{E}\!/_{\rho}} \qquad \text{Eq. D.4}$$

F = force [N]
m = mass [kg]
v = velocity [m/s]
g = gravity constant = 9.81 [m/s^2]
Δh = height above reference line [m]

Δt = impulse duration [s]
L = length [m]
σ = speed of sound through a solid [m/s]
E = Young's modulus [Pa]
ρ = density [kg/m^3]

14.9. Appendix I: Block Diagram for the Power Delivery System

According to our true hybrid design, we combined three configurations into one block diagram with logical operators. This diagram is drawn by MATLAB R2007b.



14.10. Appendix J: Concept Generation

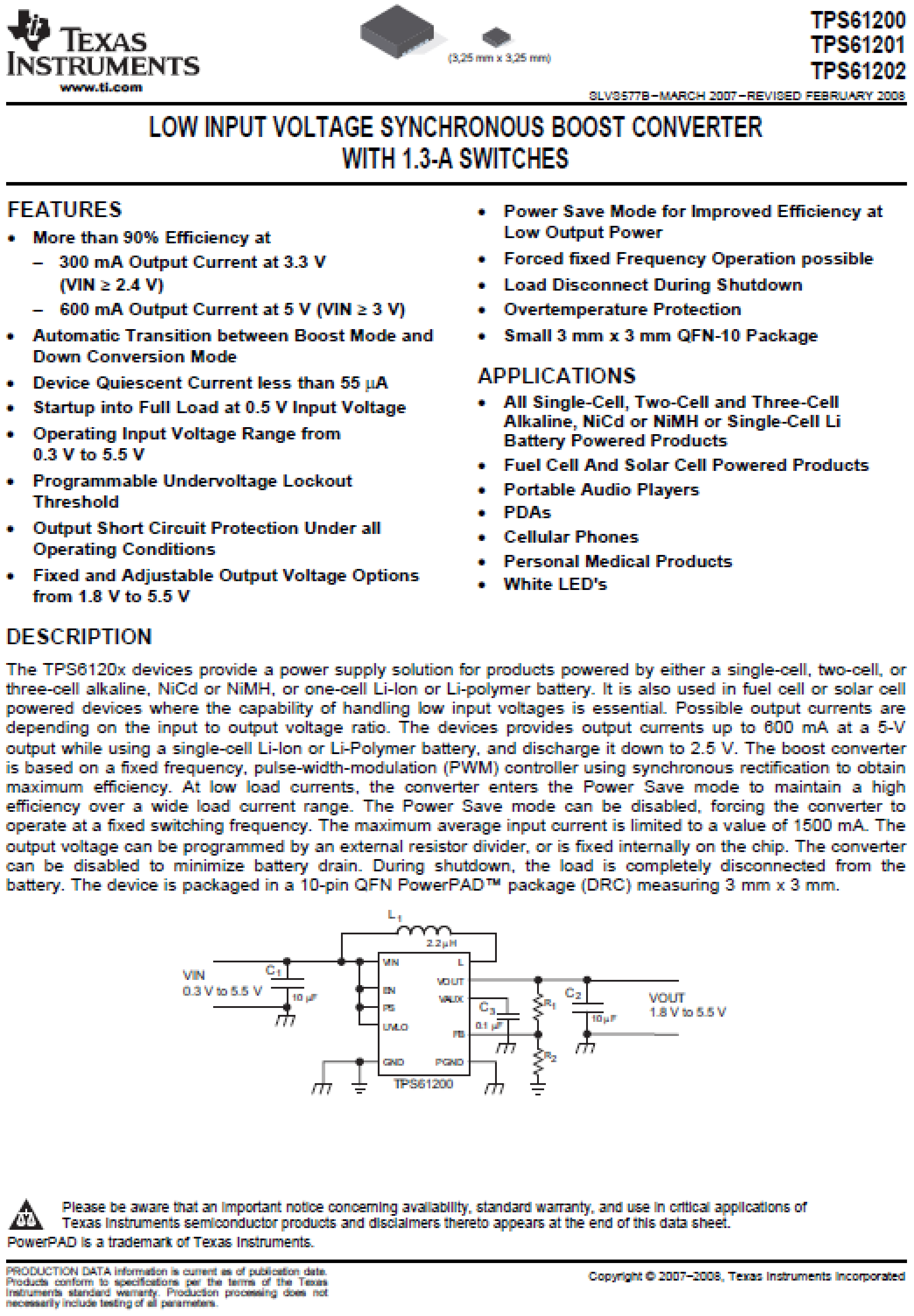
	Function	**Concept**		
Heat	Remove Heat	- Fins - Fan - Interfaces - Liquid cooling - Peltier cooling	- Ejecting heat sink - Laser cooling - Ice - liquid Nitrogen - Vents	- Forced air (hand) - Ambient - Forced air pipes - Balloon fill and eject air - Forced air (motor)
	Contain Heat	- Insulation - Coating - Vacuum	- Pre-heat methanol - Heat generator with sensor	- Shielding - Black components
	Heat Protection	- Gas coolants - Liquid coolants - White/mirrored components	- Cold interface - Plastics - Insulating materials	- Air - Ceramics/Glass
Packaging	*Protect Components*			
	Shock	- Padding • Strong materials • Elastic materials	- Dampers - Springs - Viscous liquid (sand/gel)	
	Vibration	- Dampers - Rubber mounts - Tight fittings	- Active damping - Active noise reduction - Padding	- Loose fittings - Vacuum
	Radiation	- Reflective material	- Shielding	- Solar panels
	Heat	- Heat resistant materials	- Jointed expansion	- Narrow gaps in casing
	Static Loading	- Strong materials - Exoskeleton	- Honeycomb interior - Brace/structural support	- Backbone
	Chemical	- Non-corrosive material	- Liners	- Coating
	Electrical Shock	- Resistant material - Ground strap	- Static liners - Use to power phone	- Human resistance - Circuit breaker
	Handle Methanol			
	Accept	- Cartridge • Pressurized • Non pressurized - Station fill	- By hand • Pour • Squeeze	- Interface • Screw • Puncture
	Store	- Tank • Single • Double (for circulating)	- Bladder - Sponge/Cellular Material	- Cartridge
	Circulate	- Pressure • Pre-charged • Hand pump • Spring • Mass	- Pump • Axial/syringe • Impeller pump • Hand - Capillary effect	- Squeezing - Shaking - Gravity feed

	Supply	- Tubing - Direct connection - Direct drip	- Channels - Manifold - Headers	- Nothing/free flow
	Collect from Fuel Cell	- Basin/open - Manifold	- Headers - Tubes	
	Heating Methanol	- Joule - Body/Breath - Solar powered - Pre-circulation	- Laser - Flame - Peltier - Radiation	- Chemical - Electrical Current - Ambient - Preheat
	Manage Water			
	Into Fuel Cell	- Solution	- Separate/Regulated	- From water out
	Out of Fuel Cell from Cathode	- Manifold - Tubes	- Open drip - Store and remove	- Use as coolant
	Out of Fuel Cell from Anode	- Drip - Circulating to fuel - Vaporize - Pump out	- Manifold/header - Sponge - Capture and dump - Hydrogen reforming	- Ambient - React into solid
	Manage Gasses			
	Intake Air	- Fan - Pump - Ambient - Blowing	- Piston pump - Compressed air - Oxygen reforming - Enriching with filter	- Blood cells - Hand pump
	Exhaust Air	- Circulate	- Screw	- Ambient/nothing
	Exhaust Carbon Dioxide	- Capture in cartridge - Pressurize fuel	- Ambient/nothing - Exhaust with water	- Organic reforming - Reactions
Power	Store Energy	- Battery - Supercapacitor - Inductor	- Mechanical (Spring) - Heat - Pressure	- Elastic - Kinetic
	Transfer Power	- Wires - Wireless	- Light/laser - Printed circuit board	
	Switch Modes	- Manual switches	- Solid state chips/MOSFET	
	Recharge Storage	- Direct methanol fuel cell	- External recharging	
	Power Conditioning	- Voltage regulator	- Current regulator	
	Controls	- Sensors	- Variable resistance	

14.11. Appendix K: Concept Selection

*Ratings were given from 1 to 5 for each particular concept based on how well they preformed a particular task. A 5 was given if the concept efficiently performed the requirement or if it did not negatively impact constraints. Concepts were selected in relation to each others scores.		Volume	Weight	Methanol Storage Temperature	Methanol Capacity	External Temperature	Power Requirements	Fuel Cell Performance	Refuel Time	Product Lifetime	Drop Durability	Vibration Durability	Cost to Manufacture	Safe to Operate	**Total**
Function: Methanol	**Concept**														
Storage	Cartridge	5	5	4	5	4			5	2	4	4	3	5	**46**
	Tank	5	5	4	5	4			4	4	3	3	3	4	**44**
Supply/Circulate	Direct Connection	5	5		5		5	3		5	4	5	5	5	**47**
	Tubing/ Pump	2	2		3		1	5		4	2	2	1	3	**25**
	Tubing/ Gravity	3	3		4		5	1		5	5	4	5	5	**40**
Pre-heat	None	5	5	5	5	4	5	2		5	5	5	5	5	**56**
	Pre-circulation	4	4	4	4	5	4	3		5	4	4	4	4	**49**
	Joule Heating	2	2	3	3	3	2	5		5	3	4	4	3	**39**
Function: Exhaust and Intake	**Concept**														
Intake/Exhaust Air	Ambient (Vents)	5	5	3	5	3	5	3		5	5	5	5	5	**54**
	Fan	3	2	5	3	5	3	4		3	4	4	3	4	**43**
	Pump	2	2	5	3	5	2	5		3	3	3	2	4	**39**
Exhaust Water	Ambient (Vents)	5	5	3	5	3	5	3		3	5	5	5	4	**51**
	Recirculation to Fuel	4	4	4	4	4	3	4		4	3	4	3	5	**46**
Exhaust CO2	Ambient (Vents)	5	5	5	5	3	5	3		5	5	5	5	5	**56**
	Capture in Cartridge	5	5	4	4	5	5	2		4	4	5	2	5	**50**
Function: Heat Management	**Concept**														
Heat Transfer	Ambient (Vents)	5	5	3	5	3	5	3		5	5	5	5	5	**54**
	Fan	3	3	5	3	5	3	4		3	4	4	3	4	**44**
	Liquid Cooling	4	3	4	4	4	4	4		3	4	3	2	5	**44**
Heat Protection	Insulation	4	4	4	4	5		5		5	5	5	5	5	**51**
	Shielding	4	4	4	4	4		3		4	4	4	4	5	**44**
	Coating	5	5	4	5	4		4		5	5	5	1	5	**48**
Function: Structural Durability	**Concept**														
Handle Loading Forces	Padding	3	5		4			5		5	5	5	4	5	**41**
	Exoskeleton	4	3		4			4		4	4	4	3	5	**35**
	Braces	3	5		3			4		3	4	3	5	5	**35**

14.12. Appendix L: Specification Sheet for Voltage Booster



TEXAS INSTRUMENTS
www.ti.com

(3,25 mm x 3,25 mm)

TPS61200
TPS61201
TPS61202

SLVS577B–MARCH 2007–REVISED FEBRUARY 2008

LOW INPUT VOLTAGE SYNCHRONOUS BOOST CONVERTER WITH 1.3-A SWITCHES

FEATURES

- More than 90% Efficiency at
  - 300 mA Output Current at 3.3 V (VIN ≥ 2.4 V)
  - 600 mA Output Current at 5 V (VIN ≥ 3 V)
- Automatic Transition between Boost Mode and Down Conversion Mode
- Device Quiescent Current less than 55 µA
- Startup into Full Load at 0.5 V Input Voltage
- Operating Input Voltage Range from 0.3 V to 5.5 V
- Programmable Undervoltage Lockout Threshold
- Output Short Circuit Protection Under all Operating Conditions
- Fixed and Adjustable Output Voltage Options from 1.8 V to 5.5 V
- Power Save Mode for Improved Efficiency at Low Output Power
- Forced fixed Frequency Operation possible
- Load Disconnect During Shutdown
- Overtemperature Protection
- Small 3 mm x 3 mm QFN-10 Package

APPLICATIONS

- All Single-Cell, Two-Cell and Three-Cell Alkaline, NiCd or NiMH or Single-Cell Li Battery Powered Products
- Fuel Cell And Solar Cell Powered Products
- Portable Audio Players
- PDAs
- Cellular Phones
- Personal Medical Products
- White LED's

DESCRIPTION

The TPS6120x devices provide a power supply solution for products powered by either a single-cell, two-cell, or three-cell alkaline, NiCd or NiMH, or one-cell Li-Ion or Li-polymer battery. It is also used in fuel cell or solar cell powered devices where the capability of handling low input voltages is essential. Possible output currents are depending on the input to output voltage ratio. The devices provides output currents up to 600 mA at a 5-V output while using a single-cell Li-Ion or Li-Polymer battery, and discharge it down to 2.5 V. The boost converter is based on a fixed frequency, pulse-width-modulation (PWM) controller using synchronous rectification to obtain maximum efficiency. At low load currents, the converter enters the Power Save mode to maintain a high efficiency over a wide load current range. The Power Save mode can be disabled, forcing the converter to operate at a fixed switching frequency. The maximum average input current is limited to a value of 1500 mA. The output voltage can be programmed by an external resistor divider, or is fixed internally on the chip. The converter can be disabled to minimize battery drain. During shutdown, the load is completely disconnected from the battery. The device is packaged in a 10-pin QFN PowerPAD™ package (DRC) measuring 3 mm x 3 mm.

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

PowerPAD is a trademark of Texas Instruments.

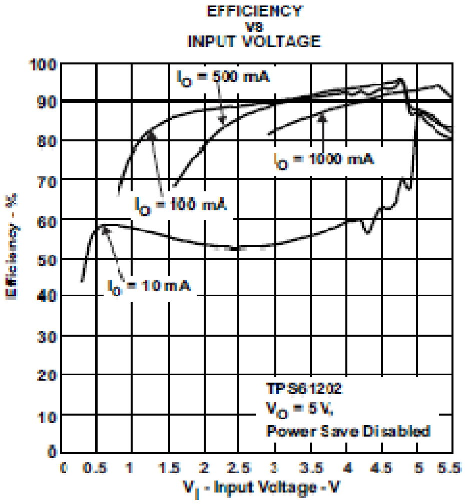


Figure 11.

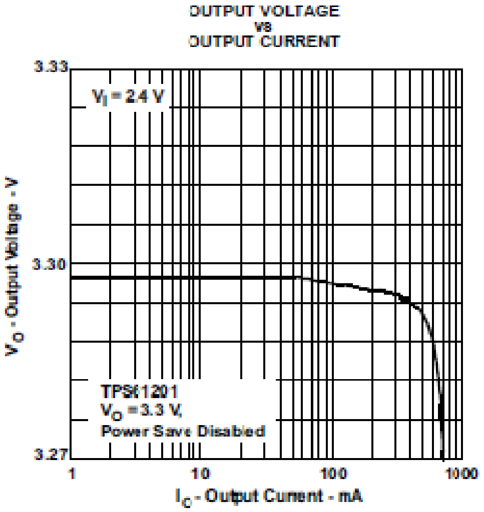
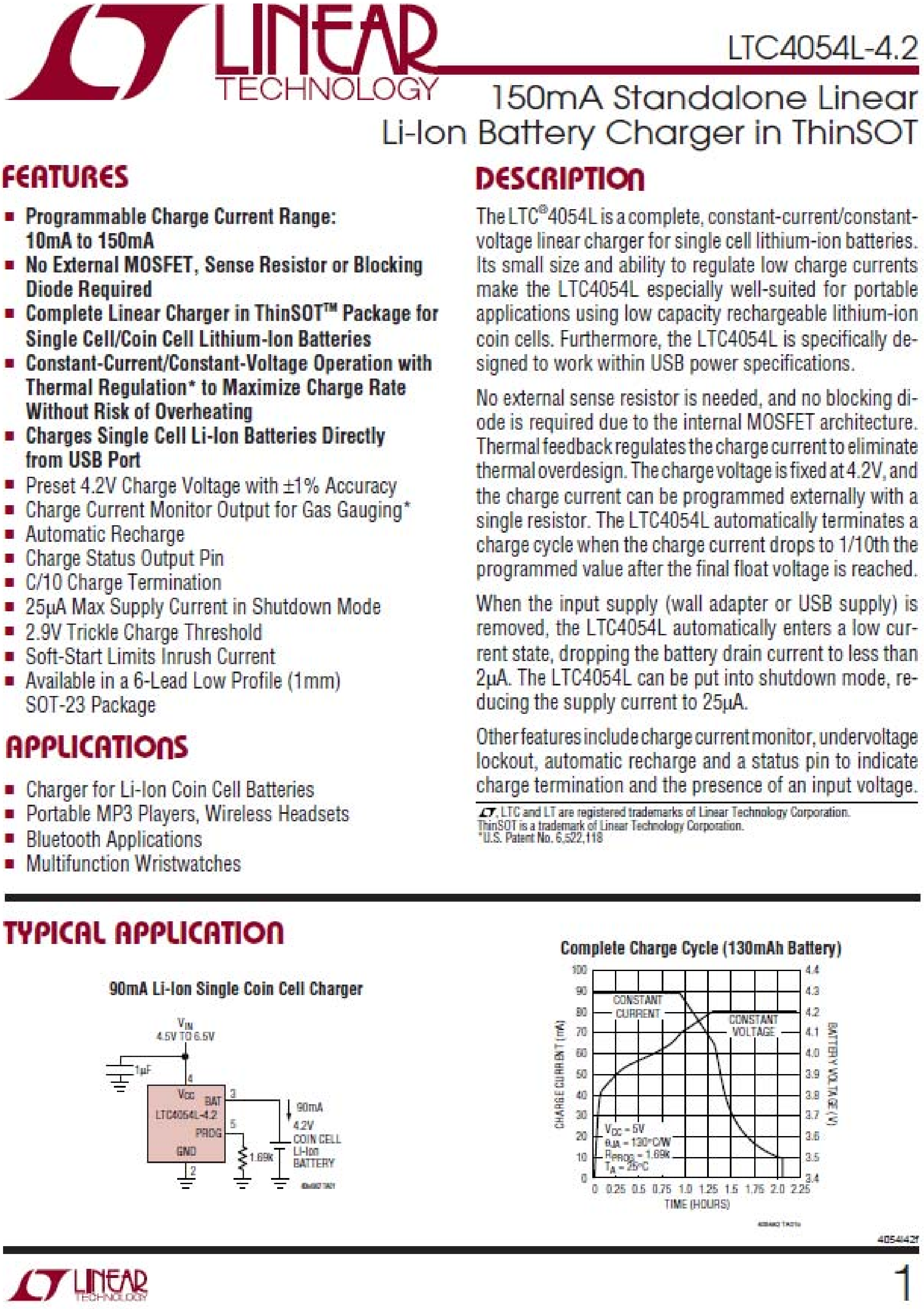


Figure 12.

14.13. Appendix M: Specification Sheet for Battery Charger



LTC4054L-4.2

150mA Standalone Linear Li-Ion Battery Charger in ThinSOT

FEATURES

- **Programmable Charge Current Range: 10mA to 150mA**
- **No External MOSFET, Sense Resistor or Blocking Diode Required**
- **Complete Linear Charger in ThinSOT™ Package for Single Cell/Coin Cell Lithium-Ion Batteries**
- **Constant-Current/Constant-Voltage Operation with Thermal Regulation* to Maximize Charge Rate Without Risk of Overheating**
- **Charges Single Cell Li-Ion Batteries Directly from USB Port**
- Preset 4.2V Charge Voltage with ±1% Accuracy
- Charge Current Monitor Output for Gas Gauging*
- Automatic Recharge
- Charge Status Output Pin
- C/10 Charge Termination
- 25µA Max Supply Current in Shutdown Mode
- 2.9V Trickle Charge Threshold
- Soft-Start Limits Inrush Current
- Available in a 6-Lead Low Profile (1mm) SOT-23 Package

APPLICATIONS

- Charger for Li-Ion Coin Cell Batteries
- Portable MP3 Players, Wireless Headsets
- Bluetooth Applications
- Multifunction Wristwatches

DESCRIPTION

The LTC®4054L is a complete, constant-current/constant-voltage linear charger for single cell lithium-ion batteries. Its small size and ability to regulate low charge currents make the LTC4054L especially well-suited for portable applications using low capacity rechargeable lithium-ion coin cells. Furthermore, the LTC4054L is specifically designed to work within USB power specifications.

No external sense resistor is needed, and no blocking diode is required due to the internal MOSFET architecture. Thermal feedback regulates the charge current to eliminate thermal overdesign. The charge voltage is fixed at 4.2V, and the charge current can be programmed externally with a single resistor. The LTC4054L automatically terminates a charge cycle when the charge current drops to 1/10th the programmed value after the final float voltage is reached.

When the input supply (wall adapter or USB supply) is removed, the LTC4054L automatically enters a low current state, dropping the battery drain current to less than 2µA. The LTC4054L can be put into shutdown mode, reducing the supply current to 25µA.

Other features include charge current monitor, undervoltage lockout, automatic recharge and a status pin to indicate charge termination and the presence of an input voltage.

LT, LTC and LT are registered trademarks of Linear Technology Corporation.
ThinSOT is a trademark of Linear Technology Corporation.
*U.S. Patent No. 6,522,118

TYPICAL APPLICATION

90mA Li-Ion Single Coin Cell Charger

Complete Charge Cycle (130mAh Battery)

4054l42f

1

14.14. Appendix N: Fuel Cell Trade Study

There are limited numbers of companies making DMFCs to be sold for retail. Five potential options for a suitable DMFC are listed, described, and pictured. Comments are given as to the viability of each product with respect to our project.

1) **Parker TekStak – Price: $199 (one cell)**

Our team has determined that this product is the most suitable for our project. The key factor is its power output. In ideal conditions, one cell can produce up to 1W, and has a maximum potential of 0.75V. Our calculations (based on the power curve graph given in the description) show that the cell can produce about 480mW at 0.3V (the lowest acceptable input to the booster chip) which means that the cell can easily power the phone in standby mode with extra power to charge the battery. The other key feature is that it is designed to be simple to assemble and operate and it comes with a detailed instruction manual and DVD. This is helpful because we need to be able to familiarize ourselves with the technology as quickly as possible in order to stay on track to meet key milestones. Drawbacks include that the fuel cell is bulky, and that it requires both a fuel circulation pump and an air pump.

Figure N.1: Parker TekStak DMFC

2) **Educational DMFC Set – Price: $524.76**

The maximum power output for this product is 50mW, meaning that between 2-4 of these fuel cells would need to be connected in order to meet the power needs for the cell phone and battery charger, which would place this option well beyond a reasonable budget for this project. The key feature, however, is that fuel is gravity-fed into the cell, eliminating the need for a fuel pump.

Figure N.2: Educational DMFC set

3) **DMFC Set – Price: $90.16**

This product operates with a simple design similar to option (2) however, this is a smaller version with a maximum power of 10mW, making it too small for our purposes.

Figure N.3: DMFC set

4) **Dr. Fuel Cell Science Kit – Price: $622.00 or FC only for $121.00**

This is an interesting option, as the DMFC comes as part of a complete fuel cell laboratory kit, which includes testing equipment as well as a hydrogen fuel cell. Most of the kit's contents is not of value to us, as our access to the University's labs is adequate. The DMFC can be purchased alone, however, and it produces up to 100mW. Two of these fuel cells would be required to meet power needs, but even a single cell's size is too bulky for our application.

Figure N.4: Dr. Fuel cell science kit

5) **Fuel Cell Hardware- Price: $1895.00**

The last option is a set of hardware that allows the user to test different Membrane Electrode Assemblies (MEAs) and does not come with an MEA, meaning one would need to be purchased from a supplier or constructed by the user. This kit is simply too pricey and would require extra time and attention just to get a DMFC operational.

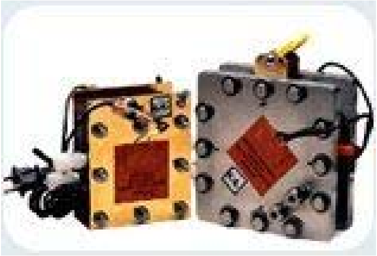
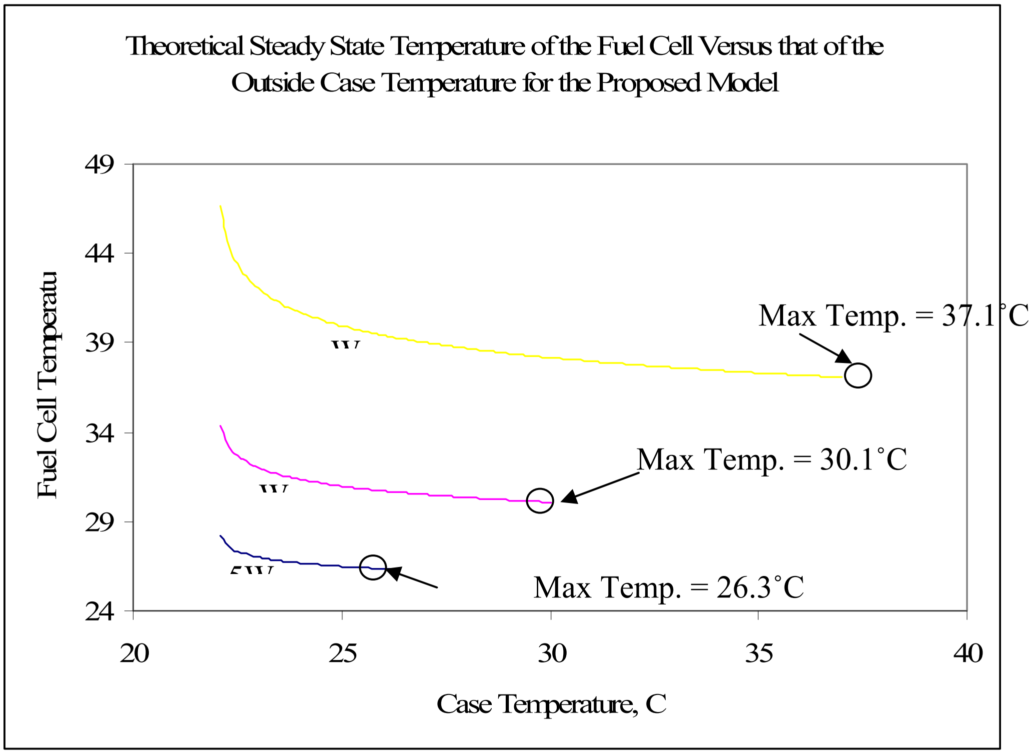


Figure N.5: Fuel cell hardware

14.15. Appendix O: Fuel and air pump specifications:

Part Number	Product Description	Maximum Supply Voltage (VDC)	Maximum Flow Rate (Free Flow)	Maximum Continuous Operating Pressure (psi)
TEK-AP-301	Air pump kit- for use with DM & HP stacks	12	2 LPM	15
TEK-LP-401	Liquid pump kit- for use with DM stacks	6	80 mL/min	9

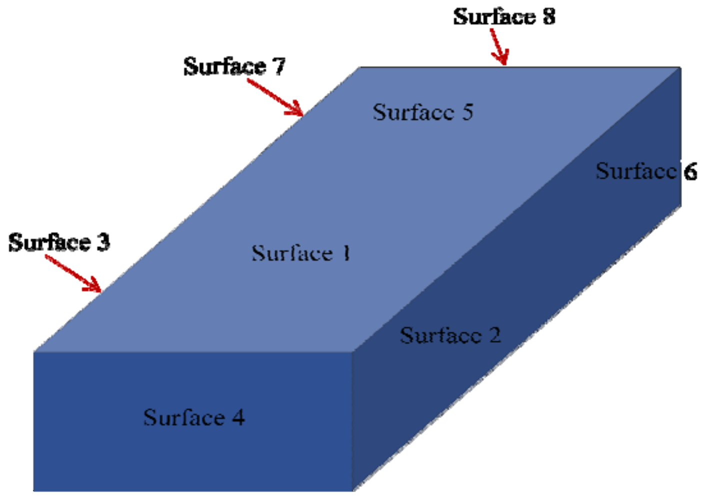
14.16. Appendix P: Heat Package Theoretical Model

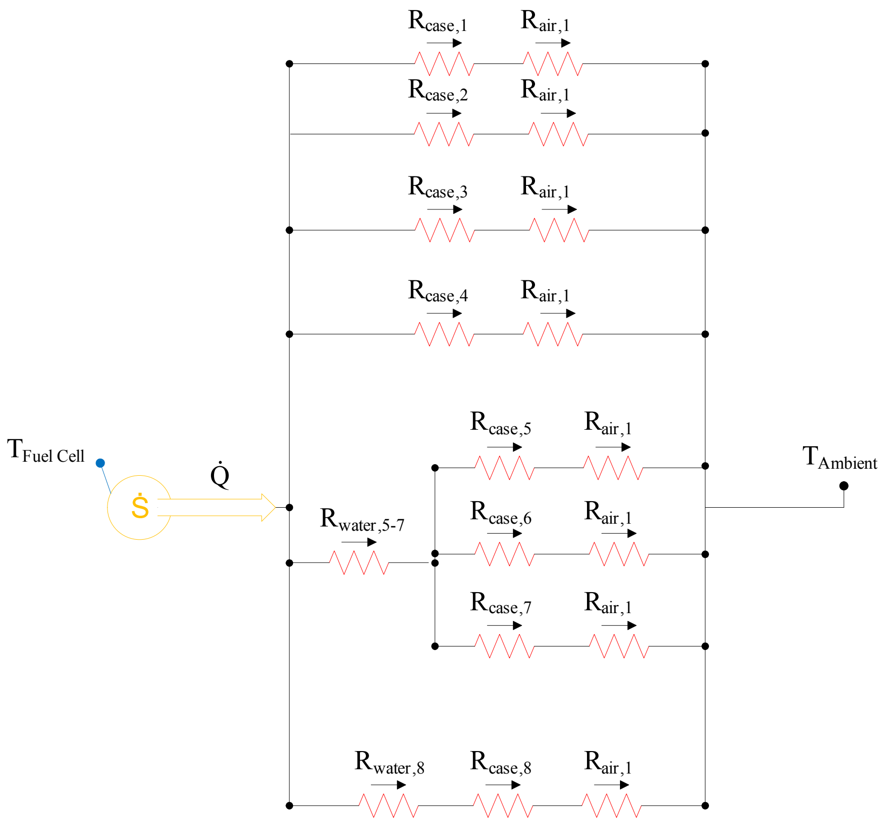


14.17. Appendix Q: Heat Package Testing Experimental Results

Test	Steady State Temperature			Time Required [Min]
	Inside [˚C]	Outside [˚C]	Ambient [˚C]	
0.5W	26.6	26.5	23	50
1W	30	30	23.6	90
2W	32.6	36.4	22.5	55
3W	47	58	22	90
1W Insulated	43.5	40.2	22.9	120
1W Cold	4.6	3.4	3.4	110

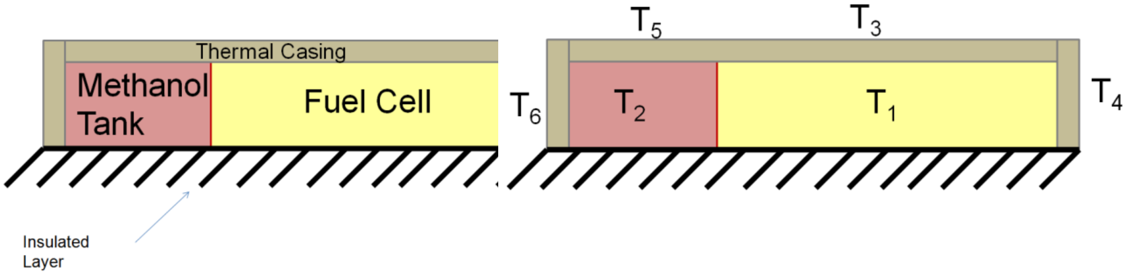
14.18. Appendix R: Heat Packaging Thermal Resistance Layout





14.19. Appendix S: Heat Transfer Analysis

Simplistic 2-Dimensional Model



Conductance Heat Flow

Thermal Conductance

$$\dot{Q} = \frac{(T_1 - T_2)}{R_{Sum}}$$

Resistance for Thermal Buoyant Flow

$$R_i = \frac{L_i * \langle Nu \rangle}{A_{k,i} * k_i}$$

Rayleigh Number

$$Ra_L = \frac{g B_f (T_s - T_{f,\infty}) L^3}{\nu_f \alpha_f}$$

Prandtl Number Dependence

$$a_1 = \frac{4}{3} \frac{0.503}{[1 + (0.492/Pr)^{9/16}]^{4/9}}$$

Resistance for Conducting Material

$$R_i = \frac{L_i}{A_{k,i} * k_i}$$

Nusselt Number, Vertical Plate Thermal Buoyant Flow

$$\langle Nu \rangle = \frac{2.8}{\ln[1 + 2.8/(a_1 {Ra_L}^{1/4})]}$$

Nusselt Number, Horizontal Plate Thermal Buoyant Flow

$$\langle Nu \rangle = \frac{1.4}{\ln[1 + 1.4/(0.835 * a_1 {Ra_L}^{1/4})]}$$

Constants:

$\dot{Q}$ = heat transfer rate = 1.3 W
k_{air} = thermal conductance of air = 0.025 W/m*K
k_{case} = thermal conductance of the case = 0.201 W/m*K
Pr = Prandlt number = 0.69
B_f = 3.426E-3 1/K
ν_f = 15.66E-6 m^2/s
α_f = 22.57E-6 m^2/s
$T_{f,\infty}$ = 22ºC

Air Flow Analysis

$$N_{oxygen} = \lambda * {}^{1}/_{x_0} * {}^{I_{el}}/_{4F}$$

$$I_{el} = 6F * N_{MeOH}$$

N_{MeOH} = Molar consumption rate of Methanol
N_{oxygen} = Molar consumption rate of Oxygen
x_0 = percentage of oxygen in air = 21%

F = 96,485.3415 s*A/mol
λ = 2
Oxygen molar mass*N_{oxygen} = $\dot{m}$
$\dot{m} = \rho A v$ = mass flow rate
ρ = density of air = 1.2E-3 g/cm^3
A = area of inlets = 0.93 cm^2

Fluid Stream Heat Loss
$Re_L = \frac{u_{f,\infty} L}{\nu_f}$ = Reynolds number

$$\langle Nu \rangle = 0.664\, {Re_L}^{1/4} Pr^{1/3}$$