Final Report

HARNESSING WASTE ENERGY FROM HUMAN MOTION

MECHENG 450 SEC 003
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ABSTRACT

The demand for portable power for mobile devices in today's world has been increasing. Often times these devices must be recharged in places where it may be inconvenient or impossible to do so. Recent products in the market harness the waste energy from walking or running to generate power. This energy can be used to supplement battery-powered devices, or to charge a backup battery while the primary unit is in use. This project will improve upon the existing products to produce a lightweight, user-friendly device that will generate 5 Watts of power.

EXECIUTIVE SUMAMRY

Harris Corporation is interested in an eco-friendly device that can employ human energy to generate over 5 Watts of power. Specifically, we must identify and prototype a technology that can satisfy these criteria as passively and efficiently as possible for application in powering portable devices. Our goal is to engineer this product to produce clean electricity in a manner that is safe, reliable and consistent. The solution will be packaged so it is comfortable and easy to operate for the user with little extra effort exerted.

To achieve these customer requirements, we have minimize the weight, temperature, sharp and moving parts; while maximizing power generated and energy storage capacity. The important engineering specifications are to use less than 10 percent extra metabolic energy per electrical output and to maintain a surface temperature of less than 50 degrees Celsius. The weight of the device must be less than 2 kg for limbs and 6 kg for one's frame. In addition to outputting 5 Watts of power, the device needs an energy storage capacity of 2.5 Watt-hours.

To accomplish these tasks our team will have to overcome many challenges. To generate the requested power while meeting the size and weight constraints, it will require the ability to balance these competing agendas. Also, many of the components involved in harnessing energy are outside classical mechanical engineering. Time and cost will also present issues within the project.

Our current design uses an array of electromagnetic generators, each approximately 9 in long and 1.9 in diameter. Moreover, each device will be integrated into the soldier's equipment using all-purpose lightweight individual carrying equipment (ALICE) clips. Our engineering analysis on this design shows ability to meet all customer and engineering specifications. Modeling shows that the device can potentially produce up to 1.2 Watts per canister. The final prototype's system is completely module. The user can wear multiple canisters to meet their individual power needs.

With our present efficiency of the final prototype, we were able to generate .2 watts per canister. The black box charging system is able to store and deliver the energy as needed. The system can deliver the customer requirement of 5 Watts after the battery gets charged over time. However, further optimization of the circuitry and mechanical components are necessary to generate this power requirement instantaneously.

TABLE OF CONTENTS

1 INTRODUCTION

Harris Corporation, the sponsor of this project, is a developer and producer of communications and information processing equipment for use by the U.S department of defense and other government agencies. Harris has requested that we design and prototype a device which harnesses waste energy from human motion. Such a device could be used meet the power needs of Harris's portable electronic systems.

Currently soldiers depend heavily on electronic devices, such as communication equipment, and must carry large loads of batteries to power all of these systems. A typical soldier may carry up to 10 kg of batteries for a five-day mission. There are a variety of similar technologies, which harness waste energy from human motion, however these technologies are either still in development or are not adequate to meet our consumers needs [1-3].

The purpose of this project is to design and prototype a device that produces at least 5 Watts, and has a minimal user interference with an acceptable weight. Furthermore, the device should safely generate power from wasted human energy while minimizing metabolic cost from user (a complete ranking of the customer requirements developed with Harris Corporation is illustrated in Table 1 of the following section). If the device is successful, we will have improved the ease of the soldier's duties by eliminating excess weight from batteries they must carry. They will not have to gauge the amount of batteries to bring when going on missions of indeterminate length. Also the impact on the environment may be reduced through use of wasted human energy.

The final prototype is a hip worn linear electromagnetic generator. It demonstrates the capability to achieve all specifications requested after further optimization is conducted.

2 INFORMATION SOURCES

Since Design Review 1, we have generated many new concept designs for harnessing waste energy from walking (Appendix D). For each of these designs, we reviewed relevant literature in order to determine preliminary go or no-go design evaluation. The resulting 'go' design concepts fall into four main process methods: thermal, vertical oscillations, pendulum oscillations, impacts, and bending of joints. We have performed an in depth literature review for each of these harvesting methods in order to better understand and evaluate our preliminary designs. Of these modes of energy generation we have down selected to our Alpha Design which captures energy from vertical oscillations using electromagnetism.

We evaluated the differing mechanisms to harness waste energy and have identified benchmark systems from each category that we plan to improve upon. Of these three systems, damping vertical motion has the capability to produce the highest power output, but is dependent on a heavy system. Harnessing energy from impacts as well as thermal gradients does not appear to meet our power requirements.

2.1 Energy from Stress inducing Impacts

Harnessing energy from impacts is done through use of piezoelectric materials which create electric potentials in response to mechanical stress. These systems tend to be extremely lightweight, but unfortunately they typically generate low power and have complex electrical circuitry. Our benchmark device utilizes piezoelectric material in the heel of a shoe [3]. The energy is generated by dissipating the stresses in the shoe caused by each heel strike. This device is capable of delivering up to 2 mW while weighing an additional 28 g and having an additional volume of 40 cm^3. Currently, there is no energy storage built into the system.

2.2 Energy from Vertical Oscillations

Energy from vertical motions is harnessed by damping 'bouncing' oscillations that are created when walking [10]. The energy is typically gathered from loading and unloading a spring or from electric fields generated from an oscillating magnet. Our benchmark device is a backpack in which the load compartment freely oscillates on a rigid frame [2]. This device is capable of delivering up to 5-20 W with a load of 18-36 kg, however the additional weight of the device is only 6 kg and the additional volume is 2500 cm^3, compared to an average military backpack. There is no energy storage device built into the system.

2.3 Energy from Regenerative Breaking in Joints

Energy from joint motion is harnessed by the deceleration of the limbs, similar to regenerative breaking. Our benchmark device is a knee brace in which the waste energy is gathered in the straightening of one's leg, just before impact with the ground [1]. This device is capable of generating up to 3.5 W per knee while weighing an additional 1.6 kg and having an additional volume of 500 cm^3. There is no energy storage device built into the system.

2.4 Energy from Thermo Gradients

Energy from thermal gradients is harness by a difference in two metals that are bonded together. The metals experience a voltage difference when a temperature change is introduced between the two metals. Our benchmarked device is an experimental device for a car exhaust system and waste heat energy is dissipated through the tailpipe [8]. The device used during the calculation was able to output a power value of 300 Watts during normal cycling of the motor at a temperature difference of 100 degrees Celsius. Typical thermoelectric generators have low efficiencies, only harnessing 5-10% of the exhaust energy [7, 8]. Temperature gradients from the body to the ambient were determined to be insufficient for our application.

Gaps currently exist in the information available from our vertical oscillations benchmarking and our alpha design concept. We benchmarked a suspended load backpack which has a much larger spring mass damper system than our intended use. In order to shorten the gap between our knowledge and a final working prototype we simulated our mechanical system and electrical system separately to isolate each to determine estimated power potential. We will be talking to Professor Ulsoy at the University of Michigan in order to accurately model our mechanical system. We will also consult John Baker in order to further our knowledge of modeling electrical systems.

3 ENGINEERING SPECIFICATIONS

In this section, we present the customer requirements and corresponding engineering specifications. The customer requirements were given an importance rating in accordance with our sponsor. We set target values to our engineering specifications based on literature research and have confirmed these with our sponsor.

3.1 Customer Requirements

The target consumer, a Military soldier, requests a device that will harness waste energy from walking and convert the energy to electricity to be used immediately or be stored for later use. More specifically, the device must be able to reliably output 5 Watts of power, have a low amount of user interference, and be easy to operate. We developed a working set of consumer requirements, which are summarized in Table 3.1 (page 3). The consumer requirements were developed with our sponsor, who has a thorough understanding of the Military's needs. We rated the importance of each requirement on a scale of 1-10, with 10 being the most important and 1 being the least important. In our rating, safety and power output were determined to be most important, ease of operation and comfort were rated somewhat important, and cost and appearance were of lesser importance for our target consumer.

Table 3.1: Consumer Requirements rated in order of importance

Consumer Requirements	**Importance Rating (1-10)**
Safe to use	10
Generate and convert consistent power	10
High power delivered	10
Reliable	9
Easy to operate	7
Low excess effort required	6
Weight is acceptable	6
Size is acceptable	5
Comfort is acceptable	4
Cost is acceptable	4
Appearance is acceptable	3

3.2 Engineering Targets

In this section, we present the engineering specifications we developed from the consumer requirements. The engineering specifications were evaluated against the consumer requirements in a Quality Function Deployment (QFD, Appendix A) in order to better understand correlations and importance ratings. Furthermore, the QFD was used to benchmark existing waste energy recovery technology. This section also presents justifications for the engineering specification target values, which were based on in depth literature review and discussion with our sponsor.

Quality function deployment (QFD): The QFD links the amount of influence that each quantified engineering specifications has on each customer requirement by inputting values of 1, 3, or 9 in the relation matrix, with 9 representing the strongest relationship, 3 representing a moderate relationship, 1 representing a small relationship, and an open cell denoting no relation. After calculating the importance rating, we found that the most important engineering specification is the amount of power generated, and a target value for the minimal power output was assigned by Harris to be 5 Watts. The second most important specification was determined to be the weight. The weight supported at the core and the limbs should be limited so that the user is comfortable in wearing the device and also ensure that it doesn't cause any physical injuries to the user.

The roof of the QFD shows the correlation between the engineering specifications, where double positive (+ +) represents a strong positive correlation, single positive (+) somewhat positively correlated, single negative (-) somewhat negatively correlated, double negative (- -) signifying a strong negative correlation between the specifications, and a blank representing no correlation. We found a strong negative correlation between the high power output and the low weight specifications. We need to make sure to keep the device relatively low-weighted and still have it able to generate enough power. This will be one of the most important challenges for us. The QFD is shown in Appendix A.

Once the engineering specifications were ranked, we assigned target values to each specification in order to meet the customer requirements. These target values were determined from our correspondence with our sponsor, Harris Corporation. For our final product, we aim to meet all of these specifications and the target values we set. The engineering specifications with their ranking and the target values are summarized in Table 3.2 (page 4).

Table 3.2: Engineering Specifications ranked based on the QFD

Engineering Specification	Rank	Target
Power delivered [W]	1	=> 5
Weight supported by core [kg]	2	< 6
Weight supported by limbs [kg]	2	< 2
Energy storage capacity [Watt-hours]	3	2.5
Max surface temperature [^{o}C]	4	50
Percent of additional energy required to operate [%]	5	< 10
Number of sharp or pinching parts [#]	6	0
Volume displacement [cm^{3}]	7	< 400
Number of moving parts [#]	8	10
Time required for setup [sec]	9	30
Number of adjustable size settings [#]	10	2
Curvature of edges [mm]	11	5
Cost of materials [$]	12	30

Power delivered: The output power of the device is crucial to the success of the device and consumer satisfaction. The target value of 5 Watts is a fixed specification required by the sponsor. Although no research or engineering analysis was used in determining the 5 Watt requirement, the feasibility of achieving this specification was thoroughly investigated. Previous research about harnessing waste energy from human motion has included devices such as regenerative knee braces [1], oscillating load backpacks [2], and impacts from shoe strikes [3]. The power output of these devices ranges from 0.0009 – 20 Watts [1-3]. We can see that an output of 5 Watts is among the higher power outputs of existing devices. As a point of reference, an average soldier walking at 3 mph would be expending 300 Watts of power [4].

Weight: The weight of the device has impacts on many of the consumer requirements, including comfort, safety and the excess energy required to use the device. The reasoning behind the 6 / 10 consumer importance rating for weight is that for a soldier, weight must be ‘acceptable’. On one hand, a soldier is expected to endure more inconveniences than an average person; however, it is important that those additional inconveniences will not affect the ability to perform necessary duties. Ideally, we would like to minimize the weight of the device; however, doing so may reduce the energy storage capacity and the power generation of the device. We determined two target specifications for weight, depending on the body location that will support the weight. The target values of less than 6 kg for a core supported device and less than 2 kg for an arm or leg supported device were provided by the sponsor. These weights also limit the additional energy required to operate to device, as discussed in the corresponding section.

Energy storage capacity: Built-in energy storage is important for achieving a reliable and high power output device. Having built-in energy storage will increase reliability because the user can save up power in the system to be used at a later time, when they may be unable to provide waste energy. Additionally, the built-in energy storage can increase power output capacities through variable charging and discharging rates. For example, the user could charge the device at a rate of 5 Watts and then discharge at a rate of 10 Watts for half the time spent charging (discounting efficiency losses). The target value of 2.5 Watt hours was determined from providing 5 Watts for 30 minutes.

Maximum surface temperature: A maximum temperature is necessary to prevent burns or unnecessary discomfort to the user. Additionally, temperature must be regulated to reduce damage to other equipment that could be caused by thermal fatigue and cycling. The maximum target surface temperature of 50 degrees Celsius was chosen to ensure the device will not burn the user on prolonged contact. Temperatures of 125 degrees Celsius will burn skin [5].

Percent of additional energy required to operate: Our sponsor has requested that the energy harnessing process should be passive. We define the percent of additional energy required to operate the device as:

$$\%\,Additional\ Energy = \frac{E_{on} - E_{off}}{E_{off}} \cdot 100\% \qquad \text{Eq. 1}$$

Where, E_{on} is the energy required performing some action with the device and E_{off} is the energy required to perform some action without the device. We determined the target percent additional energy to be less than 10%. From this definition of efficiency, we take into account the energy required to carry the extra weight of the device. The target of 10% was determined from the energy required to carry additional weight plus direct interference with the user (i.e. additional energy required to bend a knee brace). A soldier carrying 6 kg of additional weight may expend up to 8% additional energy [4], which is less than our target value of 10%. Further testing on metabolic cost per electric output is needed to quantify efficiency per user effort.

Volume displacement: Our sponsor has informed us that the device should not be bulky or interfere in the wide range of motion that a soldier must be able to perform. Together we have related this requirement into a size requirement. The target value of 400 cm^3 is the maximum volume displacement the device should occupy – in a single location. However, if the displacement is well spread out, this target may be surpassed.

Additional safety measures: In addition to temperature, we have identified three additional engineering specifications that help quantify the safety of the device. It is important that the device have no exposed parts that are flanged or pinching. This is necessary to ensure the device does not harm the user or snag on the surrounding environment. Secondly, a minimum radius for all edges has been targeted to 5mm to ensure that there are no sharp surfaces. Third, the device should be adjustable to users of different sizes. Ensuring proper fitting can prevent strains due to over stretching of the material as well as excessive bouncing or snagged parts due to a loose fit.

3.3 Environmental Considerations

Here we present a brief overview of the environmental engineering considerations as outlined by the United States Department of Defense in MIL-STD-810G [6]. More in-depth considerations are located in Appendix B. It is not intended that the prototype created by this design team will meet all of these environmental specifications, rather this section will outline the tailoring guidelines that we considered when determining an Alpha Design. We will determine which test procedures will be necessary for the personal device to be worn by a soldier. Additionally, we provide detailed analysis regarding the further improvements that must be made to this proof of concept in order to meet the environmental standards set forth by the U.S. Department of Defense in the Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [6]. A detailed review of the environmental considerations is shown in Appendix B. Note: all method and procedure numbers mentioned in this section refer directly to the corresponding sections in U.S. Department of Defense in the Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [6].

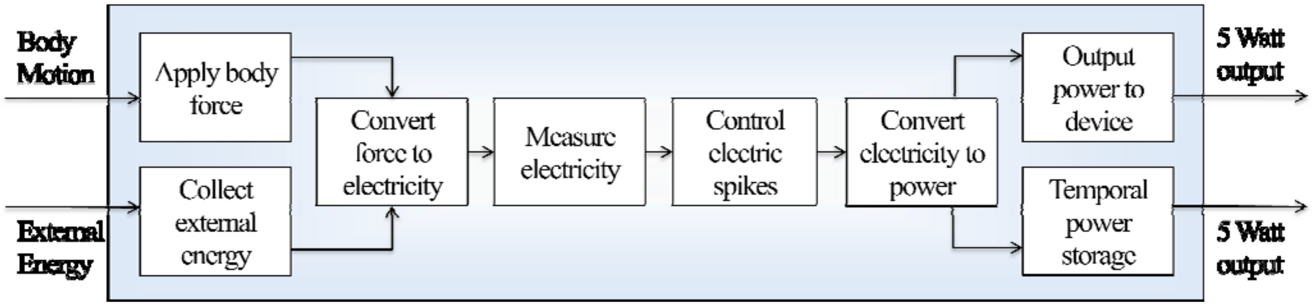
4 CONCEPT GENERATION

In this section, we will present the general steps of our concept generation. After a sufficient amount of literature search and consulting with our sponsor about our project, we continued with our concept generation process by creating a functional decomposition, conducting brainstorming sessions, constructing a concept classification tree, and finally considering combinations of ideas in a combination table. Further literature search and analysis were done in order to determine the feasibility of each design.

4.1 Functional Decomposition

In the process of concept generation, we first generated an outline (Appendix C) of tasks to complete for the project. Then a functional decomposition was created to identify the necessary functions to meet our problem description: to generate and deliver 5 Watts using wasted human energy. The functional decomposition let us identify and understand the functional relationships that we need to consider for the brainstorming sessions. We can see from functional decomposition block diagram (Figure 4.1), that our function inputs a body motion and external energy outputs 5 Watts of power through generating and converting energy. The main objectives of the functional decomposition are to convert the input mechanical/kinetic energy to an electrical force. Then we want to convert this electrical force into a controlled functional medium for storage or direct application.

Figure 4.1: Functional decomposition block diagram



4.2 Individual Brainstorming

In our individual brainstorming session, each member in the team came-up with 10 original ideas of possible energy sources and devices to harness the energy that satisfies the functions defined in the functional decomposition. We avoided including the already-existing devices in our list of 10. Individual brainstorming was done with no restrictions or bias views against existing and nonexistent technologies. All ideas were to be kept even if it seemed to be unfeasible in its first look. The generated ideas were summarized in a list, and a total of 40 ideas were taken into a group brainstorming session to discuss.

4.3 Group Brainstorming

The individual ideas were taken into group discussion to further understand the concept of each design and to generate a specific image on how it works. Sketches and a brief description of the function of the various ideas were generated, summarized in Appendix D. Each idea was reviewed with our sponsor, Harris Corporation, to get consumer feedback and to clarify any ambiguous ideas or technologies.

These ideas were sorted into different categories of energy sources. Some possible energy sources from the human body included sound from talking, oscillation and vibration from walking movement, stress, static friction, and temperature difference. External energies such as the wind and the sun were also considered in our brainstorming ideas. These ideas were further investigated with additional literature search in ambiguous areas as candidates for our alpha design.

4.4 Brainstorming Results and Possible Technologies

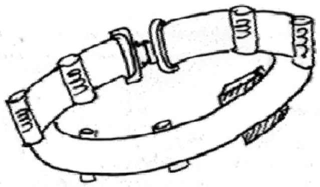
From our literature search, four main fields of technology were identified: electromagnetic, biomechanical, piezoelectric, and thermoelectric [1-3]. In this section, we will present our top candidate ideas for each field of technology and a design using a combination of the electromagnetic and piezoelectric technology.

Electromagnetic: The electromagnetic system uses the idea of electromagnetic inductance to generate power. Our "belt" idea that uses the electromagnetic system consists of little canisters that contain a magnet and copper wire coils to create changes in magnetic flux. The general schematic of this idea is shown in Figure 4.2 below.

Figure 4.2: One canister of the belt concept using the electromagnetic technology

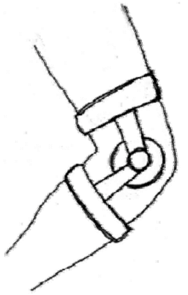
The magnet, attached to springs oscillates vertically during walking, which would produce change in magnetic flux when it is passes through the copper coils. The possible spikes created from fast oscillations during running or jumping would be collected at the capacitor and rectifier system, and then stored in the battery. The belt design would use several of these canisters to generate enough power to meet the requirements, as shown in Figure 4.3.

Figure 4.3: Belt design consists of several canisters



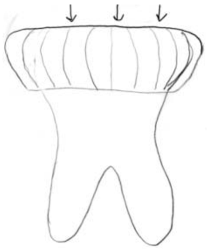
Biomechanical: The knee brace uses the energy generated from the wasted energy in the leg while walking. The knee brace will have a 'regenerative brake' (torsional spring) attached to the knee. The regenerative brake would collect the kinetic energy generated after swinging the leg forward when taking steps. The kinetic energy would be stored and converted into electrical energy in a generator to deliver power. Figure 4.4 shows the general idea of the knee brace design.

Figure 4.4: Knee brace with torque generator



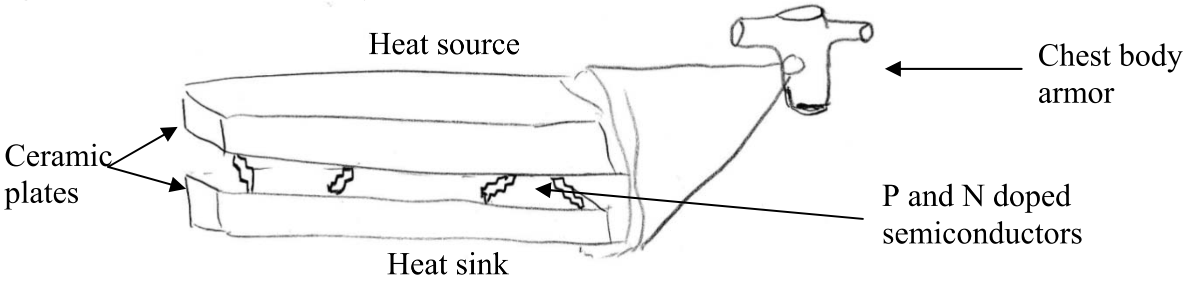
Piezoelectric: One idea we had using the piezoelectric effect is the piezoelectric tooth cap. This tooth cap is made of piezoelectric material, covered with some kind of material that would secure safety when it's placed in the mouth. The piezoelectric material generates an electric field in response to an applied mechanical stress. The stress applied from chewing and talking would generate some voltages, which would be converted into power. A drawing of the piezoelectric tooth cap is shown in Figure 4.5.

Figure 4.5: Piezoelectric tooth cap



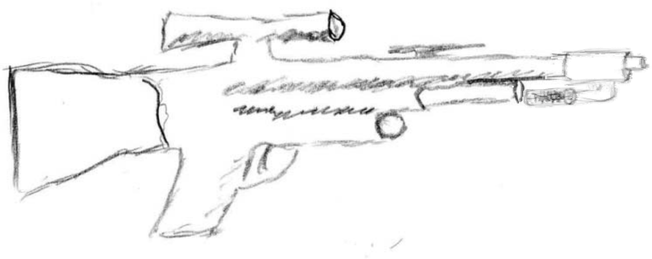
Thermoelectric: Our body suite with fin idea consists of fins that go out from the chest into the ambient to harvest human core heat energy. The thermoelectric suite with fins uses the idea of the Seebeck effect. The temperature difference of the human body and the ambient temperature creates an electric potential, which converts into electric power. Sketch of the thermoelectric body suite is shown in Figure 4.6.

Figure 4.6: Thermoelectric body armor



Electromagnetic and piezoelectric combined: Our gunshot generator idea combines the electromagnetic and piezoelectric technologies to generate power from the wasted energy in a gunshot. This device would be divided into two parts; one is the electromagnetic system attached to the silencer and the other is the piezoelectric system on the shoulder pad. The silencer system, shown in Figure 4.7, has a tube connected for the air gust to escape into the electromagnetic system to generate power. The force from air gust would create oscillations.

Figure 4.7: Electromagnetic gun silencer



The shoulder pad, shown in Figure 4.8, would collect the mechanical stress applied from the impact from the gunshots, and generate power using the piezoelectric effect. Piezoelectric material would be implemented in the shoulder pad where the gun will be in touch with the body.

Figure 4.8: Piezoelectric shoulder pad

4.5 Concept Classification Tree

The concept classification tree shows the breakdown of the possible human body movements that can create energy, and the matching technologies to harvest those energies. The concept classification tee was used to identify the possible technologies for different energy sources from the human body movement. First, human movements with a potential of generating wasted energy were listed as talking, eating, and walking. We also included external energy such as the wind or the sun. From each movement, we identified the energy sources, and matched the technologies that can be used to harness the generated kinetic/external energy to electrical energy. From the concept classification tree, we found that the walking movement has the most potential to generate energy, and the piezoelectric technology has the most potential to generate power from the various energy sources from the human body. The concept classification tree is shown in Figure 4.9.

Figure 4.9: Concept classification tree identified 4 major fields of technology to use

4.6 Combination Table

The combination table shows the possible combinations of ideas that we have come-up with. For example, our idea of harvesting energy from a gunshot uses the combination of the external energy applied to the body and human motion specific to our target customer. Stress, sound and vibration for the energy source, and the piezoelectric and electromagnetic technologies were the combination for the gunshot idea. The combination table lets us to identify any possible combinations that we may have missed or overlooked in our brainstorming sessions. The combination table is shown in Figure 4.10.

Figure 4.10: Combination table

5 CONCEPT SELECTION PROCESS

In this section, we will provide our down selecting process and methods for the alpha design. Literature search, benchmarking, and calculations were performed to determine the feasibility of each field of technology and design ideas. The 40 generated design ideas were assessed first by a go/no-go basis, and then, the ideas left were compared and assessed using Pugh charts.

5.1 Technology Down Selection

We ranked our concepts generated during the brainstorm into 4 main areas of power generation: electromagnetism, biomechanical, piezoelectric, and thermoelectric. These methods were then tested for feasibility of energy generation based off the best-case scenario with 100% efficiency.

We calculated our power values for the different methods either by using benchmarking or using generalized calculation. For the calculation of electromagnetism in the belt idea, we used Faraday's law along with Ohm's law. This produced a power output of about 1.2 Watts per device considering 100% efficiency. The biomechanical knee device was benchmarked, and found to produce 7 Watts while walking with devices attached to both knees [1]. For our piezoelectric power output, we also used a benchmark from a study done which was only able to create 0.8 Watts per shoe [3]. For the thermoelectric calculation, we used the Seebeck coefficient of two common metals used in thermoelectric devices and our anticipated temperature difference across the metal. This gave an estimate power output of about 0.0009 Watts per device [8]. This makes it unfeasible to assume we would be able to create such a device.

From our literature search and benchmarking, we determined that the piezoelectric and thermoelectric energy generation methods would not produce enough electricity to meet our engineering specification of generating a minimum of 5 Watts. We therefore were able to remove those ideas from our alpha design candidate selection and focus on the biomechanical and electromagnetism systems for energy generation.

We also considered combinations of these devices in order to generate our requisite 5 Watts of output. However, combining concepts is very complicated to match voltage and current and would require bulky electronic components. Also many of our technologies don't produce even close to enough energy to supplement the other devices. Therefore we decided to use just one technology.

5.2 Pugh Chart

We created a Pugh chart using the remaining concepts from our brainstorm, specifically the knee torque generator, the belt with linear arrays of electromagnetic generators, the armband using a rocker magnet to converting arm swings to electricity, the suspended load backpack, the piezoelectric shoe, and the thermoelectric generator. We used the engineering specifications for our design criteria and weighted the criteria similar to our QFD (Appendix A). We then took our knee brace device as our datum or reference and compared the other designs to its effectiveness at meeting our criterion. We choose the knee device as our datum because of our familiarity with the device. From the datum, we compared our other concepts using a plus (+) and minus (-) system that ranged from triple plus (+++) to triple minus (---) depending on how much better or worse the device met the specification compared to the knee generator. The weighting was multiplied by the plus or minus dependent on the number of pluses or minuses, this was then tallied and given a score that was either higher or lower than the knee generator. The Pugh chart comparing the devices is shown in Appendix E.

5.2.1 Advantages and Disadvantages of Each Device

In this section, we will provide the details of each design assessed in the Pugh chart by stating the advantage and disadvantages of each device.

Knee device: The advantages of the knee device are the reliable power output and adjustability. The knee device has the ability to generate consistent energy from walking. Our benchmarked knee regenerative braking device [1] could generate up to 3.5 Watts per knee while walking in constant generation mode. The energy is generated using either the wasted energy at the end of waking motion or the entire swing of the knee. This lets the knee device adjust the amount of energy to be generated depending on the load of the charging devices. Disadvantages of the knee device are its comfort and the potential for failure. A knee device seizing in the field could have dangerous repercussions for the user. Although the knee device is relatively light so that it does not cause any significant strain to the leg or knee when walking, the placement of its weight could cause the user to fatigue faster than normal as well as cause a significant amount of discomfort. The device would also require wires running up the leg to power any device presenting packaging concerns.

Belt: The advantages of the belt device are that it is reliable, robust, simple, and adjustable. The power generated from the belt is adjustable by the module electromagnetic generators that can be added or removed from the belt based on the needs. The belt design with the electromagnetic generator is also reliable in generating consistent amount of energy from walking or running because a belt is able to be worn in virtually all conditions. The disadvantages of a belt device are that it could become bulky and heavy if the electromagnetic canisters were made too big, and the belt could be cumbersome to wear if it was too wide.

Armband: The advantages of the armband are its ease of installation and its low profile and weight. The armband has low interference with the user comfort, and it has the potential to generate the necessary amount of energy. The armband was calculated to be able to produce 5.3 Watts using both arms during walking. Our calculation of power generated during walking was obtained using equation 3 and equation 4 on page 19. Disadvantages of the system are its technical risks. While using electromagnetism to generate electricity, we would have to design a slider system to move the magnet through the coil. To the best of our knowledge, this has never been done and could have unforeseen pitfalls.

Backpack: Advantages of the backpack are its ability to generate massive amounts of energy dependent on load and oscillation. The backpack is also a well-documented technology that has been tested and proven to work. Our benchmarked backpack device was able to produce 5-20 Watts while walking with a 40-80 lb backpack at 3 mph [2]. The backpack itself does not weight 40-80 lbs, however this is the necessary total load a user must carry to generate 5-20 Watts. Disadvantages of such a system are the weight and bulkiness of the backpack. The benchmarked backpack required large weights, 40-80 lbs, in order for it to be functional and also required the user to alter his or her stride in order to accommodate for the energy generation device. The heavy-loaded backpack would not be comfortable and require excess effort to generate energy.

Shoe: Advantages of the shoe device are the weight characteristics and low profile. The device could be as simple as a shoe insert and would be potentially non-invasive. The shoe insert would not interfere with user comfort as well. Our benchmarked shoe device [3] was benchmarked to produce about 0.8 Watts per shoe. The disadvantage of the shoe is the low power output, which would not produce the specified 5 Watts with the shoe alone. Also, the technology isn't fully developed yet and we may have to do additional expensive research in order to implement the device in a shoe. The piezoelectric material is also cost inefficient.

Thermoelectric generator: Advantages of thermoelectric generators are that they require no motion to generate energy. Additionally, thermoelectric generators have no moving parts, which decrease the likelihood of failure of the device and injury to the user. The major disadvantages of thermoelectric generators are that they require large temperature gradients and provide a low power output [7, 8].

5.2.2 Technical Justification of Pugh Chart

After identifying the advantages and disadvantages of each device, we quantitatively evaluated the advantages and disadvantages of each system using Pugh charts (Appendix E). This section presents our justification of the ratings for each device.

Safety: For our safety criterion we felt that the placement of our systems on the belt, arm and back were all safer than the knee due to the risk of seizure of the knee device during combat. The shoe we felt had the same safety as the knee device due to submersion concerns. The thermoelectric generator was rated as a two minus mainly due to concerns over hyperthermia or overheating due to the energy harvesting mechanism.

Deliver 5 Watts while walking: For our 5 Watt consideration we predicted the belt and arm band using electromagnetism would be similar to the knee. The backpack was benchmarked to generate a much higher power output and therefore was given two pluses. Our shoe benchmark was significantly less than 5 Watts and was given three minuses. For the thermoelectric generator, we used the Seebeck constant difference and predicted temperature gradient to obtain our numbers for thermoelectric power and found it to be significantly less than 5 Watts for our uses.

Power reliability: For reliable power we took the belt and the armband to be slightly better because of the increased chance of generating energy due to a crawling movement. We felt the backpack and shoe would be similar to the knee due to the device not being weighted during a crawling motion. For the thermoelectric device, we gave it two pluses due to the steady power created due to heat transfer.

Technical risk: For technical risk we believe the knee torque generator, the belt, arm and backpack devices using electromagnets, and thermoelectric to be mature technology and gave them the same rating. Piezoelectric technology however is not nearly as readily available due to manufacturing and products on the market. For this reason we gave it two minuses.

Easy to operate: Ease of operation was rated based on installation basis and usability. We believed the belt to be slightly easier than the knee brace due to the fact you would already have to wear a belt and not a knee brace. For the armband, thermoelectric generator, and backpack we felt it would be the same as the knee brace due to the extra equipment needed to wear. The shoe was given a plus due to the necessity of shoes for walking. The size of the shoes needed for energy generation was also factored into the equation to determine ease of operation.

Low excess effort: Low excess effort was rated based on the extra energy required by the user to operate the equipment during energy generation. We felt the knee, belt, armband, and thermoelectric generator devices would all be similar in effort required due to minimal stresses exerted on the body. The backpack device was rated with one minus because it would have a significant increase in weight on the body due to the immense loads being carried.

Weight: The weight of the belt would be larger compared to knee device and gave it one minus. The armband is a similar profile to the knee and therefore we gave it the same rating as the knee. The backpack would be significantly heavier than all of the technologies due to the immense loads required to move it and we gave it three minuses. The shoe uses piezoelectric generation and would be integrated into a shoe maintaining almost the same weight. Therefore we gave it two pluses. The thermo generator would be of a comparable weight to the knee device.

Size: For size we felt that the knee and belt would be of a similar profile. We felt that the armband would smaller in comparison to the knee and gave it a one plus. The backpack is much bigger than a knee brace and a lot bulkier so we gave it two minuses. The shoe is of a similar size to the knee brace, and the thermoelectric generator would be bigger than the knee giving it a minus.

Comfort: Comfort was rated based off of perceived rubbing and feel. We felt that belt would be more comfortable to wear than the knee with less rubbing and gave it a plus. We thought the armband to be similar as far as feel to the knee. We gave the backpack, shoe and thermoelectric generator all minuses mainly due to strain on back and quicksand feel of a step. This would cause reduced feel and we gave them all a minus.

5.2.3 Best Candidate on Pugh Chart

From our Pugh charts (Appendix E) we determined the belt and armband devices to be the best option for our project to meet all our specifications. These were ranked to be the best candidates according to their versatility, energy generating ability, and low weight profiles. After evaluating these criteria, we decided to precede with prototyping the belt design based on the high rankings noted on the Pugh chart.

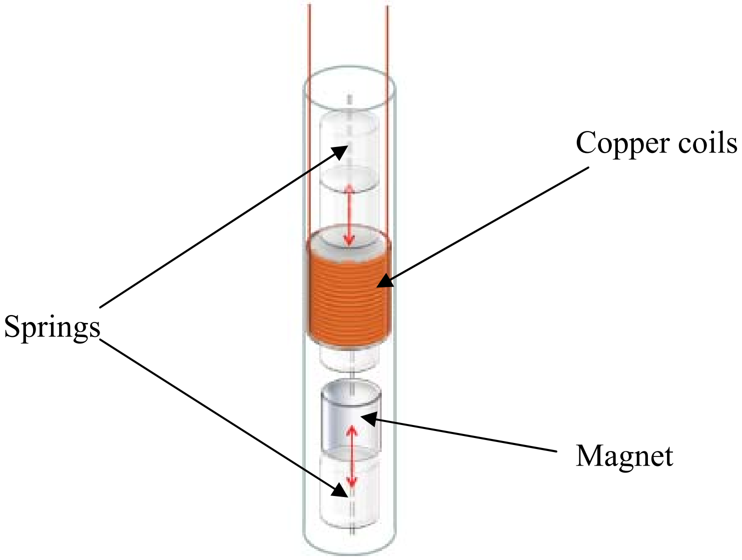
6 ALPHA DESIGN

After our down selection from the concept selection process, our Pugh charts led us to select the belt device as our alpha design. Our main mode of generating energy for the belt will be an electromagnetic device.

6.1 Belt Device Specifications

Our alpha design of a human powered generator is a modular belt with 11 cylindrical canisters, each roughly 23 cm in length and 3.8 cm in diameter. Each modular device will ideally produce 1.2 Watts walking at 3 mph at 2 Hz; however, these numbers are estimates of what our final design might look like based off our modeling. Each device in our prototype is assumed to deliver roughly 15% of its generated power to the battery after loses in resistance and circuitry and expected power is modified to an output of about 0.2 Watts. We modeled the generator for the belt using an average human natural frequency of 2 Hz while walking as well as an average hip displacement of about 5.08 cm [9]. This hip displacement was determined through experimentation and papers studying the motion of walking. The magnet used was a linear polarized magnet moving through a coil with 600 turns and a total of 6.5 Ohms of resistance. The estimated weight of the system is 4 kg in total with 5 canisters. Our equations shown for this calculation are shown in equation 3 and equation 4 on page 19. Figure 6.1 shows one of the electromagnetic power canisters with the magnet and the coils. The canisters will be attached to the belt using Alice clips. An Alice belt is the standard issue belt that a foot soldier will wear and designing to attach to it could reduce inventory a soldier would have to use.

Figure 6.1: Power Canister



The magnet is attached to springs at one end and oscillates through the coils creating change in magnetic flux. The wires are connected into a black box through the belt either with wiring. Please refer to the Engineering Analysis section, for more information about the electromagnetic generator.

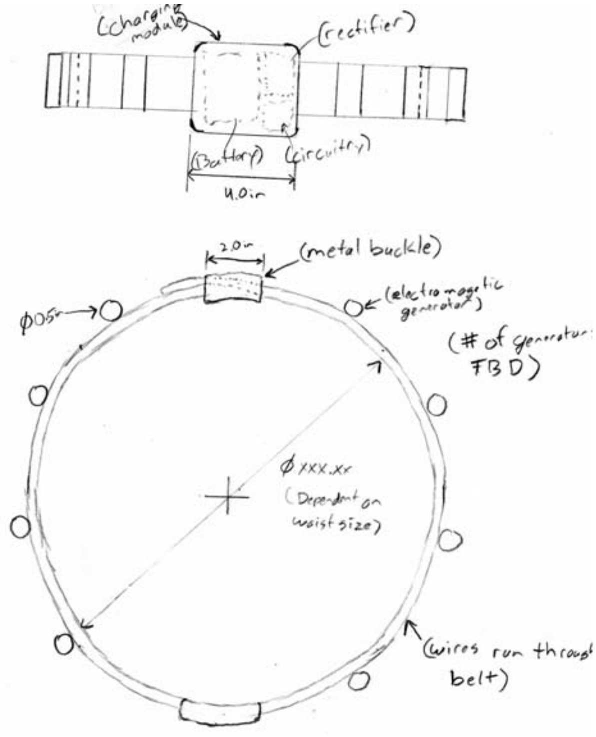
6.2 Functions and Corresponding Components

Our device harnesses energy by using the oscillating motion of walking. Walking provides a steady power output and can be modeled easily. However we will also need to accommodate for spikes in energy due to fast movement or unusual movement cycling. Our components can be broken down into two different parts, the electromagnetic generator and the electrical black box.

6.2.1 Electromagnetic Generator

The natural oscillations of the body are harvested using a mass spring damper system that passes a magnet through a cylindrical coil system. The magnet will be attached to a spring on both sides and its velocity would dictate its damping using Lorentz's law. The generator device is arranged in nodes around the belt, as shown in Figure 6.2 (page 18). These canisters are attached using Alice clips, and therefore may be removed or added for the user to manually modify the amount of power generation he or she is outputting.

Figure 6.2: Belt system



This requires special calculation of mass, spring constant and damping. The spring gives us the ability to store the energy of the oscillating motion of the hip so the magnet can be propelled through the coil. Without a spring we would lose much of the motion of the body due to the weight of the magnet.

Energy is generated in the coils when the magnet passes through the coil due to Faraday's law (equation 2). Faraday's law states that for a change in magnetic flux, $d\Phi_B/dt$, in a metal wire there is an emf voltage, V_{emf}, that is induced. This voltage change is directly related to the number wraps of the coils in the cylinder. Therefore the more wraps in the coil, N, the higher the emf voltage can get with the same change in flux. However increasing wraps in the coil slightly increases the resistance in the system which would reduce the power. In practice, increasing the number of coils will reach diminishing returns because the distance from the magnet to the outer coils increases with the amount of over wraps. We are using one magnet at this time oscillating through the coil but we would like to explore the possibility of using two magnets oscillating opposite each other through the coil. The power the generator can output is linked to the amount of voltage output and the resistance of the wire.

$$V_{emf} = -N\frac{d\Phi_B}{dt} \qquad \text{Eq. 2}$$

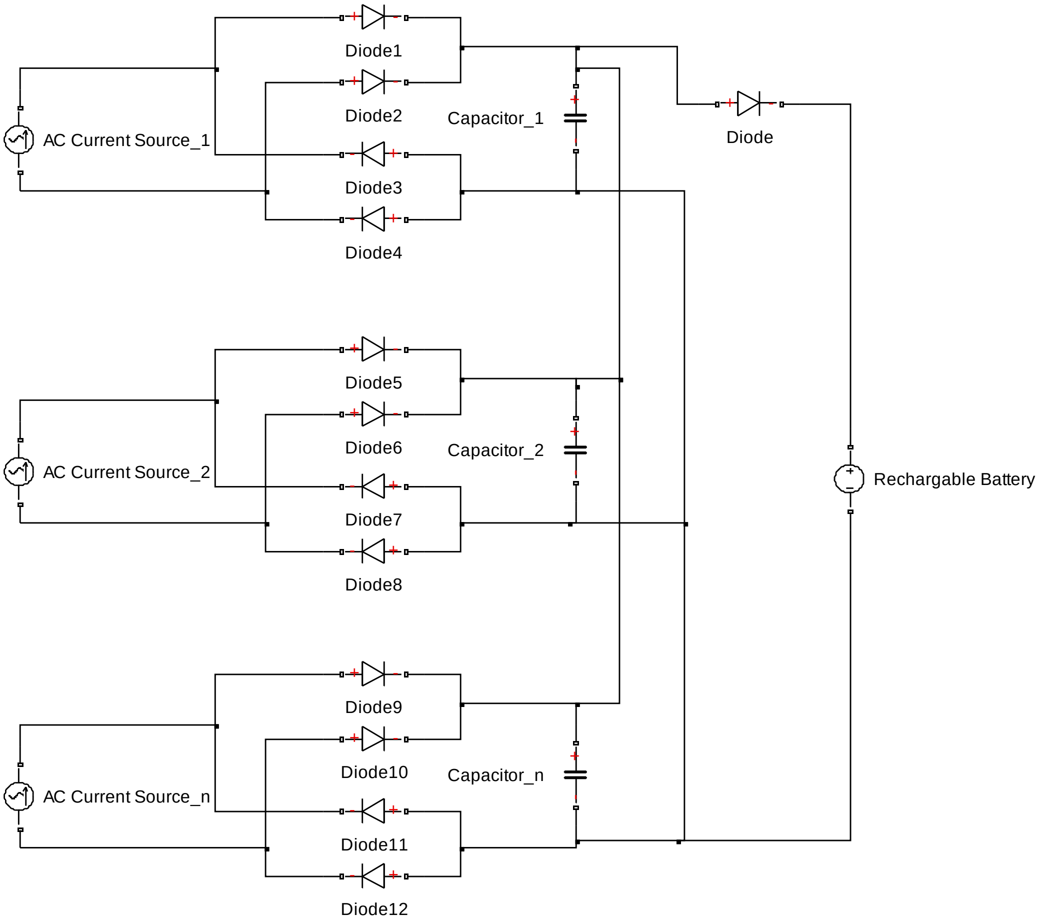
6.2.2 *Electrical "Black Box"*

The electricity that comes out of our system is an alternating current of around 2 Hz; in order to use this energy, we must convert it to direct current. To do this we are using a rectifier circuit. A rectifier uses a transformer, diodes, and capacitors to produce a smooth direct current from an alternating current. This is a pivotal part of the generation process because batteries and most hand held devices need direct current electricity to function.

After the current is rectified, it can be used to charge a battery. However between steps and changes in walking velocity or oscillation can produce dangerous spikes in voltage and current that would damage the battery. In order to combat this, we are using a series of capacitors to even out the voltage spikes created during walking variations. We are using approximately as many as 4 capacitors depending on the strength and size of capacitance. We are looking into using a super capacitor, which is a large storage device capacitor and the addition of that may reduce the size of the anticipated capacitor.

Once the voltage and current spikes are leveled out we are using a battery as a long-term storage device. We are using a nickel metal hydride batteries due to their high charge density and low cost with around 5 Watt-hours of storage capacity giving about an hour of charge on a 5 Watt load. Our battery has the capability of a 10 C value, which specifies the maximum charge and discharge rating of the battery. A 10 C capability gives us a maximum 50 watt charge and discharge rating. This should be able to account for any charging or discharging spikes and give us a good safety factor. A schematic of the circuit diagram is shown in Figure 6.3.

Figure 6.3: Circuit diagram



We had to install certain components in our system to protect it against different electrical failure modes. We have developed a state of charge (SOC) monitoring system that controls how low or high our battery can charge and discharge. Over charging and over use of the battery is a major problem and can lead to battery failure modes such as exploding, film blocking charging or dendrites through the separator shorting the battery. We have solved this problem by using coulomb counting and a hardwired computer chip that will monitor battery charge. If our battery contained multiple strings of cells we could also look into a cell voltage monitoring system. The system would work either using a shunt resistor system, switch capacitors, or a power electronics system. The cell voltage monitoring system would prevent overcharging in specific battery cells either due to different SOC levels between batteries or battery failure of a single cell. We must also account for back charging in the system. This happens when the battery is charged a higher voltage than the generator and can drain the battery of its charge. We plan on combating this problem by using diodes in the circuitry to the battery. Also as a safety precaution, we will include fuses in the system to protect against current spikes in the final design.

In order to deliver power to the portable devices, we used a system of plugs on a black box device holding the battery and rectifier. The device had coaxial power connectors for each portable device. The devices may need to be modified to plug into the black box but some cell phones and other small portable devices already use this technology and may not need to be converted. We used a DC to DC converter as not to supply more than the recommended voltage for the portable devices.

7 ENGINERING PARAMETER ANALYSIS ON ALPHA PROTOTYPE

In this section, we will provide our detailed engineering design parameter analysis. We will discuss our plan of approaching the design problems and the engineering fundamentals that we have addressed in order to meet the project goals.

7.1 Targets

Harris Corporation has set our power generation target to 5 Watts of power and approved all other specifications we have developed for the energy harnessing design. Harris requires that our design should be able to safely generate power from human energy while not significantly impeding movement. This will be accomplished by minimizing metabolic cost for the user and not obstructing the user from performing day-to-day activities.

To determine which of our designs best accomplished these customer requirements, preliminary engineering analysis was performed. We then identified our best design candidate and performed further analysis on it to determine the power output and other parameters for evaluating the engineering specifications. We will determine which electrical components are necessary to achieve design goals by doing a circuit analysis. This will require a significant amount of electrical engineering and will be a particularly difficult challenge as this is not our core field of study. This task will require review of electrical engineering principles and technical assistance from professors and experts in the field of electronics.

Our final design will produce electricity utilizing oscillatory motion and kinetic energy from walking. This generator will be placed on the user's hip via an ALICE (All-purpose Lightweight Individual Carrying Equipment) clip and the main components of our electromagnetic generator will consist of a spring, magnetic wire, and coil.

7.2 Circuitry

We have identified the need for a coil, rectifier, diode, and a capacitor in our circuitry. Technical assistance from John Baker was utilized in determining different circuitry options. The components of the circuitry have been modeled on a circuit diagram to convert, smooth and deliver the power output from the generator device to the mobile devices being charged. To accomplish these requirements, a rectifier is needed to convert the AC to DC for storage; a capacitor/battery system was implemented to store this power. A power adaptor system using coaxial connectors was utilized to deliver electricity to the devices. Different types of batteries have been analyzed for application and we optimized the specifications for safety, weight, capacity and cost. A diode is installed in the circuit to ensure that current only travels in one direction to protect both the battery and user from harm. A fuse needs to install near the battery to guard against electrical shorts and power surges from unexpected movements such as running or jumping for the final design. We initially designed our circuit on a breadboard and upon proving our circuit valid; we used a proto-board to help guard against damage from vibrations due to walking.

7.3 Packaging (shape/material)

The housing for our prototype is constructed of PVC plastic tubing. This material was ideal for the prototype because of its extensive availability, economical price, and machinability. The device has a magnet, attached to a spring, oscillating through this tube which will provide a guide for the path of the magnet through the coil.

After conducting expert interviews with military personnel and our sponsor, it was determined the housing of the prototype is to be attached to the user by using a modified ALICE belt worn by the military (Figure 7.2). The top of the canister device will have an attachment mechanism which allows the soldier to affix the canister to their gear using an ALICE clip (Figure 7.2). This aids in keeping the device in its vertical operating position.

Figure 7.2: ALICE Belt and ALICE Clip

7.4 Modeling

In our modeling section we will explore the relationship between the motions of the user walking with the movement of the magnet in the coil of our system, then further on to the actual power generated. The motion of the user can be described as a sinusoidal wave with amplitude of 2.5 inches [10]. This motion oscillates the canister and the spring will oscillate the magnet at particular amplitude with the same frequency as the walking motion. The equation that describes this motion is shown in equation 3. The relationship between walking and voltage generated includes variables frequency (ω), amplitude (A) and displacement (x). X is current position in coil and A is total amplitude. The equation for this relationship was derived from Faraday's Law, along with the number of turns in coil (N), strength of magnet (B) and length of coil in field (L) in order to model the design placement and performance of device. This relationship can be seen in equation 4.

$$m\ddot{x} + b\dot{x} + kx = AB\omega\cos(\omega t) + Ak\sin(\omega t)$$ Eq. 3

$$V = BNxL\omega$$ Eq. 4

The preliminary analysis of the displacement of the magnet in the coil was predicted to be very close to the distance that the localized area of the body travels vertically in one step. The determined voltage (V) from Eq. 4 and resistance of the coil and the load resistance of the battery, determined to be .32 ohms, were then entered into equation 5 to tabulate power (P) outputs. The resistance (R) of the wire is given in ohms per 1000 meters [11] and was determined according to equation 8. The length of wire was calculated relative to the number of turns, and the diameter and length of coil. It was also necessary to determine the force that would be exerted on the spring in order to determine the settling position of the magnet and the maximum force that could be applied to the spring before failure. The settling position is important due to the magnet oscillating around that point so we must position the coil at that area. The equation showing this relationship is shown in equation 6. This was then factored into the free spring length and position of the coils with respect to the end of the spring which is mounted to the end of the canister. For a more detailed description of the calculation of spring length see section 7.4.4.

$$P = \frac{V^2}{R} \qquad \text{Eq. 5}$$

$$F = -kx \qquad \text{Eq. 6}$$

The displacement of magnet (x) will be maximized by determining the correct spring constant to use from our resonance frequency ($f_{resonance}$) of the user walking in radians per sec of the mass as shown in equation 7. This displacement (x) will be determined as a function of time from the different variables in equation 3 including time (t), frequency (ω), and amplitude (A) of magnet along with magnetic damping (b), and mass (m) and spring stiffness (k). These variables will give a maximum displacement output (x) to input ratio occurring at the resonance input frequency (ω) of walking. Equations 3 and 11 show an output to input ratio and are derived from a force balance equation in Appendix J.

$$f_{resonance} = \sqrt{\frac{k}{m}} \qquad \text{Eq. 7}$$

$$R_{coil} = \frac{\rho l}{A_{wire}} \qquad \text{Eq. 8}$$

To determine the acting damping on the magnet from the induced current in the coil, we use equations 9, 10, and 12 to determine the b value to use in equation 11. To determine the acting magnetic field on the coils, equation 9 is used with magnet parameters such as residual magnetic field (Br), gap distance from the magnet to the coils (δ_{gap}), and the diameter of the magnet (D_{mag}). Equation 8 is the resistance of the coil that the current feels as it is created. The parameters for this equation are the static resistivity of the wire (ρ), length (l), and the cross sectional area of the wire (A_{wire}). The inductance of the coil is shown in equation 12 with parameters: permittivity of free space (μ_o), number of coils (N), radius of the coil (R^2_{geom}), and the characteristic length (h). These values are plugged into equation 10 to determine the damping that the magnet experiences due to the current in the coil.

$$B = B_R \left[1 + \frac{2\delta_{gap}}{D_{mag}} \right]^{-1} \qquad \text{Eq. 9}$$

$$b = \frac{(NlB)^2}{R_L + R_{coil} + j\omega L_{coil}} \qquad \text{Eq.10}$$

$$\frac{X_1(s)}{X_2(s)} = \frac{bs + k}{ms^2 + bs + k} \qquad \text{Eq.11}$$

$$L_{coil} = \frac{\mu_o N^2 \pi R_{geom}^2}{h_{geom}} \qquad \text{Eq.12}$$

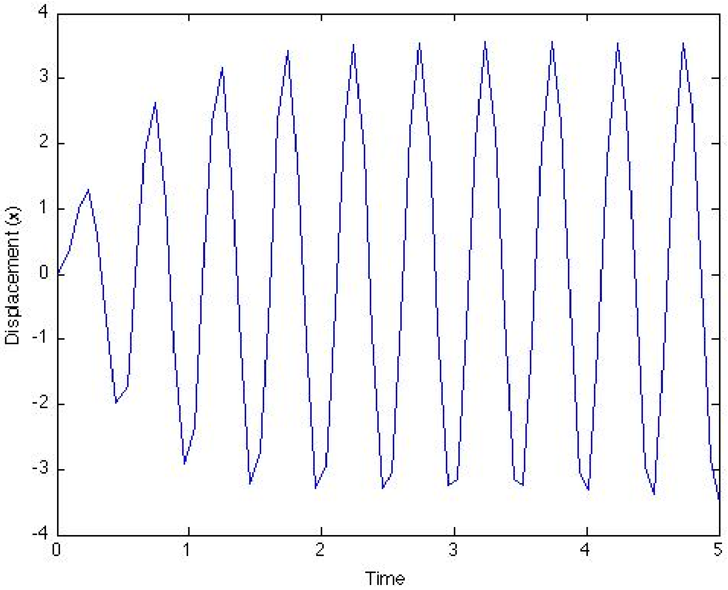
The parameters in equations 3-12 have been optimized in MATLAB and Simulink to maximize performance for all of the parameters. The simulation using equations 3 and 11, with the values for the parameters that satisfy the displacement constraints of the magnet in the canister system, outputs a voltage of 3.74 V and a power of 0.45 W.

7.4.1 Scaling Issues

Due to cost and material constraints our device will only generate a fraction of the consumer required 5 Watts. This can be resolved though scaling our device by using multiple devices. A main concern is that if the user is required to wear an excessive amount of these devices, the devices will be considered a burden greater than the equivalent amount of batteries and therefore not used.

If we had the resources to obtain a magnet with a B_r value of several orders of magnitude greater than our current design and have the proper cicuitry the threshold of 5 Watts would be achieved with less canisters. (See section 14 and 15 for more details on possible improvements in design.) Another parameter that holds us back from reaching our target in one canister is our exceeding low frequency, which the human body oscillates. Figure 7.3 shows the MATLAB output of the magnet displacement over time.

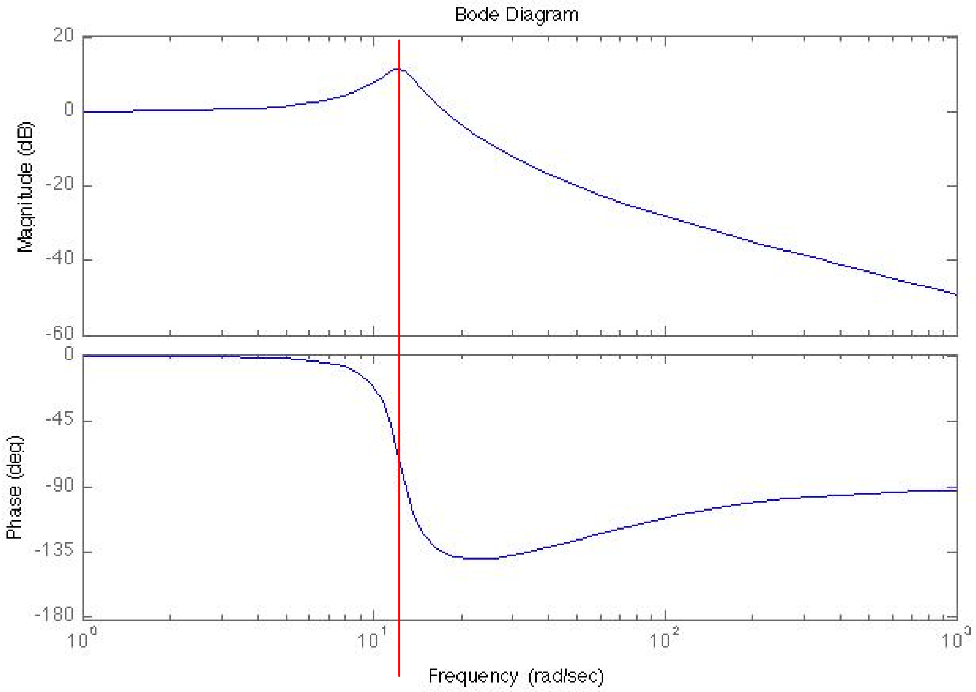
Figure 7.3: Magnet Displacement over time



7.4.2 Bode Diagram

To determine the parameters that maximize the ratio of the output magnet displacement to the input frequency that the user is walking a Bode diagram was utilized. The Bode diagram uses the transfer function of the equation of motion (equation 11). As seen in Figure 7.4, we have modeled our MATLAB model to resonate at 2 Hz.

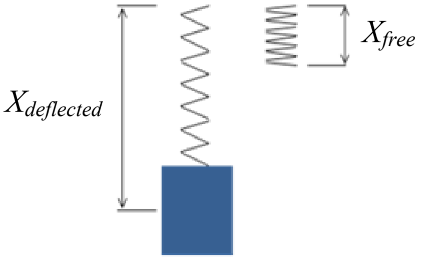
Figure 7.4: Bode plot of MATLAB model reaching resonance frequency at 2 Hz



7.4.3 Dimensions

The dimensions of the prototype were chosen to best satisfy the customer and engineering requirements. The inner diameter of the tube was selected to minimize the distance between the coil and the magnet. The wall of the tube between the coil and the magnet was further minimized through lathing maximizing the effective magnetic field (*B*) value (equation 9). The predicted amplitude of the magnet during oscillations and the amount of extra space that may be needed to accommodate the use of an extension has been considered. The initial change in length of the spring as a result of weight of magnet on the spring will increase the length of the canister if an extension spring is used. To prevent a collision of the magnet with the end of the canister and a subsequent waste of kinetic energy, the output displacement at maximum must still be less than the distance to the end of the canister about the equilibrium position. Figure 7.5 (page23) shows the spring deformation when the mass is attached, and equations 13 and 14 let us calculate the length of the spring when the magnet was attached.

Figure 7.5: Stretched spring when mass (magnet) is attached



$$\frac{F}{k} = X_{center} - l_{free} \qquad \text{Eq. 13}$$

$$X_{\text{center}} = X_{\text{free}} + X_{\text{deflected}} + \frac{1}{2} L_{Magnet} \qquad \text{Eq. 14}$$

7.4.4 Spring Selection

Although a combination of compression springs that match the natural frequency that the user walks and have an equilibrium position with the magnet in the center of the coil have been calculated, an extension spring was selected due to in stock material availability and cost issues. Having an appropriate combination of custom compression springs would also minimize friction of magnet against tube due to sagging and the device would also be able to work in variable operating positions as oppose to one side up as with an extension spring.

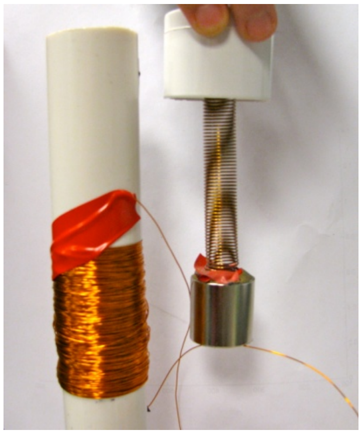
Data for the springs damping is unavailable. Before testing the prototype the damping effect of the springs must be determined. The damping value of springs was found through estimation methods. An excitation was applied to the spring. Using a ruler and timer the rate at which the amplitude of the spring is dampened was determined through observation. This level of detail is valid because the damping effect of springs with very low spring rates is typically negligible.

The selected spring demonstrates all important engineering fundamental of the ideal final design. The spring rate that matches the users walking frequency (in Hz) with an equilibrium position leaving enough room on either side of magnet to allow for necessary oscillations was achieved for the final prototype. The selected spring must not respond to the presence of a magnetic field. Two materials that satisfy these criteria are Inconel and phosphor bronze.

The calculated spring rate at natural frequency of 2 Hz was determined to be 15.2 N/m. The mass of the spring was neglected in this calculation because the mass of the magnet is much greater and considered a point load on the end of the spring while the spring’s mass is located along the spring thus rendering it less important.

We custom ordered springs made of phosphor bronze with the correct spring constant. Specifications on the spring are listed in Appendix N. As shown in Figure 7.6, this spring lets the magnet hang in the middle of the canister with no external force applied.

Figure 7.6: Magnet hangs in the middle for the canister with no external force



7.5 Testing

We are testing different components of our design separately because of logistical issues such as material shipping time and availability, borrowing testing equipment and lab scheduling. The efficiency of this device will be determined through testing to verify calculations. To accurately predict the efficiency of the final prototype, our alpha prototype must correctly represent all important engineering content. See section 12 for procedure and results on testing.

7.6 Safety

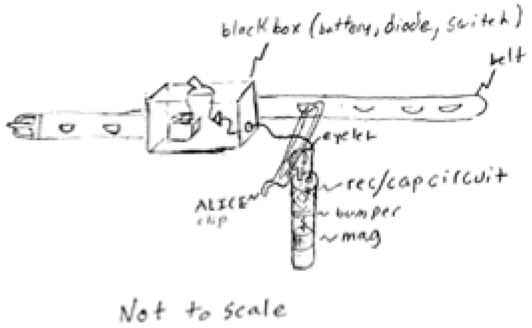
There are many safety concerns that we considered. The final design will contain no dangerous moving parts which could result in injury to the user. The design contains no pressure accumulating cylinders, high forces, or rapidly moving parts. There are however electrical components. A fuse, diode and water proof packaging will protect user from electric shock. Repetitive motion injury will be avoided because this design does not restrict the movement of any joins or muscles. A bumper will be placed in lower end cap of canister to prevent possible failure in event of impact of magnet with bottom of canister or any circuitry components.

Preliminary analysis has been conducted of the material our design casing will be made of and have decided to investigate using PPS plastic for the final design. This plastic has a good rating for UV resistance and will be able to seal the canister and black box from external elements such as water and dirt. It also provides magnetic shielding. Also it is relatively cheap and available in the pipe sizes we will require. Though we were unable to find off-the-shelf pipes made of this material, thus, our prototype was made in PVC.

8 FINAL DESIGN DESCRIPTION

To meet our engineering specifications, we designed our product as a thin plastic tube that will contain a magnet and spring assembly that will oscillate within a set of copper coils at the frequency of a human walking. This generation is scalable and charges a battery contained within an electrical black box located on the users belt. Figure 8.1 shows the general idea of what our final prototype would look like. In this section, we will describe how the final design works, and have detailed description of the components included in the canister, the belt system, and the black box.

Figure 8.1: Final design of belt-generator system



8.1 Process Description

As the user walks, electricity is created due to the changing magnet field though the coils of wires around the plastic canister. The energy is then transferred to a set of rectifier diodes to change the AC to DC. This voltage is used to charge a capacitor which acts to smooth the voltage changes. All of this electricity manipulation is contained within a single canister that can be combined with other canisters to supplement total electricity generation. From the canister assembly, the electricity is transferred along a set of wires contained within a belt to our black box which will house a battery along with a DC to DC converter and charge management board to change the voltage and current input using built in hardware to charge the battery. This battery will then be connected to a set of output ports that could charge a number of mobile devices. For an illustration of the proces description see below figures.

8.2 Canister Description

Our modular concept for the canister design is intended to allow soldiers to vary the amount of canister carry based on their individual power needs. The canister is designed to be a standalone system; this means the electrical black box can be charged by any amount canister devices without having to modify the components inside. Each canister will be able to clip to a soldiers belt using an ALICE clip attached to it. It will transfer electricity using a USB wire plug in system included in the belt. A CAD transparent view of the final design is shown below in Figure 8.2. For engineering drawings of the components included in this section please see Appendix G. For list of materials used in these devices as well as the prices please see Appendix I.

Figure 8.2: CAD model of the final canister design

8.2.1 Magnet

A neodymium rare earth magnet is one of the most powerful naturally occurring magnets available. We chose to use this rare earth magnet from modeling in MATLAB and due to its high magnetic field. The size of the magnet was determined by optimizing natural frequency of the system using spring constant and mass. The1 inch magnet size was selected because of its high mass for good mechanical energy from oscillation as well as it being a standard industry inner pipe diameter size. This allows us to not have to do any complicated inner pipe diameter machining and will provide a lubrication effect from the thin inner wall of air that will cushion the magnet as it oscillates in the tube. Also the coils will be very close to the magnet which is essential for good energy transfer between the magnet and coils. Specifications on the magnet are listed in Appendix M.

8.2.2 Coil

The magnet wire is a copper based wire that is coated in varnish. We chose a 26 gage magnet wire for our project by modeling power versus wire gage in MATLAB. We found that the wire diameter didn't affect the maximum power the canister could create very much and choose 26 gage wire due its low resistance and small diameter. In order to generate the most energy per canister, we took our system parameters modeled in MATLAB and determined that at 600 turns we can optimally generate 1.2 watts of electricity. As the number of coils on the canister goes up the system can create more voltage, but also will provide more and more apposing magnetic field due to increased current generation. Optimizing power within the system was balancing the current and voltage generation to fit our circuitry needs. It was our design objective to put the coil as close to the magnet as we could without endangering the structural integrity of the plastic canister. The closer the coil is to the magnet, the more energy the coils can capture from the changing magnetic flux.

8.2.3 Inner and Outer Casing

The casing for our final design will consist of PPS plastic, Polyphenylene sulfide, inner tube that will provide a guide through which the magnet will slide. We chose to use this plastic due to its high strength, UV resistance, corrosion resistance, and its natural magnetic shield properties. The magnet will be free to oscillate within the inner tube. This casing will have a groove machined into the wall at the center of the tube of around 2 inches in length which will provide a pocket where the coil wires will be wound around. The thickness of the wall of this pocket will be as small as possible in order to maximize the change in magnetic flux in the wire. Preliminary test has shown that we can take the wall thickness to a 1/16th of an inch without providing significant structural degradation. The inner casing will be fit into a groove in the PPS plastic end cap and will sit there in a press fit. Grooves will be cut into the side of the inner tube to allow airflow to facilitate heat dissipation around the magnet during oscillations. Included inside the inner casing will be the rectifier and capacitor system. They will attach to the walls of the inner container using metal fasteners. The inner tubes outer diameter will be fitted into the groove cut into the end caps. The cap will include two holes, one for an eyelet and the other for the wire going to the black box. The spring will be glued between the axial side of the top end cap and the magnet. The cap will have a groove milled into it for a press fit separating the inner and outer tubes. The outer casing will fit around the groove milled into the end caps. Then it will be glued in place using an epoxy because the casing must be able to sustain impacts due to the environment such as rocks. The casing must also be sealed from moisture. The engineering drawings for these parts are all shown in Appendix G.

8.2.4 Spring

We have chosen to use a metal spring in order to oscillate our magnet following the model we created using MATLAB and Simulink. A metal spring has some advantages and disadvantages in our system, mainly the wide majority of springs used are ferrous and are adversely affected by a strong magnetic field. To combat this, we have decided to use a non-ferrous spring. We are looking into designing a custom phosphorous bronze spring that meets our specifications. At this time we have selected an extension spring as our best candidate but a compression spring may still be used for the final design. The advantages of an extension spring over a compression spring include longer stretch length.

8.2.5 Clip to Belt

To attach our design to a belt we have decided to use standard military ALICE clips. The ALICE clip has many advantages over conventional attaching methods. ALICE clips are made of durable metal that will not unintentionally become unfastened. The clip will be attached to the canister via an eye hook that will be installed at the top of the canister. Attaching the device in this fashion on the soldier will not restrict their movement and will also ensure the canister will always be pointing in the vertical operating position.

8.2.6 Voltage Conversion and Smoothening

We will have to convert AC power generated by the canister devices into DC power for purposes of charging the battery. A bridge rectifier changes AC voltage to DC voltage by using a combination of diodes. We chose to use a bridge rectifier due to its low cost, small size and high efficiency. The specific rectifier we chose to use is known as a schokkty type rectifier. These rectifiers are good for our application because they are fast switching and have a very low forward voltage switching point. This will allow us to get as much of the voltage as we can out of the system. The operating range of up to 20V is sufficient for our needs.

After the diodes in the rectifier convert the electricity to DC current, we will use a capacitor to smooth the voltage spikes into a more consistent flow of energy to the black box. A ceramic disc capacitor with 2.2 micro Farads and 25 Volts operating range is appropriate for the amount of energy the device will generate. The capacitors in different canisters will be wired in parallel so they will have the same voltage even if they are oscillating at different frequency.

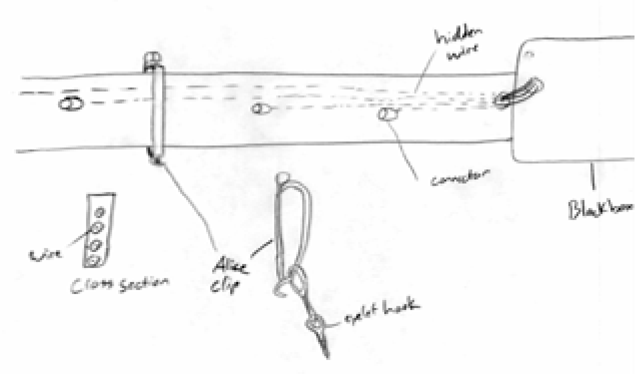
8.2.7 Wiring

Our design must transfer the smoothed energy safely to the black box in an efficient and snag free design. To accomplish this we will integrate the wiring into the belt harness of the soldier. The devices will attach to the belt through coaxial power connections that will be integrated into the ALICE belt. The canister will deliver its output through the wiring in the top end cap and attach to the belt by a coaxial power connector. We will use copper wire embedded into the belt to transport the energy from the canister devices to the black box.

8.3 Belt

The device attaches to the belt using a modified military ALICE belt. The modifications will include a wire for every loop that a canister device may be attached to. The wires will be embedded into the belt, running from the loop to the main wire coming out of the black box. There will be a coaxial power port at the end of the wire at the loop. The coaxial power port will have a cap on it to protect it from the environment. The canister will attach to belt loop in two ways. The mechanical portion will be attached via an ALICE clip between belt loop and canister eyelet. The electrical part will be connected with a male/female USB setup. Figure 8.3 shows the general idea of how the wiring is done in the belt and how the canisters and black box will be connected.

Figure 8.3: Belt with internal wiring showing coaxial and ALICE clip connections



8.4 Storage Device – Black Box

The black box storage device will be used by the system as a power conversion, storage and delivery system. For engineering drawings of the components included in this section please see Appendix G. For a list of materials used in these devices as well as the prices please see Appendix I.

8.4.1 Energy Storage

To store energy we used a battery PCM charging module that includes its own charging hardware and software. The PCM includes a DC to DC converter that accepts a range of voltages from 2 to 10V and adjusts the current and voltage to best suit the battery. The battery will be charged using CCCV charging methods which means constant current constant voltage. Essentially this will charge the battery using as much current as the generators put out. After the state of charge of the battery reaches a certain level the charging module will provide a constant voltage independent of current. This is equivalent to a "quick charge" you may see on things such as cell phone chargers where it takes 1 hour to charge a battery to 80% and an additional 1 hour to charge the battery to a full 100% SOC, state of charge. The battery charging module will also provide software that will automatically shut off the battery charging when the battery reaches 100% SOC and shut off battery discharging at 0% SOC to prevent battery failure. Also there will be a diode in the system that prevent any back charging that could drain the batteries charge into the capacitors in the event the generators are not in use.

8.4.2 Casing

The casing for the black box must be water proof, UV resistant and impact resistant. The casing will be made of the same type of material as the outer housing of the canister devices.

8.4.3 Power Distribution

The battery will deliver its power to charge other electronics through a coaxial power port. This docking port will be integrated into the black box system and will be several ports to accommodate multiple devices. A USB setup will be used so that the electric device can also be charged directly rather than charging through a battery system.

9 FABRICATION PLAN

The fabrication plan of the mechanical and electrical portions for the mockup, the alpha prototype, and the final prototype are explained in this section. This section will give a brief overview of the manufacturing and assembly process, while more detail for the fabrication plan may be seen in Appendix K, the safety report.

9.1 Mockup

The manufacturing of the prototype's mechanical components can be completely fabricated in the ME 450 machine shop. The manufacturing and assembly of the prototype was intentionally designed with simplicity as a priority. The fabrication plan of the mock up and the initial circuit design for testing is explained in the safety report in Appendix K.

9.2 Alpha Prototype

The process for the manufacturing the alpha prototype is similar to that of the mock up only the tube of the device is cut longer to 9" to accommodate the extension spring used in this design. There is a 5/64" tap hole drilled for the eyelet to hang magnet. The circuitry manufacturing is described in the Safety report in Appendix K.

The top cap has an eyelet threaded into its center to attach the spring with magnet hanging. The tube wrapped with magnet wire is then inserted into the top and bottom caps. The technique of assembly of the capacitor and rectifier system in the circuitry is described in the safety report (Appendix K). The leads of the magnet coil are then soldered to this circuitry system via wire. Figure 9.1 shows the CAD model of the assembled canister prototype.

Figure 9.1: Assembled canister device

9.3 Final Prototype

The PVC plastic tubing inner portion of the device for the prototype will have its middle section turned down to create a pocket for the magnet wire to wrap around taking wall thickness down to .05". The inner and outer tubing will be cut down to 9" with a band saw. The top and bottom cap are cut with the water jet down to a size of 1.6" in diameter. The top cap and bottom cap has holes drilled for ventilation with a 5/64" drill bit. As well the top cap has a hole drilled for wires with a 3/8" drill bit and two holes drilled for the two eyelets. The tapped holes for the eyelets were drilled with number 53 drill bit. The electrical circuitry components will be manufactured with the same basic process as described in the safety report in Appendix K only they will be integrated into the black box power system. In addition two holes will be drilled in the black box for the input and output channels to store and deliver power. The black box also has a viewing window drilled in it with a 3/4" so the user can see the charge status of the battery.

Instead of the bread board for proof of concept testing in the Alpha design, the electronic components are integrated into a proto board upon validation. The proto board is then glued into the black box charging system along with a charge management board and rechargeable battery. The inner components of the black box will be connected via soldered wire. The cable connecting the canister to the black box is be fed though the hole in the top cap of the canister and sealed secure with epoxy. One end of the cable is attached to the black box through the coaxial power port affixed to a hole in the side of the box. The other end of wire is attached to leads coming off magnet coil with solder. The inner tube than has two o-rings put on in to prevent vibration inside larger tube casing. The inner tube is then placed into the larger 1.5" inner diameter tube. The interface between the caps and tubing are then secured with glue to protect workings from the environment and maintain structural integrity.

9.4 Final Design

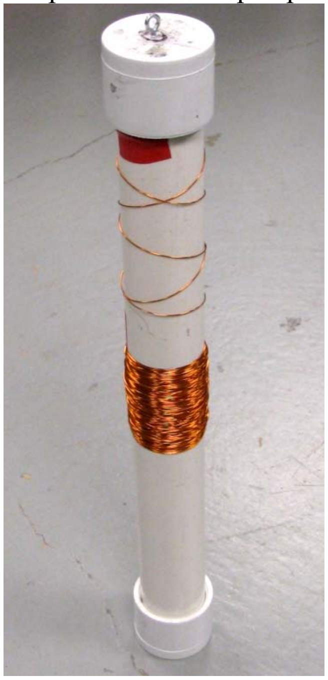
The final design only has a few differences from the final prototype. Connections between interfaces will need more reliable sealing from environment if further more long term testing is to be conducted outdoors. The holes that all wires are fed through should also include grommets. The outer casing will not have ventilation holes like the final prototype; instead the design will have internal ventilation holes to allow for air circulation inside tubing as magnet oscillates. These further upgrades will help create a more robust version of our design including a plastic designed to withstand the rough terrain a soldier experiences and provide magnetic shielding.

10 ALPHA PROTOTYPE DESCRIPTION

The alpha prototype shows the most important engineering fundamentals without requiring us to manufacture several canisters containing all specifications of our final design. For our alpha prototype, we used a PVC pipe for the canister. PVC pipe is a standard plastic plumbing pipe that is found in most hardware stores for transporting water. We chose PVC for the alpha prototype due to its wide spread availability, ease of machining, and cheap price. PVC pipe will let us show how the magnet will oscillate within our canister without spending excess money on expensive environment resistant materials.

Only the inner canister with the magnet, spring, and magnet coil system was used for the alpha prototype. No outer casing was placed because our primary goal with the alpha prototype was to conduct proof tests that validated that our mechanical canister system and the circuitry system was working. The circuitry system was temporarily built on a protoboard for testing purposes. Figure 10.1 (page 30) shows the canister portion built to dimension, with a height of 9 inches and a pipe diameter of 1 inch. The caps are off-the-shelf PVC caps, which press-fits to the canister tubing. Holes were drilled in these caps for air flow and an eyelet was placed on the caps for spring and ALICE clip attachment. Detailed dimensions and engineering drawings for the alpha prototype can be seen in Appendix G.

Figure 10.1: Picture of the canister portion of the alpha prototype



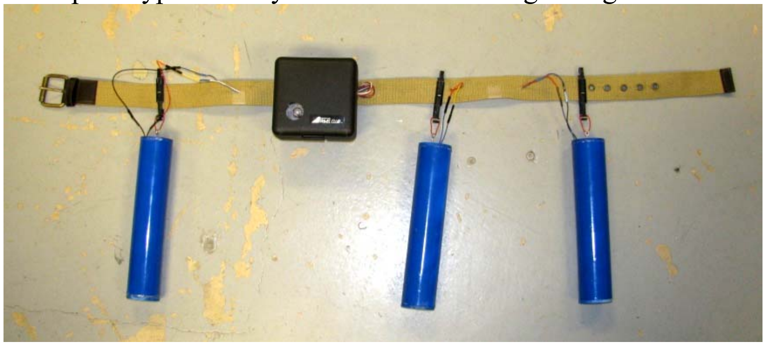
The circuitry system consisted of a full-bridge rectifier, a capacitor, and a resister to represent a battery. The purpose of this circuitry was to convert and smooth the AC current into DC. Testing was done using the alpha prototype and a simple circuitry on the protoboad. More detail about the testing procedure and results are summarized in section 12.2 (page 34).

11 FINAL PROTOTYPE DESCRIPTION

For the final prototype, we will hold it to the exact same dimensional criterion as the proposed final design with a few exceptions. The final prototype will also have a rectifier and capacitor assembly inside of the black box. This is due to space and packaging concerns we have with the capacitor. Our capacitor appears to be too big to fit into the canister, but the final design capacitor should be fine. Our prototype has air holes drilled into the outer casing, but the final design will be sealed from the environment.

The final prototype assembled is shown in Figure 11.1. As seen in the figure, the final prototype consists of three electromagnetic generators and a black box integrated into a belt system. We were only able to built three canisters total due to money constraints.

Figure 11.1: Final prototype - belt system with electromagnetic generators and a black box



Our prototype will generate, transport, and store energy in the same ways that our final prototype will, but it will not provide all of the features and ease of use that our final design will. This is mainly due to our budget constraints as well as our time line. It will validate the final design concept, but without having to build multiple intricate devices.

11.1 Canister

The canister portion of the final prototype was built off of our alpha prototype. The PVC caps were removed, and the canister was placed inside a PVC tube with a diameter large enough to fit the whole device. Figure 11.2 shows the inside canister on the left and the assembled and painted canister on the right, The canister is then sealed with a round PVC cap which has 6 holes drilled in with an eyelet on the top and bottom, shown in Figure 11.3.

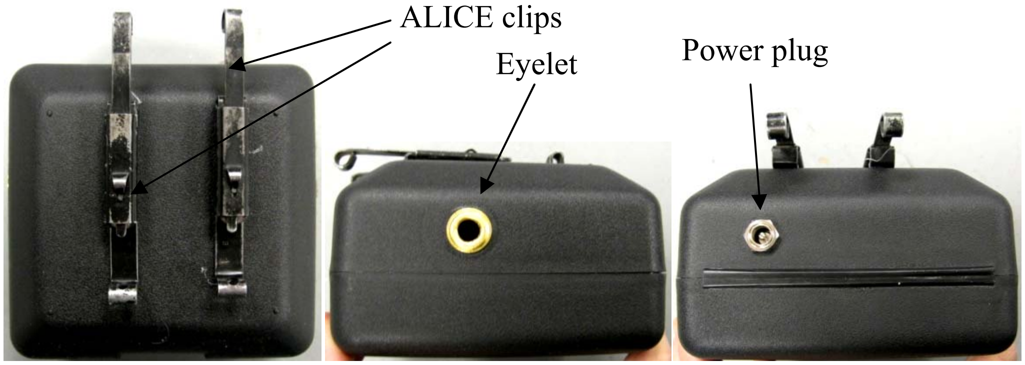
Figure 11.2: Final prototype canister, the inside portion shown on the left, and the assembled canister shown on the right

Figure 11.3: Cap of the canister has holes for air flow and eyelets for spring and ALICE clip attachment

11.2 Black Box

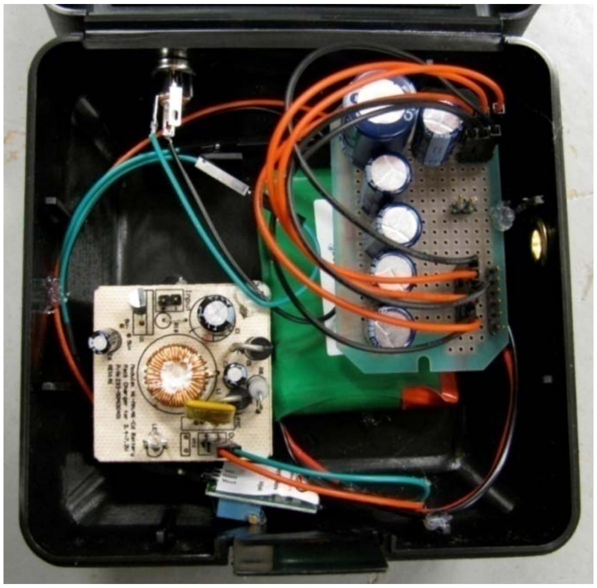
The black box will be mainly the same as our final design. The only differences being the material and size of the box. The black box for the final prototype will have slightly larger dimensions than the final design, and it will not be made of the same material we discussed in the final design. We will use a plastic pre-manufactured box, shown in Figure 11.4, in order to save on costs of manufacturing and materials. The box fits the specifications we laid out for it; however it will be slightly larger to fit the wires and connectors we will use for the initial prototype. Our final design will have a manufactured circuit board specifically designed to minimize its profile. As shown in Figure 11.4, the black box with have ALICE clips on the back for attaching to the belt, an eyelet for connecting wires to go through on the side, and a power plug for powering electronic devices on the top.

Figure 11.4: Bottom view, side view and the top view of the black box



Our black box contains a full-wave bridge rectifier and capacitor system, DC to DC converters, PCM lithium-ion polymer battery charging module, and a Nickel-metal hydride 7.2V battery. Figure 11.5 shows our black box circuitry and energy-storage system. Mode detail of specifications of each component can be found in Appendices O-R.

Figure 11.5: Black box with circuitry and energy storing system



Please note that our final prototype is using very inefficient circuitry components. Our DC to DC converter, battery charging module, and rectifier were purchased on price and functionality. Given our monetary concerns, we were unable to purchase or custom make circuitry that would have provided greater efficiency. The specifications for efficiency of each of the mentioned devices we purchased was less than 70% which adds up quickly to about 20 to 30% total energy delivered to the battery. With more expensive circuitry we can expect efficiencies of 80 to 90%.

11.3 Belt

The final prototype design will include a belt specially made with wires sewed into it but will not include coaxial docking spaces due to monetary concerns. We can do this because we primarily concerned with the power generated and not usability of the devise under adverse environmental conditions or splash concerns on the belt and connectors. Figure 11.1 on page 30 shows the assembled belt and Figure 11.6 below shows the belt system worn on a person.

Figure 11.6: Belt system worn on a person

12 VALIDATION OF RESULTS

This section will include our testing results of our mockup, alpha prototype, and final prototype. From the proof of concept testing with our mockup and alpha prototype, we modified our design as needed, and finally were able to obtain the power output measurement with our final prototype.

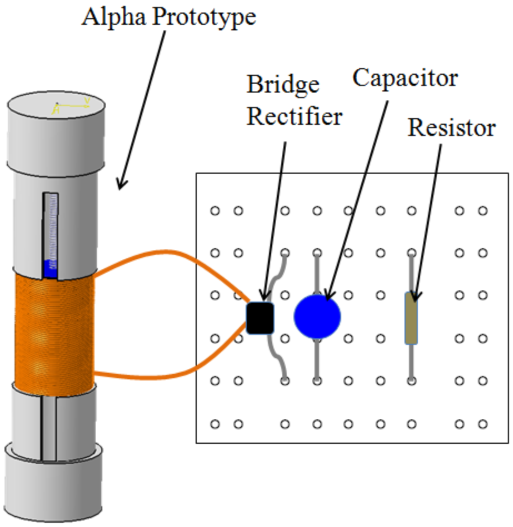
12.1 Mockup Testing Results

Mockup testing was primarily done for a proof of concept of the electromagnetic system. The test was simply to show that the magnet-spring system outputted some voltage. Once we proved this concept, we manufactured our alpha prototype with the correct dimensions and components. A multimeter was used during this testing to measure voltage across the coil of the mock up. Although springs that match the resonance frequency that the user walks were unavailable at this time, by shaking this mock up with our hands we were able obtain a reference voltage spike for proof of concept. The MATLAB model showed an output peak voltage of 3.74 V while the mock up generated a voltage of comparable peaks, averaging around 3 V. Additional testing is needed to draw any conclusion from these results.

12.2 Alpha Prototype Testing Results

Our alpha prototype testing was conducted using a bread board with our bare circuitry hooked up to the two ends of the coil of the generator. The generator was oscillated at 2 Hz with amplitude of 2 inches to simulate the motion of a human walking. This generated an AC voltage that was passed through a rectifier on the breadboard. This converted the signal to DC which was smoothed out by three 1000 microFarad capacitors in series or a total of 3000 microFarads of total capacitance. A resistor was placed in series with the capacitors and voltage and current were measure across it through the use of a multimeter and oscilloscope. Figure 12.1 shows the test setup for the alpha prototype. The AC voltage across the resistor was measured using an oscilloscope.

Figure 12.1: Test setup with alpha prototype and circuitry system on the protoboard



An optimization of number of coils and power output was done using the MATLAB model shown in Appendix L. From this model, we found the optimum number of turns in the coil to be 600 turns, which maximized the power output per canister to 1.4 Watts with an output voltage of 12 Volts.

We validated this model by measuring the actual output voltage from the prototype with the same specifications in the model. We built our alpha prototype based on this optimization with 600 turns in the coil, then connected the canister generator to an oscilloscope and measured the direct voltage output. We measured the direct voltage output from the canister to be about 11.8 Volts, which matched out MATLAB model. By comparing the output voltage of the MATLAB model and the measured value, we found that the MATLAB model matched with the canister portion of the generator prototype, and therefore that the model was valid.

12.3 Final Prototype Testing Results

In this section, we will provide the total power output we obtain with our final prototype. We also conducted validation tests to show that scaling was valid.

12.3.1 Power Output

Our primary goal for testing was to measure the power output. After verifying that the canister was outputting the expected voltage, we hooked the generator up to our black box circuitry system. We measured the voltage output from the circuitry using the oscilloscope, and the current output from the circuitry using a multimeter.

We took measurements for each of the three canisters that we had built and verified that each of the individual canisters was outputting approximately the same voltage and current. Table 12.1 shows the raw data for the output voltage and current for each of the canisters.

Table 12.1: Output voltage and current for the three canisters are approximately the same

Canister #	I_{max} [A]	I_{min} [A]	V_{max} [V]	V_{min} [V]
1	0.05	0.03	6.70	3.70
2	0.04	0.02	6.40	3.90
3	0.04	0.02	6.00	3.40

Using the collected data of output voltage and current in Table 12.1, we calculated the power output using equation 15. We determined that the average power output per canister to be about 0.2 Watts. This is only 14% of what the MATLAB model said. We see from the voltage output that the efficiency of the circuitry is very low, and this is the reason why our output power is so low.

$$P = IV \qquad \text{Eq. 15}$$

12.3.2 Validation of Scaling

To validate that scaling of the canisters for our design was applicable, we measured the output voltage and current (1) with a single canister, (2) with two canisters connected in parallel, and (3) with three canisters connected in parallel.

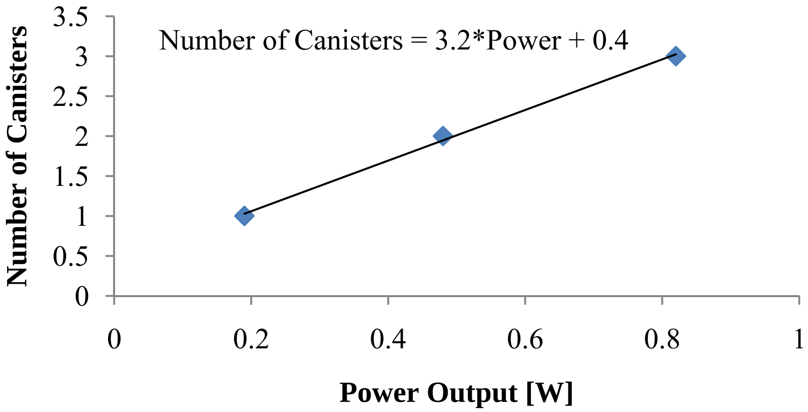
Table 12.2 shows the determined values of the maximum power, minimum power, and the average power output with one canister, two canisters, and three canisters. We see that power output increases with adding canisters to the system.

Table 12.2: Power outout with different number of canisters connected to the circuitry system

	Pmax [W]	Pmin [W]	Pavg [W]
1 Canister	0.28	0.09	0.19
2 Canisters	0.66	0.29	0.48
3 Canisters	1.19	0.45	0.82

When we plot the average power output against the number of canisters connected, we found a linear relationship between the power output and the number of canisters attached. As seen in Figure 12.2, the power approximately triples with each additional canister.

Figure 12.2: Correlation between number of canisters and power output



From this, we were able to conclude that scaling was valid, and assuming that this correlation is correct, we need at least 17 canisters to meet our specification of 5 Watts. The weight of each canister is about 0.5 kg and the weight of the black box and belt system together is about 0.4 kg. When we have 17 canisters attached to the belt system with the black box, the total weight comes to about 8.7 kg. This is slightly over our engineering specification.

13 VALIDATION OF ENGINEERING SPECIFICATIONS

In this section, we will provide validation of the engineering specifications for our final prototype. We will go through each engineering specification specified in section 3.

13.1 Power Delivered

The power delivered by the device was identified by Harris Corporation to be the most important specification and will appropriately have the most in-depth validation approach. The power will be validated in two parts. First we determine a test procedure to model the input of the system (i.e. the frequency and amplitude of oscillations of a soldier's waist while walking or running). Secondly we use the test procedure to excite the device and measure the power that is dissipated across the rechargeable battery.

Previous research has determined the frequency and amplitude of oscillations of a person's waist while walking or running. Based on the research, we can model the input to the device with vertical oscillations at 2 Hz and an amplitude of 2 in. This will be performed by 'shaking' the device in a confined height equal to the displacement, and the frequency matched with a metronome.

While exciting the system as described above, we will then determine the power delivered to the battery. Voltage and resistance measurements across the battery will be measured using a digital storage oscilloscope (Agilent DSO3102A, 100 MHz, 1 GSa/s) and volt-ohm multimeter (HP34401A). These measurements will be recorded using LabView and the maximum, minimum and average power delivered to the battery will be calculated using the following equation:

$$P = \frac{V_{RMS}^2}{R_{bat}} \qquad \text{Eq. 16}$$

Where P_{bat} is the power delivered to the battery, V_{RMS} is the average voltage across the load, and R_{bat} is the resistance for the battery.

As result, our final prototype with three canisters generated a total of 0.82 Watts. With the determined scaling factor, we concluded that our prototype with poor efficiency would require 17 canisters to generate 5 Watts. Therefore, it cannot meet the specification of 5 Watts with our initial goal of having less than 10 canisters.

13.2 Weight

The actual weight of the device was measured using a scale. We found that each canister weighed about 0.5 kg, and the belt and the black box assembled weight about 0.4 kg total. If we scale up the number of canisters to 17, the total weight of the assembled belt system would be 8.7 kg. This is over our specification, and therefore the we were unable to meet the weight specification of under 6 kg.

13.3 Energy Storage Capacity

The energy storage capacity of the device is equal to the maximum energy that can be delivered to the battery from the device. This will be calculated from the power delivered to the battery (as described in the previous section) and the time that the rate of power delivered can be sustained:

$$E_{max} = P \cdot t \qquad \text{Eq. 17}$$

where E_{max} is the maximum energy that can be stored in the battery and t is the effective time that the battery can be charged until the voltage of the battery exceeds the voltage in the capacitors, or the battery reaches its rated capacity.

Using this approach for determining energy capacity, rather than the maximum rated capacity of the battery, takes into account the possibility that the device may not be able to charge the battery 100%. This would occur if the battery voltage exceeded the capacitor voltage in the system prior to being fully charged.

Our energy storage capacity of the final prototype was calculated to be 5.92 Watt-hours using equation 17, which met the specification.

13.4 Maximum Surface Temperature

Surface temperature will be measured at steady state with a thermocouple while the device is at maximum power output. The specification is met if the max temperature is below 50 ^{o}C. With our final prototype, we did not notice any significant temperature change in the canister or the outside surface of the black box. This implies that the surface temperature in contact with the body was kept under 50^{o}C, and we met our specification.

13.5 Percent of Additional Energy to Operate

We will be unable to test or verify the percent of additional energy required to operate the device due to the availability of necessary testing equipment. Based on engineering specifications, the maximum percent of additional energy required to operate the device is to be 10%. An appropriate test would be able to accurately measure the calories expended while wearing the device for a fixed amount of time, compared to the calories expended without wearing the device.

13.6 Number of Sharp or Pinching Parts

Based on the engineering specifications, there are to be no sharp or pinching parts. This was also tested by visual inspection of the device while in three configurations: storage, set-up, and deployment.

13.7 Volume Displacement

Based on the engineering specifications, the maximum volume of the device is to be 400 cm^3. We define the volume of the device as the displacement of the battery module plus the displacement of each generating canister multiplied by the total number of canisters. With our final prototype, the volume displacement of a single canister was 460cm^3. Our prototype did not meet this specification.

13.8 Number of Moving Parts

Based on the engineering specifications, the maximum number of moving parts is to be 10. We have identified the moving parts in our system to be the spring and magnet in each canister generator. This specification was tested by simply counting the total number of springs and magnets required for our device to generate a power output of 5 Watts.

13.9 Time Required for Setup

We tested the time required for setup by timing how long it takes a single user, already familiar with the system, to attach all the generators and battery module to his or her equipment. The time will start with the device in a temporary storage position and will end when the device is in its operational position. This time was less than the specified value of 30 seconds, and therefore we met the specification.

13.10 Number of Adjustable Size Settings

The current design utilizes ALICE clips to integrate the device into harnesses already worn by soldiers in the military. Consequently, the device can adjust to any number of size settings depending on the size of a soldier's personal equipment. By eliminating the need for a separate mounting belt, we no longer need adjustable size settings and decrease the time required for setup.

13.11 Cost of Materials

Based on the engineering specifications, the cost of materials is to be under $30. The actual cost of materials will be computed from supplier quotes for bulk orders. This will more accurately reflect a comparable material cost if this device were to be produced in bulk.

13.12 Environmental Considerations

This section presents a brief overview of the environmental engineering considerations as outlined by the United States Department of Defense's MIL-STD-810G [6]. It is not intended that the prototype created by this design team will meet all of these environmental specifications, rather this section will outline the tailoring guidelines that we considered when designing the device. Limitations in materials, budget and testing facilities limit the environmental considerations that can be tested. We provide detailed analysis regarding the further improvements that must be made to this proof of concept in order to meet the environmental standards set forth by the U.S. Department of Defense in the Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [6]. A detailed review of the environmental considerations is shown in Appendix B. Note: all method and procedure numbers mentioned in this section refer directly to the corresponding sections in U.S. Department of Defense in the Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [6].

14 DISCUSSION

In this section, we will present a brief discussion on our design and possible improvements that could be made for better performance.

14.1 Design Critique

We have successfully designed, built and tested an electromagnetic generator for use in passively harnessing energy from human walking. Our prototype has achieved most of the engineering specifications, in particular we met our requirements of weight, energy storage capacity, maximum temperature, number of sharp or pinching parts, number of moving parts, number of adjustable size settings, curvature of edges, and time required for setup. Unfortunately we were unable to achieve the size constraint or the 5 Watts of instantaneous power output.

Overall, we feel the mechanics of our design are strong. Existing technologies rely on cumbersome loads [2] or invasive braces that could lock up and inhibit motion [1]. Our design, which uses an array of linear electromagnetic generators, is desirable due to the versatility and scalability of the system. The design is not dependent on the user carrying or wearing anything additional to the device itself. Possible Improvements

14.2 Possible Improvements

The weaknesses of the prototype are the low efficiency and large size. We have estimated the efficiency of the prototype to be 15%. Much of the energy loss is occurring in the circuitry of the design, which provides ample room for improvement.

14.2.1 Improvement in the Circuitry System

Due to budget limitations, the two DC to DC converters in the system have a combined efficiency of 50%. These could either be replaced with more efficient converts, or eliminated altogether. If the DC to DC converter prior to the charging module was eliminated, the ripple voltage would have to be better regulated (likely with increased capacitance) and turn on voltages would have to be regulated (perhaps with diodes of fixed turn-on voltages). Additionally, if the DC to DC converter that is after the battery were removed, than the versatility of the system would be reduced because the supplied voltage and current would limited to the battery's ratings. The current prototype utilizes electrolytic capacitors, which may also reduce the efficiency of the system. An improved design may utilize super capacitors, which will reduce the space requirement and improve efficiencies because the power loss does not scale quadratically with the ripple current.

14.2.2 Improvement in Size

In addition to the improvements that can be made to the circuitry, we would also suggest scaling the size of the system smaller. Originally we wanted to utilize higher numbers but smaller size canister generators for the design. Due to budget constraints (price per magnet) however, we determined to use larger canisters.

A simple model on power output per canister generator for using the scaled down dimensions was generated in MATLAB (Appendix W). We used this model and ran the model with different size and types of magnets. With a magnet, half the size of what we used in our prototype, we found that the output power assuming same efficiency as our prototype would be about the same for this scaled down device. The model uses a 0.5" by 0.5" by 0.5" square magnet, which the specifications may be found in Appendix X. In using this magnet, we would have square casing rather than tubes, which may increase the cost in manufacturing. Though, having the same number of canisters (20 canisters) of 1" by 1" by 3" generating 5 Watts of power would have much smaller volume displacement and mass. If this design were to be prototyped, we can estimate that the volume displacement to be 980 cm^3 and the mass to be 4 kg, while generating 5 Watts of power. This design still doesn't meet the volume displacement specification, but will significantly improve the total mass and power output specifications.

15 RECOMMENDATIONS

After completing our prototype, we have come to some conclusion regarding our design decisions. We have created a great initial design, but it can be improved in a multitude of ways. The main improvements will be centered on improving the efficiency of the generator to hit our 5 watt target. We believe this is achievable through some circuitry and canister design changes.

15.1 System Level

As discussed in section 14.2.2, one idea that we originally entertained before our current final design, was to have the devices be much smaller and to be fully integrated into the belt. They would be a maximum of 3 inches in length with smaller diameter canisters. The reason we never went forward with this idea is that it doesn't produce nearly enough power to meet our demand mainly due to the magnet mass being too small. We would recommend that if Harris thinks the canisters are too big that this idea should be put into place, but with the canister and coil oscillating around the magnet. This could be accomplished by adding a solid attachment from the belt to the magnet and designing a slot in which the canister can oscillate around the support. There could be some downfalls to this design such as debris getting in the canister but we feel many of these devices around the belt could produce the requisite amount of power due to the increased sprung mass on the belt.

Another system level modification that could be explored is improving canister design to a single tube. This tube would make the device easier to manufacture and to maintain as well as making it lighter. The coils could be pre-wound and inserted into a cavity in the center of canister eliminating magnetic field loses from the plastic. The canisters could also be made thinner reducing the overall weight of the design.

Integrating the rectifier and capacitor into the canister as we had originally designed would make our design more modular and allow the user to choose whatever amount of canisters they wanted. Our prototype currently puts the rectifier and capacitor inside of the black box but if we can make our capacitor smaller we could successfully add these things to the canister.

Another idea that could be implemented easily is a specially designed ALICE clip that is permanently attached to the canister. It could be attached by a wire like device or even bolted on to the canister. This would allow the user to not fumble with hooking the ALICE clip and canister together when attaching the generator to the belt.

We could also integrate coaxial cables into belt or canister for ease of use attaching the power side of the canister to the belt. We chose to attach the electrical connectors up to the belt using a special type of circuit wire connector in our prototype, but this leave the wires exposed to the elements. A coaxial power connector could prevent water and other debris from entering the system causing failure.

15.2 Component Level

One design change we may want to experiment with is a diametrically magnetized magnet. Our final design uses axially magnetized magnets. With a diametrically magnetized magnet, the highest magnetic flux is located at the coil. This could result in a higher magnetic flux density around the coils creating more power for the user. However this design will need to be explored in more detail.

Part of the problem with why our power is low is that our magnets don't weigh enough to generate the power we want. We can increase the mass of our magnet through either increasing its axial length or adding some non-metallic weight to it. Doubling the mass doubles the available amount of mechanical energy available to the electrical load. This would not increase the canister size and reduce the amount of canisters needed by half.

Improving the circuitry efficiency could improve power output by 3 or 4 times our current power output. We are getting lot of power to the circuit but a lot of potential power is lost in electricity conversion and other circuit elements needing a lot of power to operate. There are DC to DC converters available for purchase that would be near 100% efficiency as well as rectifiers that would be more expensive but more efficient as well. This combined with a more streamlined design of the circuitry would be a huge improvement in power.

Other consideration we have made are small things such as increasing battery charge capacity to 10 Watt hours this could improve the amount of charge storage making charging while walking an option and using walking to charge the battery to then charge mobile devices after stopping. We could use Lithium polymer battery and charger to get higher charge density and low weight in our set up. We could integrate an on off switch into circuitry to stop charging if the user prefers. Another minor design could be to build in a light to show battery charge level.

16 CONCLUSION

We were asked to produce a device that generates 5 Watts of electricity from human energy, while minimizing metabolic cost to the user. In order to accomplish this, we have created engineering specifications corresponding to our customer requirements. We have gone over these specifications and the set target values with our sponsor, Harris Corporation, to ensure that it will meet both their and our expectations for our intended purpose. We did this through a consideration of a functional decomposition, a concept classification tree, and a combination table. The brainstorming ideas were down selected by usage of multiple Pugh charts. In the Pugh charts, we compared each device to our engineering specifications and importance weights to determine our best concept, the Final prototype.

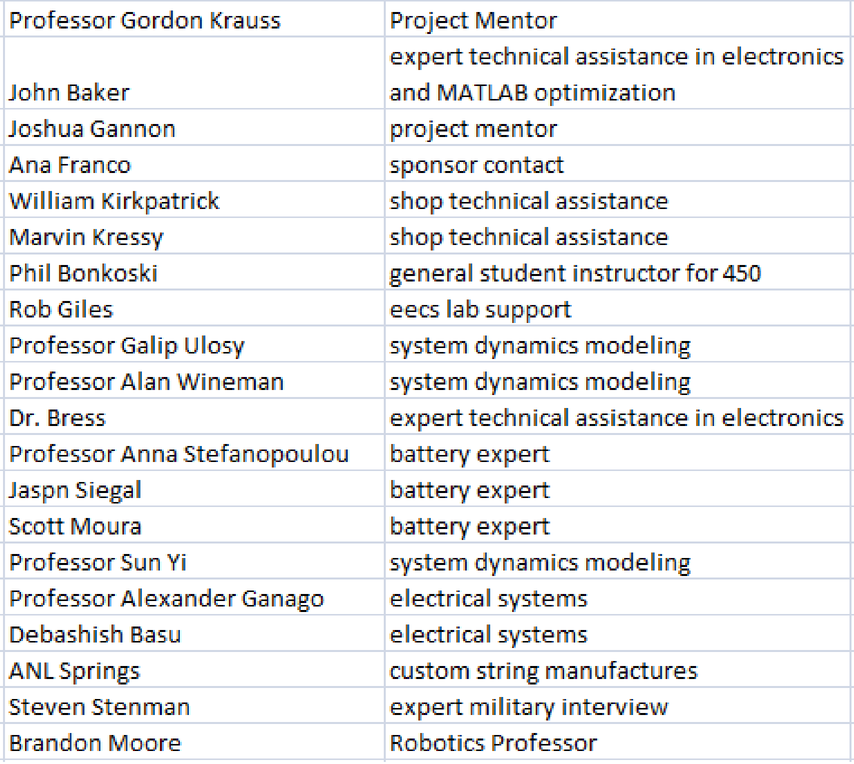
The energy must be made passively without the user's volition. This means our target customer the soldier must not be restricted in any way from performing any of their everyday military duties. After contemplating various solutions through modeling and testing of our mock up of the Alpha prototype, the canister device was finalized as the strongest option to meet these requirements.

The final prototype consists of a coupling between the mechanical and electrical portions of the device. It is a module design that can meet the individual power needs required of different soldiers in the field without inhibiting them from performing their daily task .The final prototype canister represents all engineering principles described in this report.

Further optimization of the final prototype is required to meet all required specifications. Our modeling has shown that these results are potentially achievable. The final design will generate, store and deliver energy while meeting all previously describe specifications from our customer.

17 ACKNOWLEDGEMENTS

We would like to thank all the people who have supported us throughout the project! Thank you



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Debashish Basu	electrical systems
ANL Springs	custom string manufactures
Steven Stenman	expert military interview
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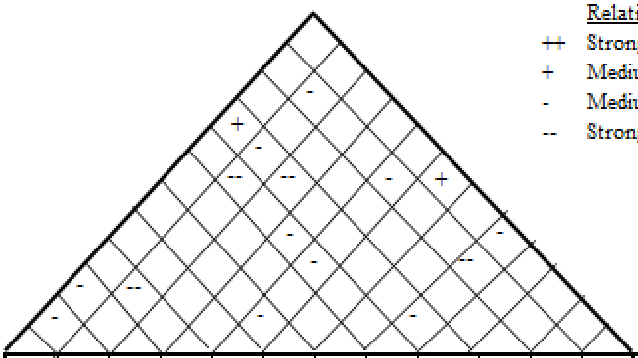
APPENDIX A QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD)

Relationships
++ Strong Positive
\+ Medium Positive
\- Medium Negative
-- Strong Negative



(+) => more is better
(-) => less is better

	Weight	Weight supported by core (-) [kg]	Power generated (+) [W]	Energy storage capacity (+) [Amp-hours]	Max temperature in contact with body (-) [°C]	Number of adjustable size settings (+)	Number of sharp or pinching parts (-)	Curvature of edges (radius) (+) [mm]	Cost of materials (-) [$]	Volume displacement (-) [m^3]	Time required for setup (-) [sec]	Percent of additional energy required to operate (-) [%]	Number of Moving Parts (-)	Benchmark Design #1	Benchmark Design #2	Benchmark Design #3
Safety	10	3			9	1	9	3		1				4	3	5
Generate and convert consistent powe	10		9									3		5	5	1
High power delivered	10		3	9	1							1		5	4	1
Reliable	9		1		1	1					1		9	4	3	4
Easy to operate	7					3					9		1	3	4	5
Low excess effort required	6	9								1	1	9		1	4	5
Weight is acceptable	6	9	1	3						1				1	3	5
Size is acceptable	5	1	1	1						9				1	3	5
Comfort is acceptable	4				3	3	3	3				3	1	2	3	5
Cost is acceptable	4		1	3		1			9	1				2	4	1
Appearance is acceptable	3							1		9			1	3	2	5
Total		143	144	125	121	56	102	45	36	98	78	106	95			
Normalized		0.1	0.1	0.1	0.1	0	0.1	0	0	0.08	0.1	0.1	0.1			
Importance Rating		**2**	**1**	**3**	**4**	**10**	**6**	**11**	**12**	**7**	**9**	**5**	**8**			
Measurement Unit		kg	W	A-hr	°C	#	#	mm	$	cm^3	sec	%	#			
Benchmarked Design #1		30	7.4	0	~	~	~	~	~	2500	~	~	~			
Benchmarked Design #2		1.6	5	0	~	~	~	~	~	500	~	~	~			
Benchmarked Design #3		0	0	0	~	~	~	~	~	40	~	~	~			

APPENDIX B ENVIRONMENTAL CONSIDERATIONS

This section presents a brief overview of the environmental engineering considerations as outlined by the United States Department of Defense. It is not intended that the prototype created by this design team will meet all of these environmental specifications, rather this section will outline the tailoring guidelines that we considered when determining an Alpha Design. We will determine which test procedures will be necessary for the personal device to be worn by a soldier. Additionally, we provide detailed analysis regarding the further improvements that must be made to this proof of concept in order to meet the environmental standards set forth by the U.S. Department of Defense in the Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [6]. Note: all method and procedure numbers mentioned in this section refer directly to the corresponding sections in U.S. Department of Defense in the Test Method Standard for Environmental Engineering Considerations and Laboratory Tests [6].

Pressure

The three main areas of consideration regarding pressure are: operation, low pressure storage, and rapid decompression. The device in review is designed for use by ground personnel and will have operating conditions close to 1 atm. Method 500.5 will be used to evaluate the device performance in response to transportation or storage in pressurized or unpressured areas of aircraft. A few specific considerations:

- Deformation of rupture of sealed containers, specifically the magnet-coil canister
- Evaporation of lubricants
- Failure of hermetic seals

We have identified the relevant procedures to be Procedure I and III. Procedure I evaluates pressure effects on the device and materials during storage and air transport. For procedure I, a low pressure of 57.2 kPa is required. Procedure III evaluates effects of rapid decompression on the device to determine if it will present a danger to nearby personnel or the transport platform. For procedure III, use 2,438m for the initial cabin altitude (75.2kPa), and 12,192m for the final cabin altitude after decompression (18.8kPa) and an altitude change rate of 10 m/s (corresponding to an altitude change rate of 7.6 m/s for a full military power takeoff).

Temperature

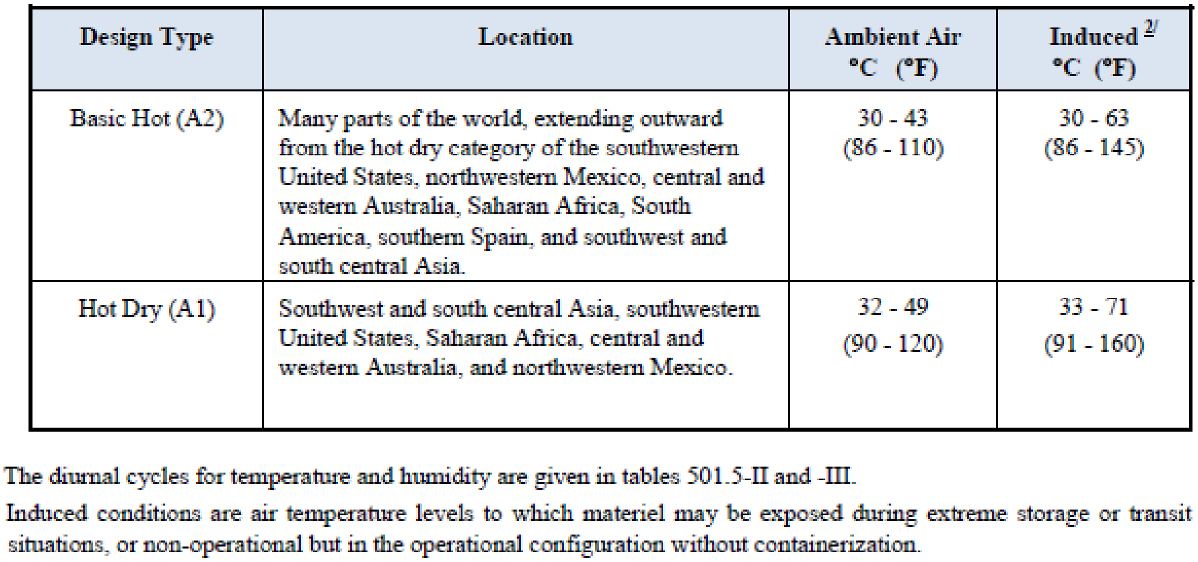
The main areas of consideration for temperature are low and high temperatures during both operation and storage as well as surface temperature and solar loading. The device in review is designed for use by ground personnel in all temperature regions. Method 501.5 will be used to evaluate device performance during and in response to high temperature effects. Method 502.5 will be used to evaluate device performance during and in response to low temperature effects. Method 503.5 and method 505.5 will be used to evaluate device performance in response to thermal shocks and solar radiation. A few specific considerations:

- Parts bind or warp from expansion/contraction of dissimilar materials
- Lubricants become more/less viscous
- Fixed-resistance resistors change in values
- Electronic circuit stability varies with differences in temperature gradients
- Transformers and electromechanical components overheat
- High pressures created within sealed containers
- Hardening, cracking, and embrittlement of materials
- Rapid water or frost formation in response to temperature shock
- Actinic (photodegredation) effects of direct sunshine (changes in elastomers and polymers)

All three procedures for high temperature considerations of method 501.5 should be considered. These procedures are Procedure I (storage), Procedure II (operation) and Procedure III (tactical-standby to operational).
All three procedures for low temperature considerations of method 502.5 should be considered. These procedures are Procedure I (storage), Procedure II (operation) and Procedure III (manipulation – ease in which the device can be assembled/disassembled by personnel wearing cold-weather clothing).

Exposure conditions and deployment configuration:
The device will be worn on the body of ground personnel and should therefore withstand temperatures equal to that of the corresponding climate. Geographical areas and the corresponding climate conditions are illustrated in Tables B.1, B.2 and B.3.

Table B.1 Summary of high temperature diurnal ranges.

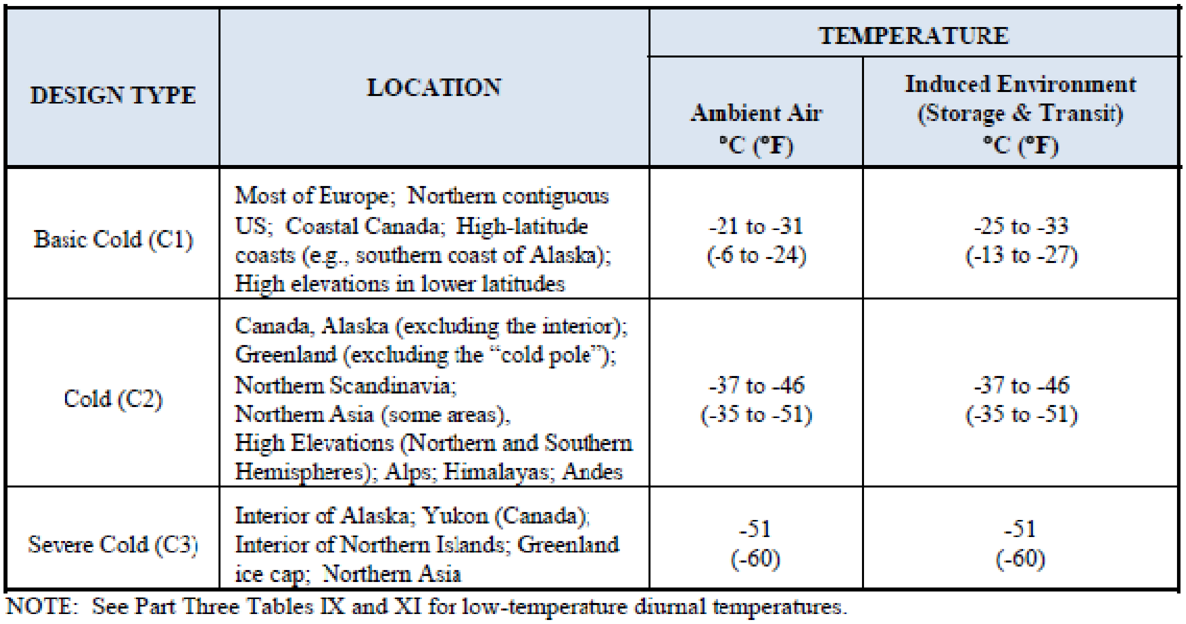


Design Type	**Location**	**Ambient Air °C (°F)**	**Induced [2] °C (°F)**
Basic Hot (A2)	Many parts of the world, extending outward from the hot dry category of the southwestern United States, northwestern Mexico, central and western Australia, Saharan Africa, South America, southern Spain, and southwest and south central Asia.	30 - 43 (86 - 110)	30 - 63 (86 - 145)
Hot Dry (A1)	Southwest and south central Asia, southwestern United States, Saharan Africa, central and western Australia, and northwestern Mexico.	32 - 49 (90 - 120)	33 - 71 (91 - 160)

[1] The diurnal cycles for temperature and humidity are given in tables 501.5-II and -III.

[2] Induced conditions are air temperature levels to which materiel may be exposed during extreme storage or transit situations, or non-operational but in the operational configuration without containerization.

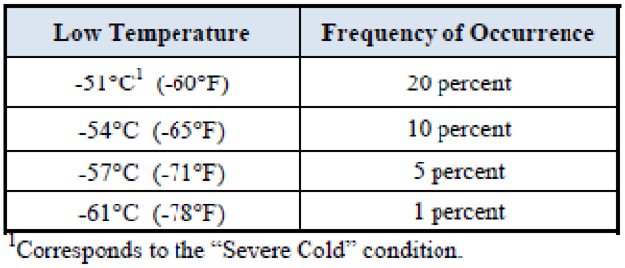
Table B.2 Summary of low temperature cycle ranges.



DESIGN TYPE	LOCATION	TEMPERATURE	
		Ambient Air °C (°F)	Induced Environment (Storage & Transit) °C (°F)
Basic Cold (C1)	Most of Europe; Northern contiguous US; Coastal Canada; High-latitude coasts (e.g., southern coast of Alaska); High elevations in lower latitudes	-21 to -31 (-6 to -24)	-25 to -33 (-13 to -27)
Cold (C2)	Canada, Alaska (excluding the interior); Greenland (excluding the "cold pole"); Northern Scandinavia; Northern Asia (some areas), High Elevations (Northern and Southern Hemispheres); Alps; Himalayas; Andes	-37 to -46 (-35 to -51)	-37 to -46 (-35 to -51)
Severe Cold (C3)	Interior of Alaska; Yukon (Canada); Interior of Northern Islands; Greenland ice cap; Northern Asia	-51 (-60)	-51 (-60)

NOTE: See Part Three Tables IX and XI for low-temperature diurnal temperatures.

Table B.3 Frequencies of occurrence of extreme low temperatures.



Low Temperature	Frequency of Occurrence
-51°C[1] (-60°F)	20 percent
-54°C (-65°F)	10 percent
-57°C (-71°F)	5 percent
-61°C (-78°F)	1 percent

[1] Corresponds to the "Severe Cold" condition.

Various configurations for storage and transport should be considered including the following:

- In a shipping/storage container or transit case
- Protected or unprotected (under canopy, enclosed, etc.)
- Modified with kits for special applications

Solar heating effects must also be considered when choosing materials in order to reduce or prevent:

- Weakening of solder joins and glued parts
- Changes in strength and elasticity
- "Deterioration of natural and synthetic elastomers and polymers through photochemical reactions initiated by shorter wavelength radiation. (High strength polymers such as Kevlar are noticeably affected by the visible spectrum. Deterioration and loss of strength can be driven by breakage of high-order bonds (such as pi and sigma bonds existing in carbon chain polymers) by radiation exposure.)"
- Difficulty in handling
- Blistering, peeling and de-lamination of composites and surface laminates

We plan on performing preliminary temperature analysis on the design prototype. The device will be subjected to temperatures ranging from -20 to 70 °C. The upper limit corresponds to maximum storage temperatures located in hot dry climates as designated by table B.1. The lower limit of -20 °C does not meet the minimum temperature shown in Table B.2, however we currently limited by the test apparatus.

Water

The main areas of consideration are rain, immersion, condensation due to humidity and icing. The device in review is designed for use by ground personal in all climate conditions. Method 506.5 will be used to evaluate device performance during and in response to rain, water spray and dripping water. Method 507.5 will help in considering the effects of humidity and method 512.5 presents guidelines for immersion considerations. A few specific considerations:

- Physical deterioration of material caused by water
- Effectiveness of cases and seals in preventing water penetration
- Capability of the device and material to satisfy performance requirements during and after exposure to water
- Corrosion of metals
- Electrical short circuits
- Binds moving parts (icing)

Procedure I of method 506.5 should be used and tests unprotected exposure to rain and blowing rain. Rainfall rates of up to 1.7 mm/min (4 in/hr) are recommended rainfall rates for this procedure. Effects of humidity are considered for three scenarios. Procedure I of method 507.5 evaluates effects of humidity during storage and typical use. Procedure II is an accelerated test and determined the effects of extreme humidity and temperature conditions, which are harsher than those found in the operating environment. Additional testing can be performed to evaluate the device in response to salt water, as outlined in Method 509.5, with emphasis on corrosion effects and electrical effects due to salt deposits.

In addition to rain and water spray, the device must withstand water immersion associated with swimming or fording. Typical immersion tests are performed up to a depth of 1 meter and must also account for the increased pressure associated with the water.

$$P = C \cdot d \qquad \text{Eq. 8}$$

Where, P is the pressure in kPa, d is the depth of water in meters, and C is a constant equal to 9.8 for fresh water and 10.045 for salt water.

In addition to water spray and immersion, we also consider freezing rain and icing scenarios. Method 521.3 describes the effects and tailoring considerations regarding freezing rain and icing.

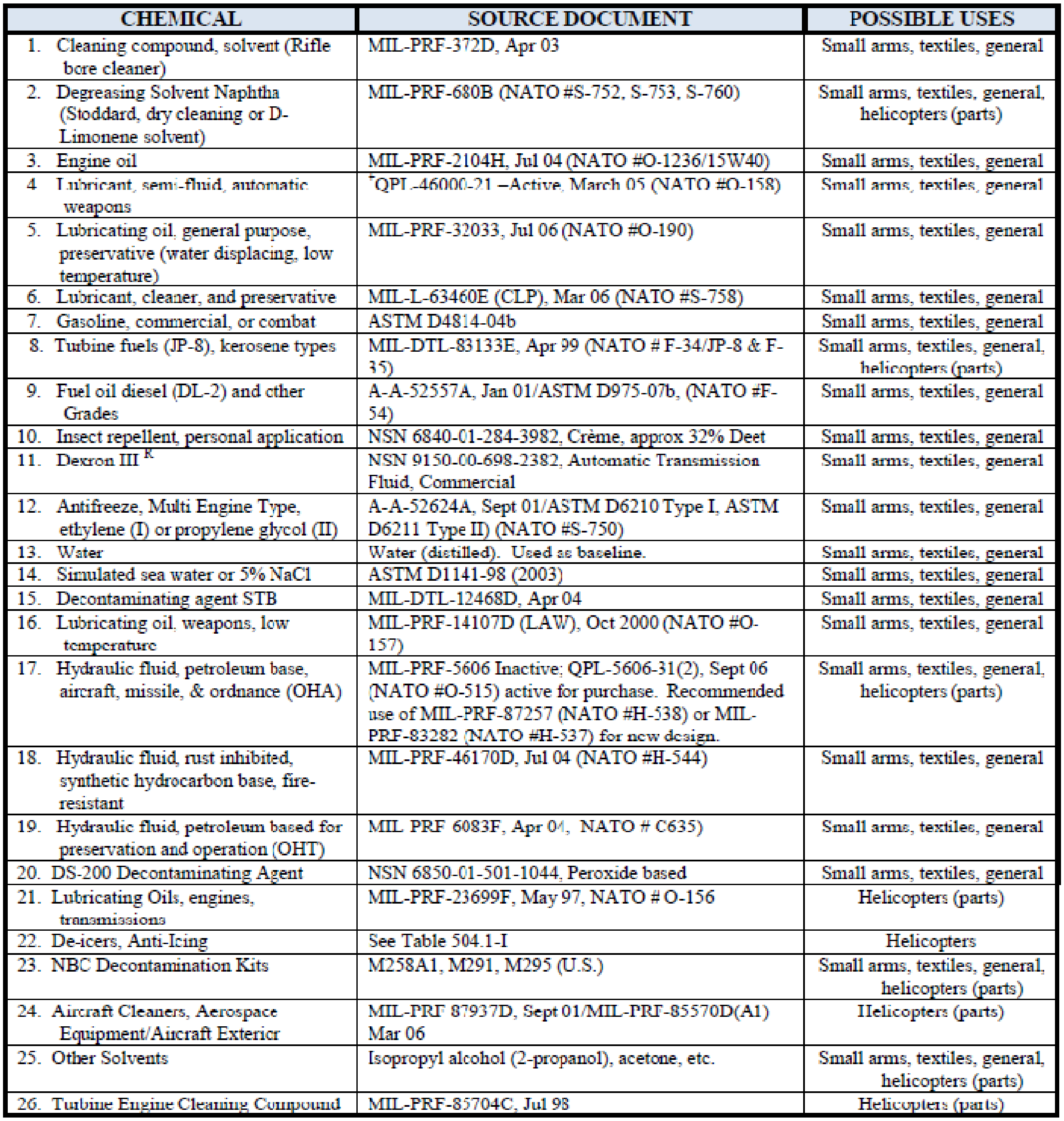
We do not plan on testing for water immersion of the preliminary prototype; however the design itself should easily lend itself to having all electronics enclosed in water resilient packaging. We do hope to develop test scenarios for humidity and indirect water spray.

Other Fluids

Small systems that are carried by ground personnel may be subject to contamination from fluids other than water. Method 504.1 will be used to evaluate device performance during and in response to fluids such as cleaning compounds, engine oil and gasoline. A complete list of these fluids can be found on the following page in Table B.4. Procedure II considers the occasional and intermittent exposure of small systems to contamination fluids.

With the exception of any exposed electrical components, all materials used in the prototype should demonstrate high resilience to all contamination fluids listed in Table B.4.

Table B.4 General test fluids used for fluid test procedure



CHEMICAL	SOURCE DOCUMENT	POSSIBLE USES
1. Cleaning compound, solvent (Rifle bore cleaner)	MIL-PRF-372D, Apr 03	Small arms, textiles, general
2. Degreasing Solvent Naphtha (Stoddard, dry cleaning or D-Limonene solvent)	MIL-PRF-680B (NATO #S-752, S-753, S-760)	Small arms, textiles, general, helicopters (parts)
3. Engine oil	MIL-PRF-2104H, Jul 04 (NATO #O-1236/15W40)	Small arms, textiles, general
4 Lubricant, semi-fluid, automatic weapons	*QPL-46000-21 –Active, March 05 (NATO #O-158)	Small arms, textiles, general
5. Lubricating oil, general purpose, preservative (water displacing, low temperature)	MIL-PRF-32033, Jul 06 (NATO #O-190)	Small arms, textiles, general
6. Lubricant, cleaner, and preservative	MIL-L-63460E (CLP), Mar 06 (NATO #S-758)	Small arms, textiles, general
7. Gasoline, commercial, or combat	ASTM D4814-04b	Small arms, textiles, general
8. Turbine fuels (JP-8), kerosene types	MIL-DTL-83133E, Apr 99 (NATO # F-34/JP-8 & F-35)	Small arms, textiles, general, helicopters (parts)
9. Fuel oil diesel (DL-2) and other Grades	A-A-52557A, Jan 01/ASTM D975-07b, (NATO #F-54)	Small arms, textiles, general
10. Insect repellent, personal application	NSN 6840-01-284-3982, Crème, approx 32% Deet	Small arms, textiles, general
11. Dexron III ^{R}	NSN 9150-00-698-2382, Automatic Transmission Fluid, Commercial	Small arms, textiles, general
12. Antifreeze, Multi Engine Type, ethylene (I) or propylene glycol (II)	A-A-52624A, Sept 01/ASTM D6210 Type I, ASTM D6211 Type II) (NATO #S-750)	Small arms, textiles, general
13. Water	Water (distilled). Used as baseline.	Small arms, textiles, general
14. Simulated sea water or 5% NaCl	ASTM D1141-98 (2003)	Small arms, textiles, general
15. Decontaminating agent STB	MIL-DTL-12468D, Apr 04	Small arms, textiles, general
16. Lubricating oil, weapons, low temperature	MIL-PRF-14107D (LAW), Oct 2000 (NATO #O-157)	Small arms, textiles, general
17. Hydraulic fluid, petroleum base, aircraft, missile, & ordnance (OHA)	MIL-PRF-5606 Inactive; QPL-5606-31(2), Sept 06 (NATO #O-515) active for purchase. Recommended use of MIL-PRF-87257 (NATO #H-538) or MIL-PRF-83282 (NATO #H-537) for new design.	Small arms, textiles, general, helicopters (parts)
18. Hydraulic fluid, rust inhibited, synthetic hydrocarbon base, fire-resistant	MIL-PRF-46170D, Jul 04 (NATO #H-544)	Small arms, textiles, general
19. Hydraulic fluid, petroleum based for preservation and operation (OHT)	MIL PRF 6083F, Apr 04, NATO # C635)	Small arms, textiles, general
20. DS-200 Decontaminating Agent	NSN 6850-01-501-1044, Peroxide based	Small arms, textiles, general
21. Lubricating Oils, engines, transmissions	MIL-PRF-23699F, May 97, NATO # O-156	Helicopters (parts)
22. De-icers, Anti-Icing	See Table 504.1-I	Helicopters
23. NBC Decontamination Kits	M258A1, M291, M295 (U.S.)	Small arms, textiles, general, helicopters (parts)
24. Aircraft Cleaners, Aerospace Equipment/Aircraft Exterior	MIL-PRF 87937D, Sept 01/MIL-PRF-85570D(A1) Mar 06	Helicopters (parts)
25. Other Solvents	Isopropyl alcohol (2-propanol), acetone, etc.	Small arms, textiles, general, helicopters (parts)
26. Turbine Engine Cleaning Compound	MIL-PRF-85704C, Jul 98	Helicopters (parts)

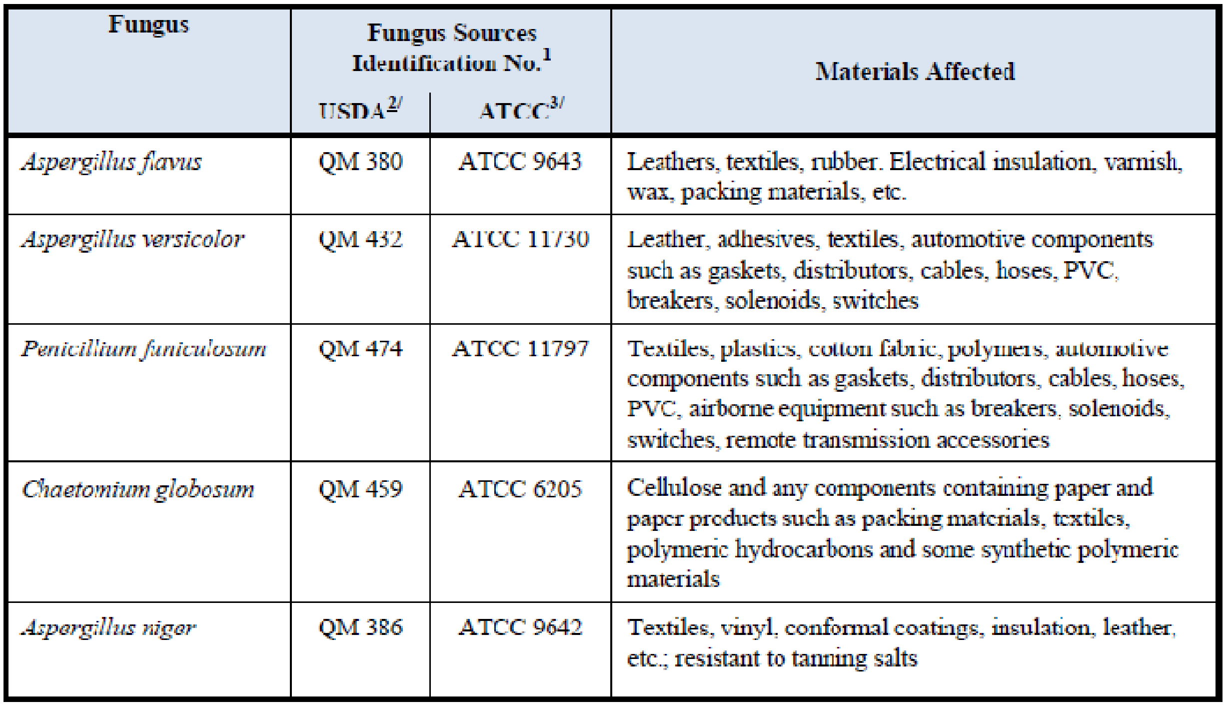
Fungus

In some instances, fungus growth can deteriorate material properties and present safety and functionality hazards to nearby personnel or equipment. Method 508.6 will provide tailoring guidelines to avoid detrimental effects of fungus growth. The purpose of this method is threefold: determine if fungus growth will occur, the impacts of the fungus on the material and device, and the ease in which the fungus can be prevented or removed (i.e. wiping off). Some materials affected by fungus growth, a detailed list of materials can be found in Table B.5. Commonly affected materials:

- Organic materials are most susceptible to direct physical break down due to fungus

- PVC and organic plastics

Table B.5 Test fungus and materials affected.



Fungus	Fungus Sources Identification No.[1]		Materials Affected
	USDA[2/]	ATCC[3/]	
Aspergillus flavus	QM 380	ATCC 9643	Leathers, textiles, rubber. Electrical insulation, varnish, wax, packing materials, etc.
Aspergillus versicolor	QM 432	ATCC 11730	Leather, adhesives, textiles, automotive components such as gaskets, distributors, cables, hoses, PVC, breakers, solenoids, switches
Penicillium funiculosum	QM 474	ATCC 11797	Textiles, plastics, cotton fabric, polymers, automotive components such as gaskets, distributors, cables, hoses, PVC, airborne equipment such as breakers, solenoids, switches, remote transmission accessories
Chaetomium globosum	QM 459	ATCC 6205	Cellulose and any components containing paper and paper products such as packing materials, textiles, polymeric hydrocarbons and some synthetic polymeric materials
Aspergillus niger	QM 386	ATCC 9642	Textiles, vinyl, conformal coatings, insulation, leather, etc.; resistant to tanning salts

We will be unable to test our prototype for fungus resilience.

Sand and Dust

Sand and dust can be detrimental to device performance, particularly when the sand or dust penetrates into small openings or between moving parts. Method 510.5 provides tailoring guidelines to improve material and device resistance to dust and sand effects. The following list provides a few examples of common problems associated with blowing dust or sand:

- Abrasion and erosion of surfaces
- Penetration or clogging of seals or openings
- Build up of electrostatic energy
- Interference of moving parts

We hope to develop a preliminary procedure to test the effects of sand and dust on our prototype. Tests we are considering including blowing sand and dust particles at the device with differing fan speeds.

APPENDIX C OUTLINE OF TASKS TO COMPLETE

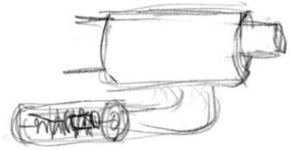
1. Problem Definition
    a. Develop profound understanding
    b. Decompose problem
    c. Identify and focus on critical sub problems
    d. Customer requirements
2. Benchmark
    a. Lead users
    b. Experts
    c. Patents
    d. Literature
    e. Competition
3. Brainstorm
    a. Individual
    b. Group
4. Explore systematically
    a. Classification Tree
    b. Combination Table

APPENDIX D IDEAS FROM BRAINSTORMING

Energy from Sound

- **Gun silencer:** The gun silencer idea shown in Figure D.1 consists of electromagnetic canister attached to the silencer to convert the force from air pressure into mechanical force, then to electricity.

Figure D.1: Gun silencer idea



- **Collect energy from sound (voice):** Our idea was to collect energy from vibrations in the human vocal code using piezoelectric materials attached to the throat.

Figure D.2: Piezoelectric throat strap to collect energy from human vocal cord

- **Carbon nanotubes implanted in vocal cords that use sound energy to produce power:** This idea is similar to the one described above. It would use piezoelectric materials implemented in to the throat.

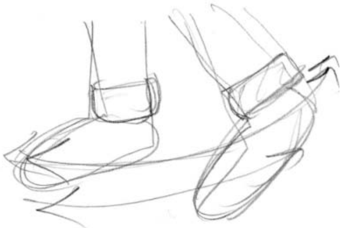
Energy from Stress and Bending

- **Energy generation when you press button of cell phone/ keyboard:** The idea for this was to collect energy from the stress generated in the buttons in the keypad when pushing. This will use piezoelectric material to generate energy.

Figure D.3: Keypad device idea

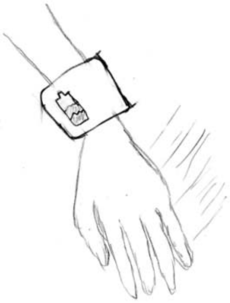
- **Device on ankle –magnets on each ankle:** The idea of this device uses the electromagnetic technology. The magnets implemented in each ankle would create change in magnetic flux every time the feet pass by each other while walking.

Figure D.4: Ankle magnet idea



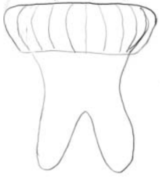
- **Device on wrist –motion of arm magnetic, oscillation:** This idea uses the electromagnetic system. The wristband with an electromagnetic device would generate energy with the swing in the arm.

Figure D.5: Wristband idea



- **Tooth cap:** The tooth cap idea gets energy from the up and down motion of jaw when eating or speaking, and the stress when chewing.

Figure D.6: Tooth cap idea



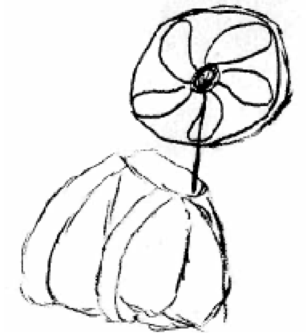
Energy from Wind

- **Turbine mouthpiece:** The mouthpiece that has a turbine in it to harness the power of you breathing. The wind that goes through your mouth while breathing will turn the turbines to generate power.

Figure D.7: Turbine mouthpiece idea

- **Portable turbine:** The portable turbine idea is shown below will have a turbine sticking out from the backpack, generating energy from the wind. The turbine can be stored in the backpack when not in use.

Figure D.8: Portable turbine idea



Vibration and Oscillation

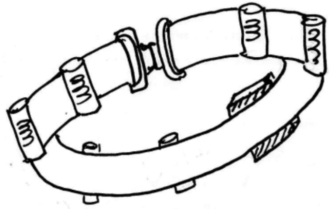
- **Knee brace:** The knee device will harness the wasted energy in the muscles around the knee in the walking motion. The device would have a regenerative brake to convert the kinetic energy applied to electricity.

Figure D.9: Knee brace idea

- **Elbow brace:** The elbow brace will harness energy from the bending in the elbow. This device works similar to the knee device.

- **Belt:** The belt idea consists of electromagnetic canisters to generate power from the vertical oscillations using an electromagnetic system.

Figure D.10: Belt idea



- **Sunglass:** The sunglass idea uses the concept of electromagnetic system and the solar energy. The blinking would create change in flux in the electromagnetic system and the sunlight would produce solar energy.

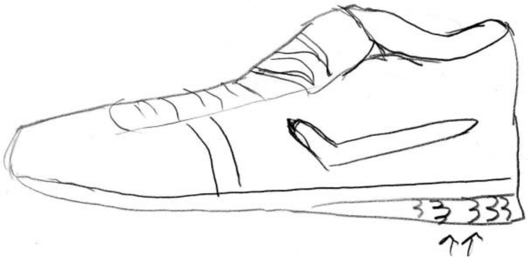
Figure D.11: Sunglass idea

- **Vibration while firing gun:** The gun idea would collect energy using an electromagnetic system. The vibrations from shooting would be converted to energy.

Figure D.12: Gunshot idea

- **Springs in heel:** The shoe idea using the electromagnetic system would have springs in the heel to generate power.

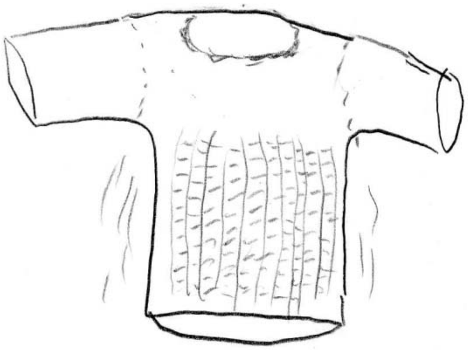
Figure D.13: Springs in heel idea



- **Heartbeat breathing:** This idea was to harness energy from the heartbeat and breathing. A turbine or electromagnetic generator would be implemented in the lungs to collect energy.

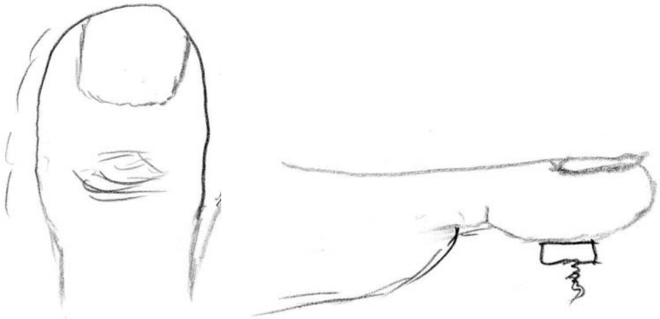
- **Body armor:** The body armor idea would collect energy from wearing a shirt-type body armor made of piezoelectric material. The small vibrations and friction from the daily human motion will be harnessed and energy would be generated.

Figure D.14: Body armor idea



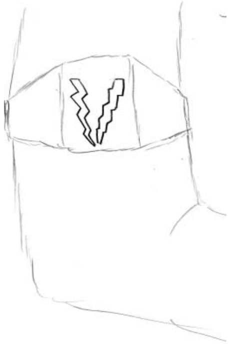
- **Toe wiggle:** The toe wiggle idea is to harness energy from the wiggling of the toe. The energy could be harnessed through a biomechanical method or from using piezoelectric materials.

Figure D.15: Toe wiggle idea



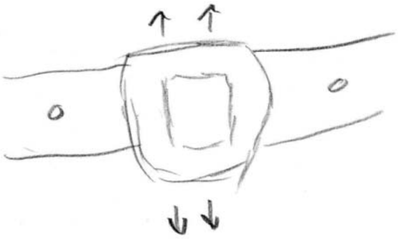
- **Armband:** The armband idea is to have a generator inside of an iPod-like device strapped to arm that uses arm motion to create energy from walking. This would use an electromagnetic system.

Figure D.16: Armband idea



- **Pedometer-type device:** This device would be attached to a belt and collect energy using electromagnetic systems.

Figure D.17: Pedometer idea

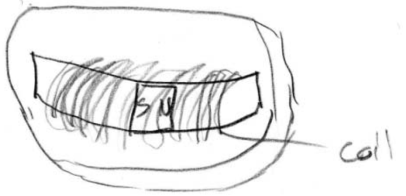


- **Anklet:** This idea consists of a generator on the ankle that would charge battery in shoe when walking. This would use an electromagnetic system or a regenerative brake biomechanical system.

Figure D.18: Anklet idea

- **Magnet in a circular path, like bearing on arm:** This device will be attached to the arm like an armband. The magnet would go around the circular path with coils, generating energy using electromagnetic inductance.

Figure D.19: Magnet generator idea



- **Suspended load backpack:** The suspended load backpack was one of the benchmarked ideas, though our idea was to implement a simple electromagnetic canister similar to the belt idea (but bigger) in the backpack.

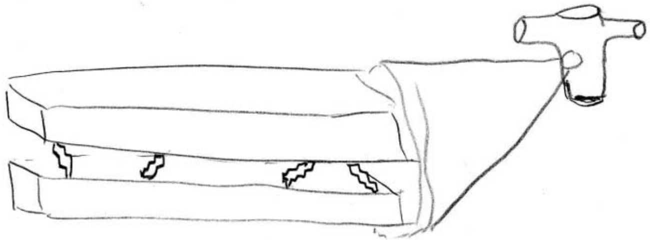
Figure D.20: Backpack idea

Energy from Friction

- **Device to harness friction in shoe from walking:** This device would generate energy from the friction in the shoe, generating static electricity.

- **Electrostatic shirt:** This shirt would generate static electricity from the friction in the opposing material of layers of fabric.

Figure D.21: Electrostatic shirt idea



Energy from Change in Temperature

- **Fins on a shirt:** This idea consists of fins attached to the shirt, which goes from the chest to ambient. The temperature difference would generate energy using heat gradient to harness body core energy.

Figure D.22: Fins on shirt idea

- **Collect energy from heat:** We had an idea to collect energy from heat. This would generate energy from the phase changes of sweat. This means that more you workout, more energy you get.

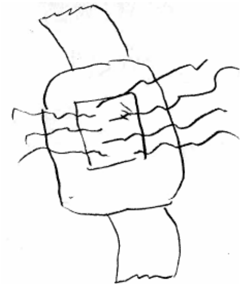
- **Clothing collecting heat energy and energy from bending:** The idea was to collect body heat to generate energy using a thermoelectric generator, and piezoelectric material to collect energy from bending.

- **Absorbent material:** This idea was to harness energy from the human sweating. The phase change in sweat to vapor has potential for energy generation. Thermo gradient would be considered.

Figure D.23: Absorbent material idea

- **Inferred radiation:** Inferred radiation from the human body has potential to generate energy.

Figure D.24: Inferred radiation idea

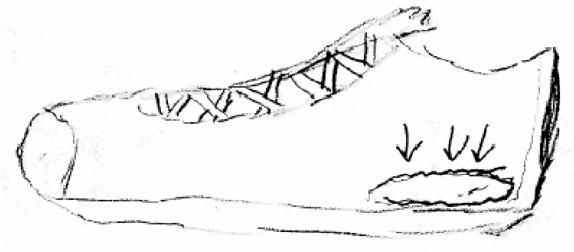


Other Spontaneous Ideas

- **Mechanical system:** The idea was to make every electrical device into a mechanical system, like the wristwatches.

- **Hydraulic pump in shoe:** A bladder that is compressed accumulates pressure that would later be converted into energy.

Figure D.25: Hydraulic pump in shoe



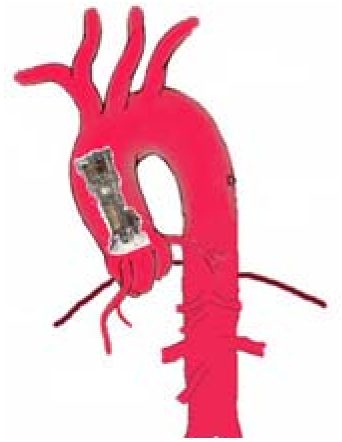
- **Swallowing:** This idea was using piezoelectric material to collect energy from the throat movement when swallowing.

- **Carbon nanotube hat:** The idea was to use carbon nanotubes in hats to harness the static electricity generated from wearing your hat

- **Carbon nanotube gloves:** The idea was to use carbon nanotubes in gloves so produce energy to power a hand held device.

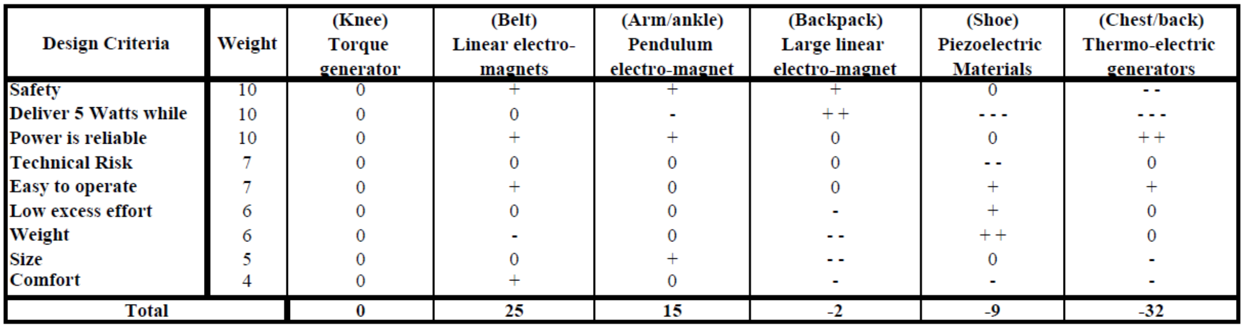
- **Turbine in heart:** We would harness the energy of the heart by putting a turbine in your aorta.

Figure D.26: Turbine in heart



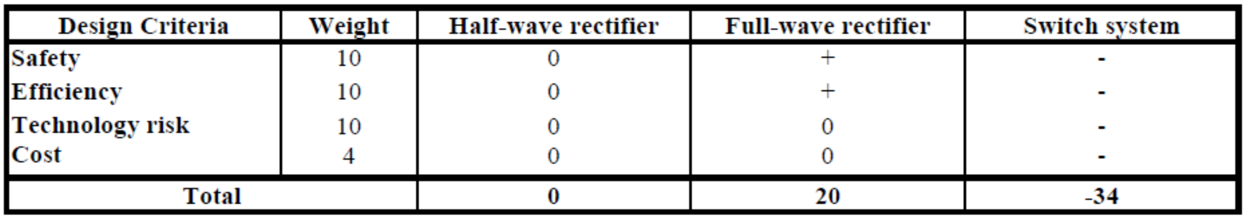
APPENDIX E PUGH CHARTS

Down selection of location, technology and device:



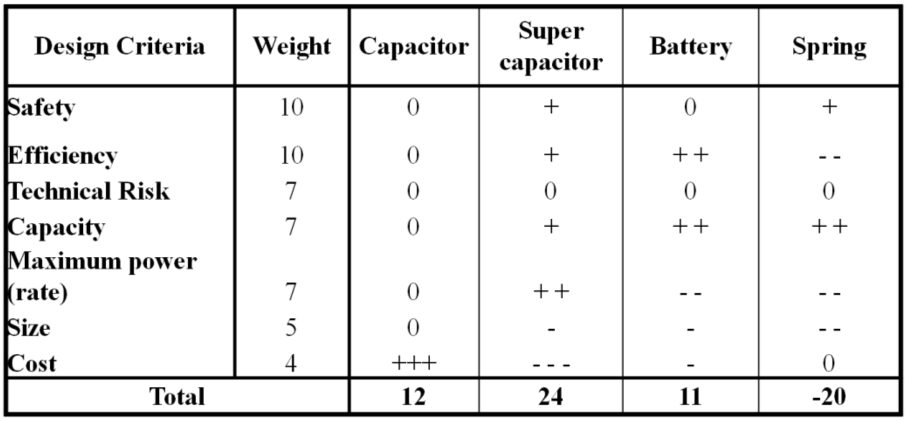
Design Criteria	Weight	(Knee) Torque generator	(Belt) Linear electro-magnets	(Arm/ankle) Pendulum electro-magnet	(Backpack) Large linear electro-magnet	(Shoe) Piezoelectric Materials	(Chest/back) Thermo-electric generators
Safety	10	0	+	+	+	0	- -
Deliver 5 Watts while	10	0	0	-	+ +	- - -	- - -
Power is reliable	10	0	+	+	0	0	+ +
Technical Risk	7	0	0	0	0	- -	0
Easy to operate	7	0	+	0	0	+	+
Low excess effort	6	0	0	0	-	+	0
Weight	6	0	-	0	- -	+ +	0
Size	5	0	0	+	- -	0	-
Comfort	4	0	+	0	-	-	-
Total		**0**	**25**	**15**	**-2**	**-9**	**-32**

Down selection of method of converting AC to DC:



Design Criteria	Weight	Half-wave rectifier	Full-wave rectifier	Switch system
Safety	10	0	+	-
Efficiency	10	0	+	-
Technology risk	10	0	0	-
Cost	4	0	0	-
Total		**0**	**20**	**-34**

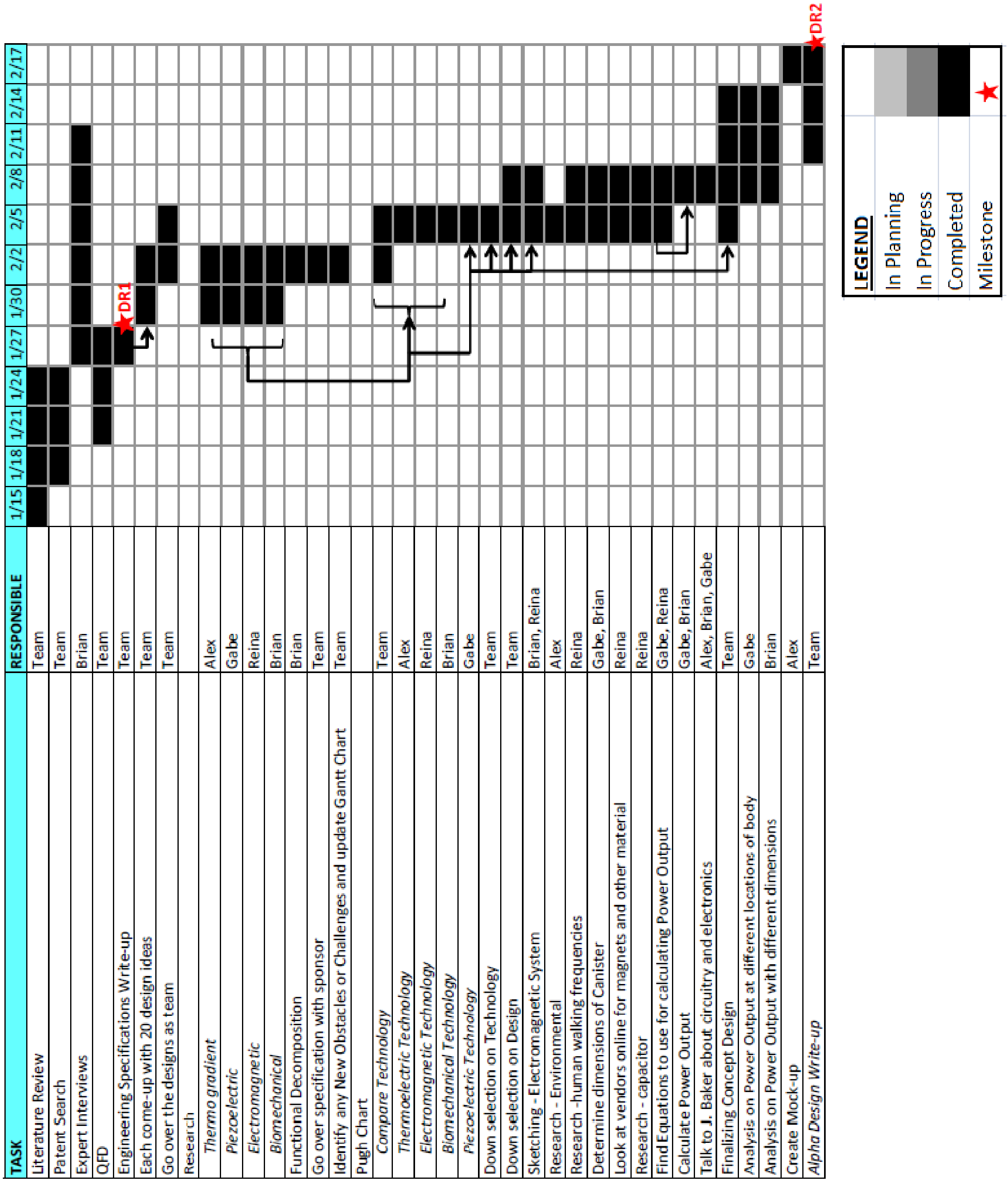
Down selection of component for controlling electrical spikes and temporal energy storage:



Design Criteria	Weight	Capacitor	Super capacitor	Battery	Spring
Safety	10	0	+	0	+
Efficiency	10	0	+	+ +	- -
Technical Risk	7	0	0	0	0
Capacity	7	0	+	+ +	+ +
Maximum power (rate)	7	0	+ +	- -	- -
Size	5	0	-	-	- -
Cost	4	+++	- - -	-	0
Total		**12**	**24**	**11**	**-20**

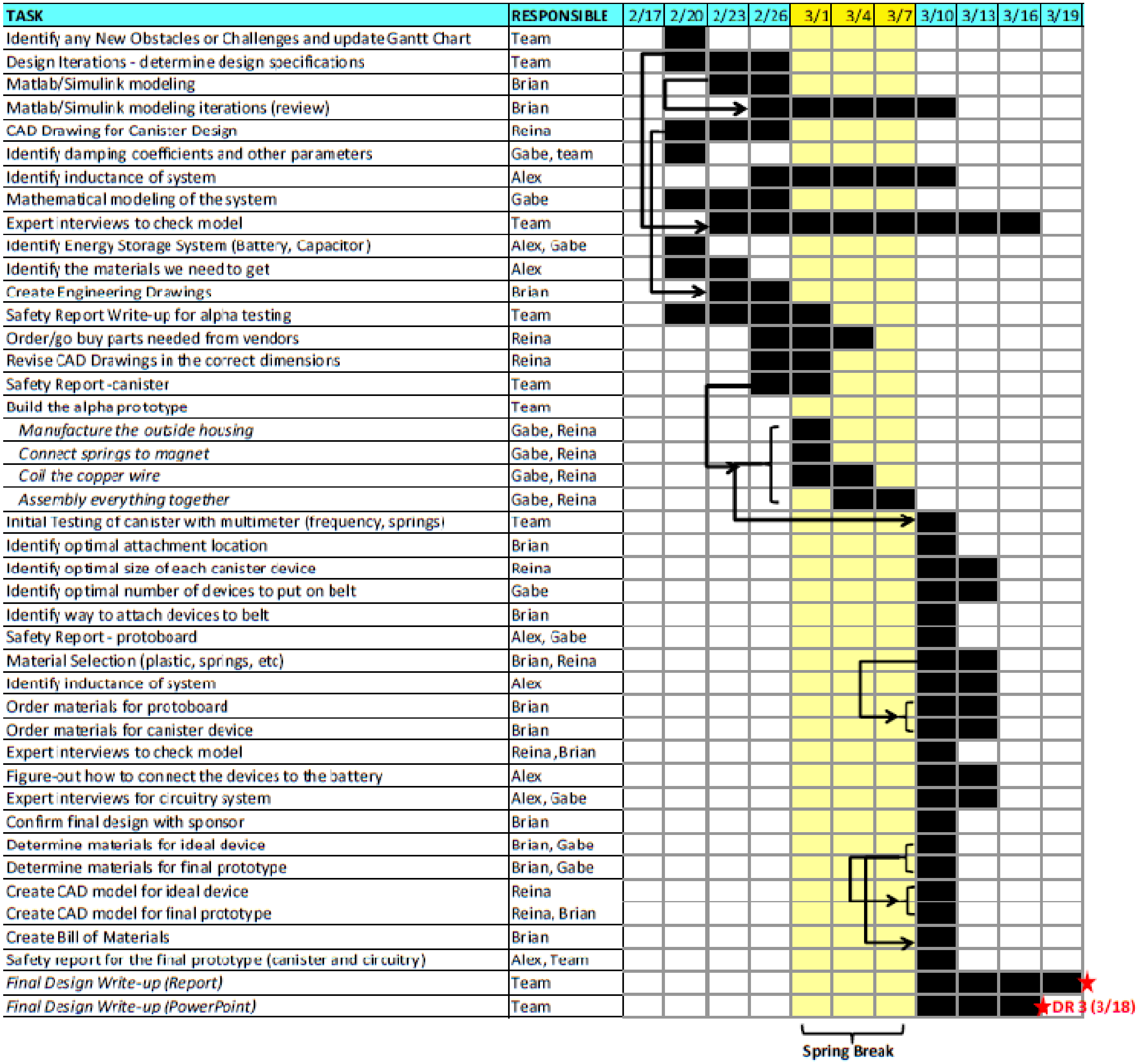
APPENDIX F GANTT CHARTS

The Gantt charts are summarized into three parts. The first two Gantt Charts cover what we have done so far, and the third is the Gantt chart for what we will be doing till the end of this project.

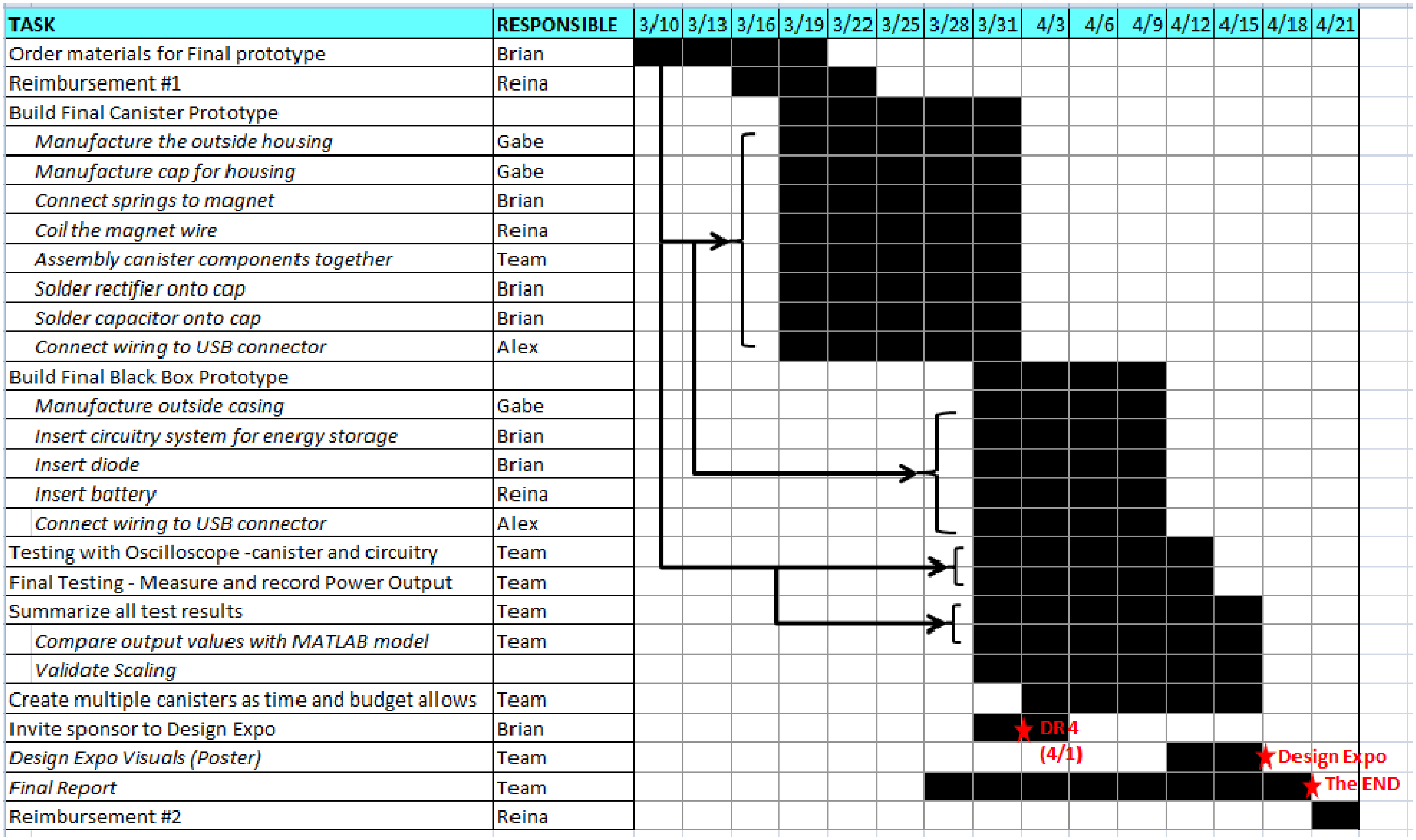


TASK	RESPONSIBLE	1/15	1/18	1/21	1/24	1/27	1/30	2/2	2/5	2/8	2/11	2/14	2/17
Literature Review	Team	■	■	■	■								
Patent Search	Team		■	■	■								
Expert Interviews	Brian					■	■	■	■	■	■		
QFD	Team			■	■	■							
Engineering Specifications Write-up	Team					■ ★DR1							
Each come-up with 20 design ideas	Team						■	■					
Go over the designs as team	Team							■	■				
Research													
Thermo gradient	Alex						■	■					
Piezoelectric	Gabe						■	■					
Electromagnetic	Reina						■	■					
Biomechanical	Brian						■	■					
Functional Decomposition	Brian							■					
Go over specification with sponsor	Team							■					
Identify any New Obstacles or Challenges and update Gantt Chart	Team							■					
Pugh Chart													
Compare Technology	Team							■	■				
Thermoelectric Technology	Alex								■				
Electromagnetic Technology	Reina								■				
Biomechanical Technology	Brian								■				
Piezoelectric Technology	Gabe								■				
Down selection on Technology	Team								■				
Down selection on Design	Team								■	■			
Sketching - Electromagnetic System	Brian, Reina								■	■			
Research - Environmental	Alex								■				
Research -human walking frequencies	Reina								■	■			
Determine dimensions of Canister	Gabe, Brian								■	■			
Look at vendors online for magnets and other material	Reina								■	■			
Research - capacitor	Reina								■	■			
Find Equations to use for calculating Power Output	Gabe, Reina								■	■			
Calculate Power Output	Gabe, Brian									■			
Talk to J. Baker about circuitry and electronics	Alex, Brian, Gabe									■			
Finalizing Concept Design	Team								■	■	■	■	
Analysis on Power Output at different locations of body	Gabe									■	■	■	
Analysis on Power Output with different dimensions	Brian									■	■	■	
Create Mock-up	Alex												■
Alpha Design Write-up	Team										■	■	■ ★DR2

LEGEND
In Planning
In Progress
■ Completed
★ Milestone



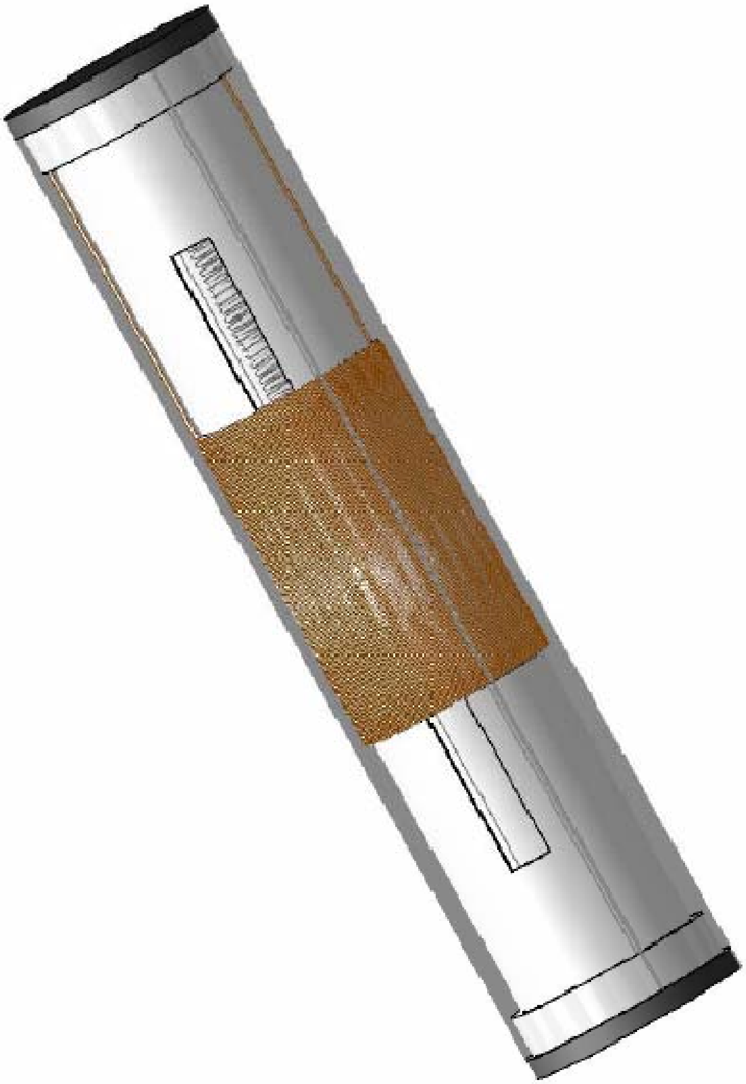
TASK	RESPONSIBLE	2/17	2/20	2/23	2/26	3/1	3/4	3/7	3/10	3/13	3/16	3/19
Identify any New Obstacles or Challenges and update Gantt Chart	Team		■									
Design Iterations - determine design specifications	Team		■	■	■							
Matlab/Simulink modeling	Brian			■	■							
Matlab/Simulink modeling iterations (review)	Brian				■	■	■	■	■			
CAD Drawing for Canister Design	Reina		■	■	■							
Identify damping coefficients and other parameters	Gabe, team		■									
Identify inductance of system	Alex				■	■	■	■	■			
Mathematical modeling of the system	Gabe		■	■	■							
Expert interviews to check model	Team			■	■	■	■	■	■	■	■	
Identify Energy Storage System (Battery, Capacitor)	Alex, Gabe		■									
Identify the materials we need to get	Alex		■	■								
Create Engineering Drawings	Brian			■	■							
Safety Report Write-up for alpha testing	Team		■	■	■	■						
Order/go buy parts needed from vendors	Reina				■	■	■					
Revise CAD Drawings in the correct dimensions	Reina				■	■						
Safety Report - canister	Team				■	■						
Build the alpha prototype	Team											
Manufacture the outside housing	Gabe, Reina					■						
Connect springs to magnet	Gabe, Reina					■						
Coil the copper wire	Gabe, Reina					■	■					
Assembly everything together	Gabe, Reina						■	■				
Initial Testing of canister with multimeter (frequency, springs)	Team								■			
Identify optimal attachment location	Brian								■			
Identify optimal size of each canister device	Reina								■	■		
Identify optimal number of devices to put on belt	Gabe								■	■		
Identify way to attach devices to belt	Brian								■			
Safety Report - protoboard	Alex, Gabe								■			
Material Selection (plastic, springs, etc)	Brian, Reina								■	■		
Identify inductance of system	Alex								■	■		
Order materials for protoboard	Brian								■	■		
Order materials for canister device	Brian								■	■		
Expert interviews to check model	Reina, Brian								■			
Figure-out how to connect the devices to the battery	Alex								■	■		
Expert interviews for circuitry system	Alex, Gabe								■	■		
Confirm final design with sponsor	Brian								■			
Determine materials for ideal device	Brian, Gabe								■			
Determine materials for final prototype	Brian, Gabe								■			
Create CAD model for ideal device	Reina								■			
Create CAD model for final prototype	Reina, Brian								■			
Create Bill of Materials	Brian								■			
Safety report for the final prototype (canister and circuitry)	Alex, Team								■			
Final Design Write-up (Report)	Team								■	■	■	■
Final Design Write-up (PowerPoint)	Team								■	■	■	



TASK	RESPONSIBLE	3/10	3/13	3/16	3/19	3/22	3/25	3/28	3/31	4/3	4/6	4/9	4/12	4/15	4/18	4/21
Order materials for Final prototype	Brian	■	■	■	■											
Reimbursement #1	Reina			■	■	■										
Build Final Canister Prototype					■	■	■	■	■							
Manufacture the outside housing	Gabe				■	■	■	■	■							
Manufacture cap for housing	Gabe				■	■	■	■	■							
Connect springs to magnet	Brian				■	■	■	■	■							
Coil the magnet wire	Reina				■	■	■	■	■							
Assembly canister components together	Team				■	■	■	■	■							
Solder rectifier onto cap	Brian				■	■	■	■	■							
Solder capacitor onto cap	Brian				■	■	■	■	■							
Connect wiring to USB connector	Alex				■	■	■	■	■							
Build Final Black Box Prototype									■	■	■	■				
Manufacture outside casing	Gabe								■	■	■	■				
Insert circuitry system for energy storage	Brian								■	■	■	■				
Insert diode	Brian								■	■	■	■				
Insert battery	Reina								■	■	■	■				
Connect wiring to USB connector	Alex								■	■	■	■				
Testing with Oscilloscope -canister and circuitry	Team								■	■	■	■	■			
Final Testing - Measure and record Power Output	Team								■	■	■	■	■			
Summarize all test results	Team								■	■	■	■	■	■		
Compare output values with MATLAB model	Team								■	■	■	■	■	■		
Validate Scaling									■	■	■	■	■	■		
Create multiple canisters as time and budget allows	Team									■	■	■	■	■		
Invite sponsor to Design Expo	Brian								■	★ DR 4 (4/1)						
Design Expo Visuals (Poster)	Team												■	■	★ Design Expo	
Final Report	Team							■	■	■	■	■	■	■	■	★ The END
Reimbursement #2	Reina															■

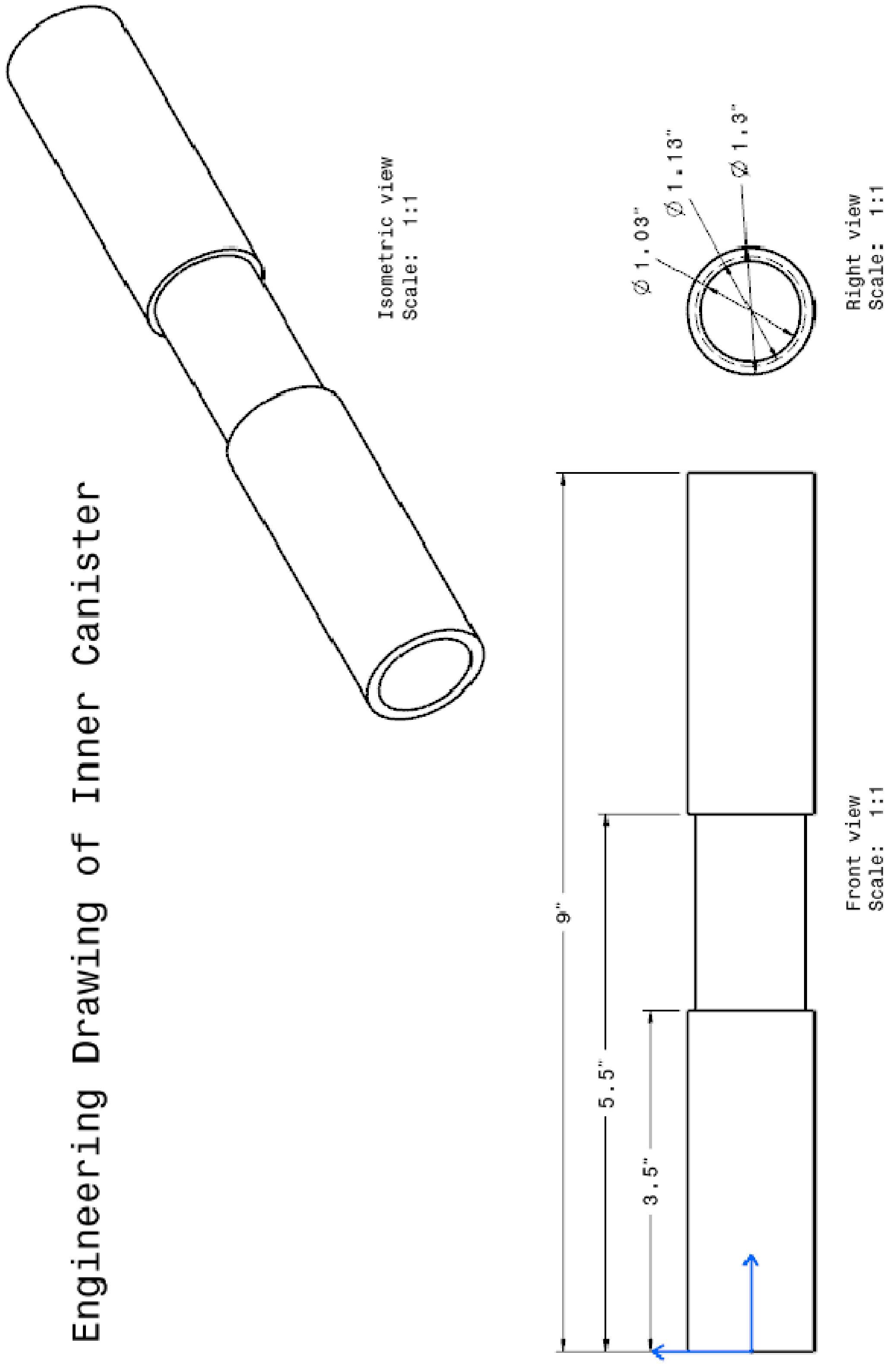
APPENDIX G ENGINEERING DRAWINGS

Final Design overview

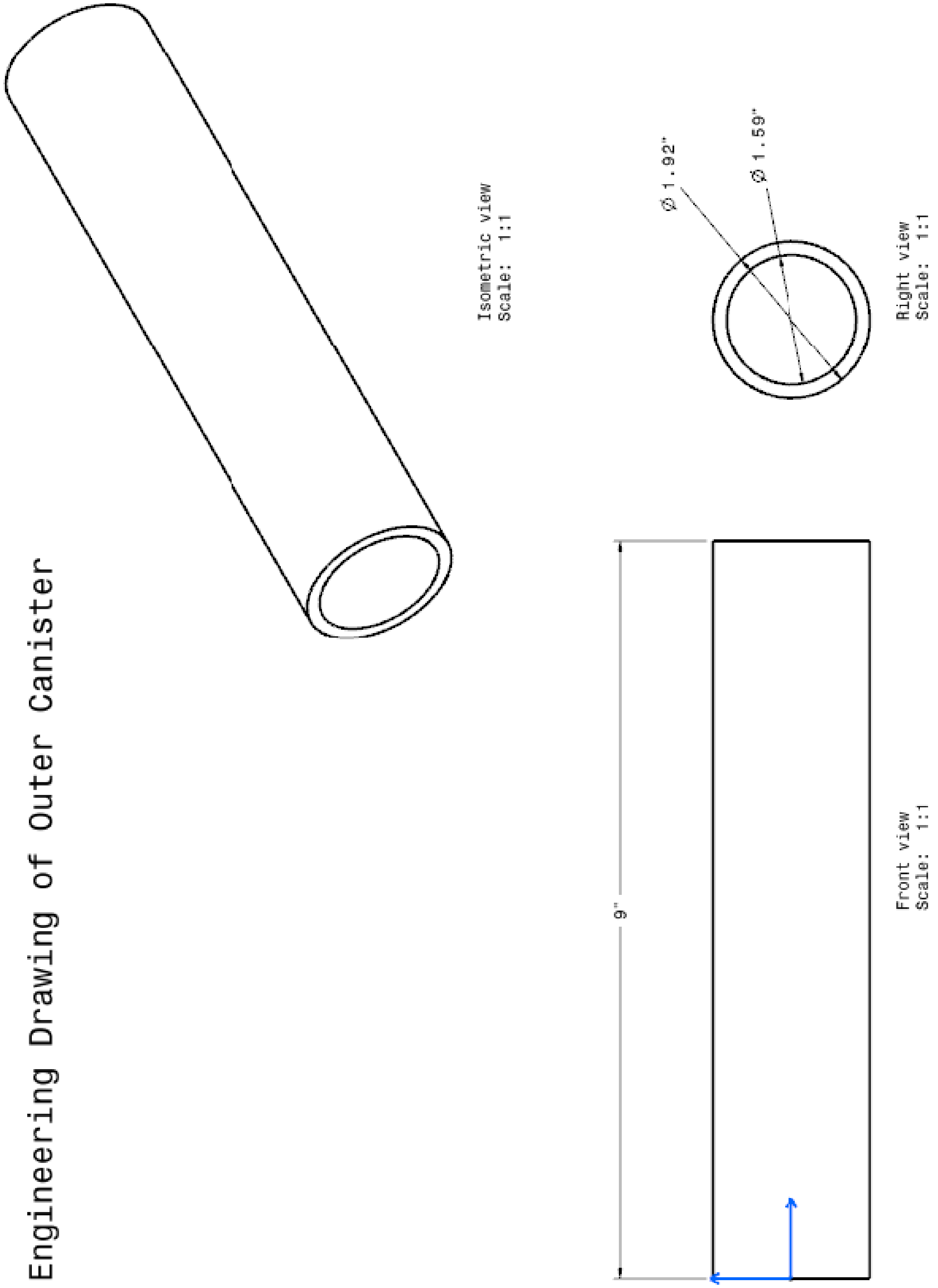


Note: outer casing is rendered transparent to see inner components. Slots are included only on the inner casing.

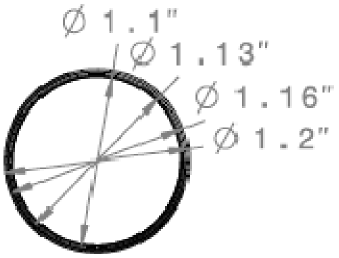
CAD drawing of Inner Canister



CAD drawing of Outer Canister

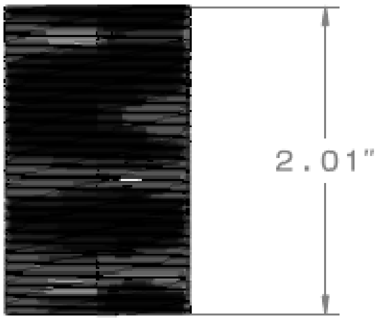


CAD drawing of Magnetic Coils



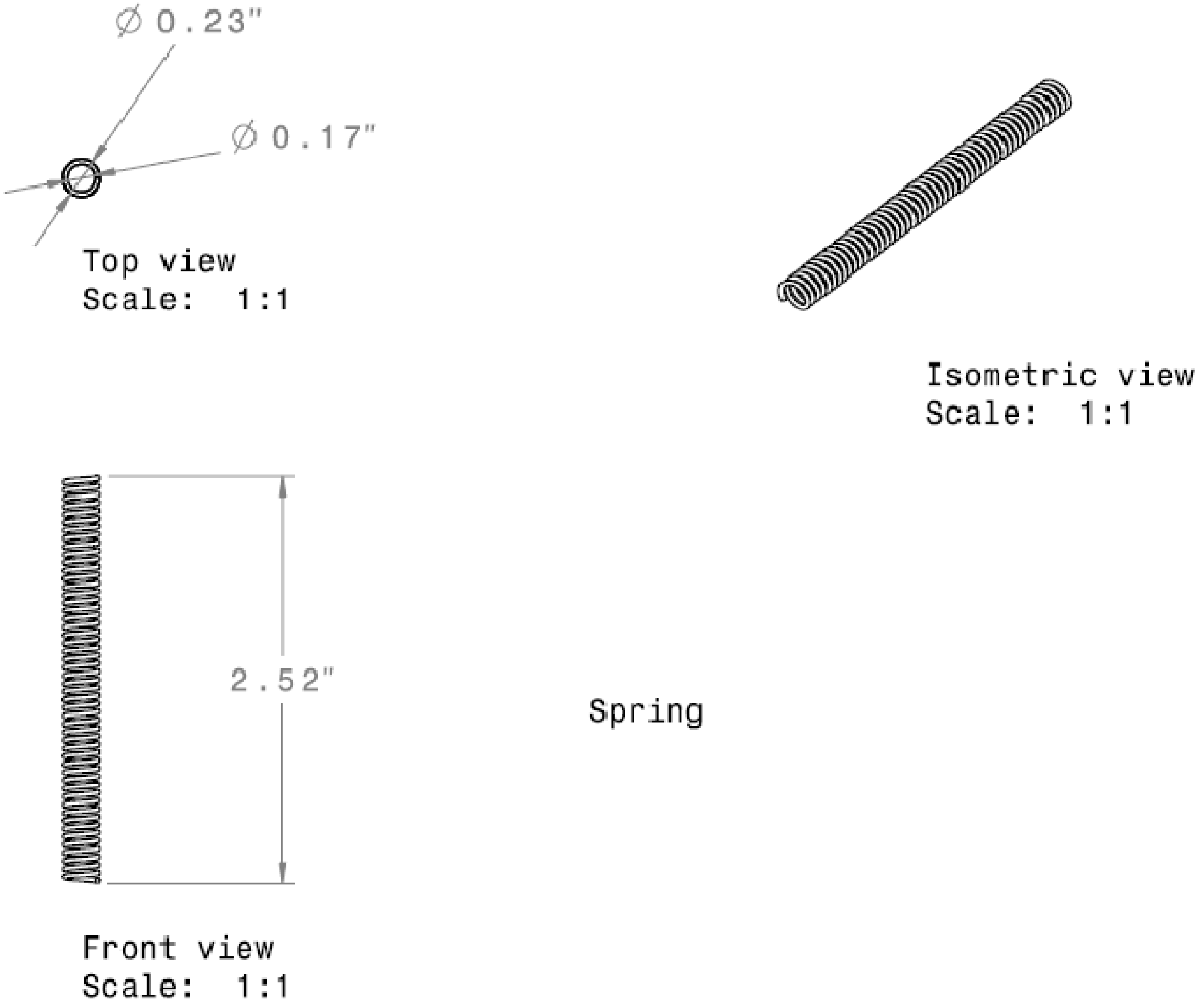
Top view
Scale: 1:1

Isometric view
Scale: 1:1



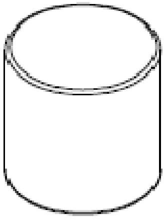
Front view
Scale: 1:1

CAD drawing of Extension Spring

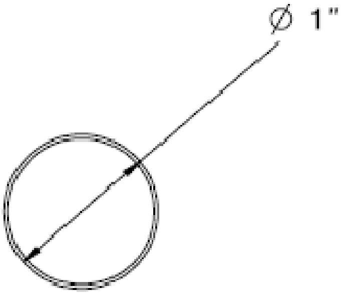


CAD drawing of Magnet

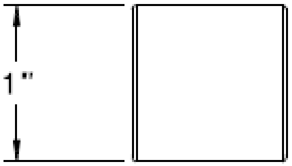
1" dia x 1" N52 Neodymium magnet



Isometric view
Scale: 1:1

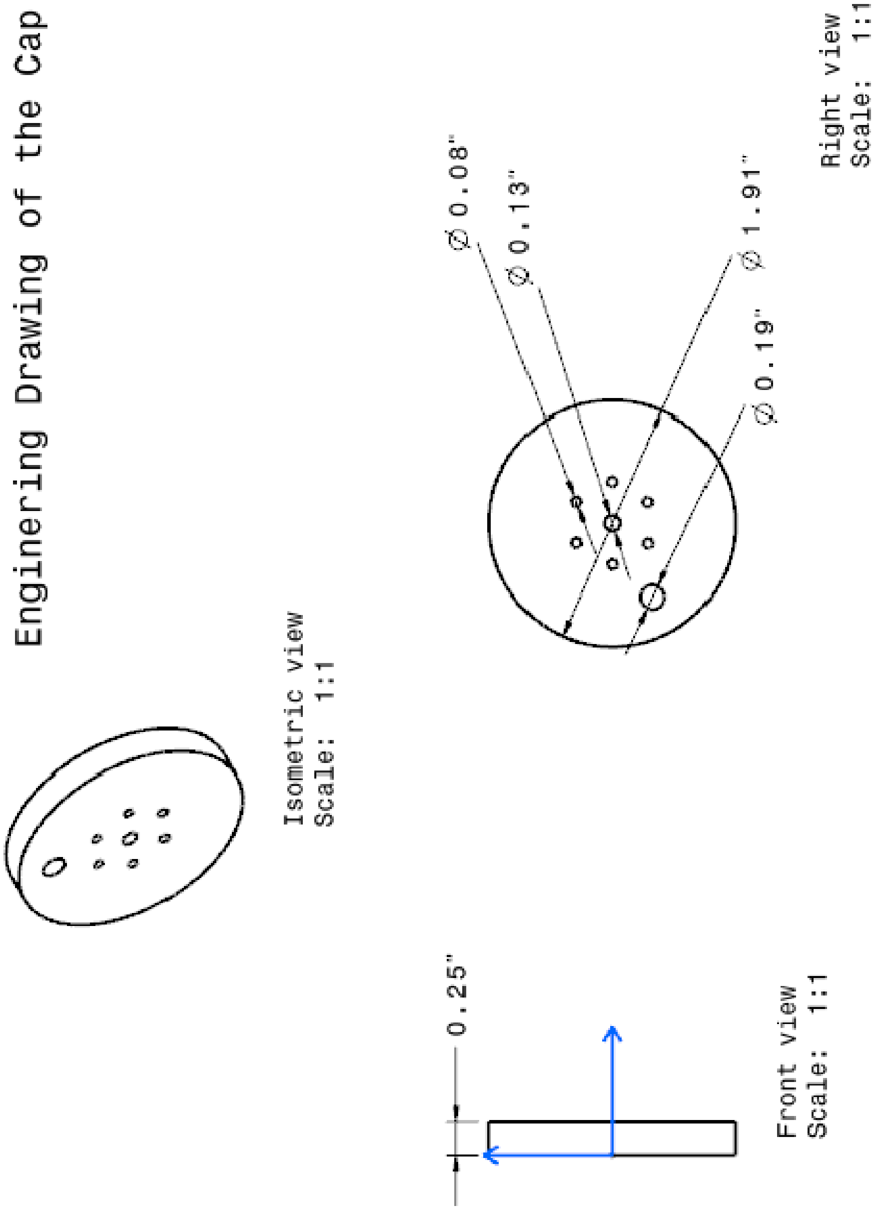


Front view
Scale: 1:1

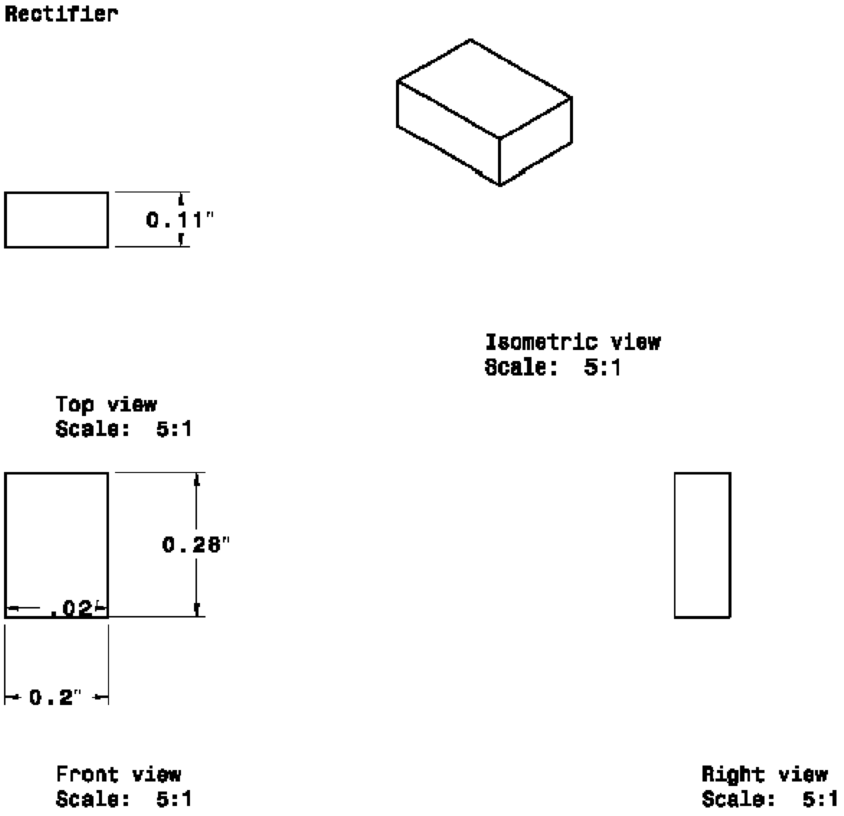


Right view
Scale: 1:1

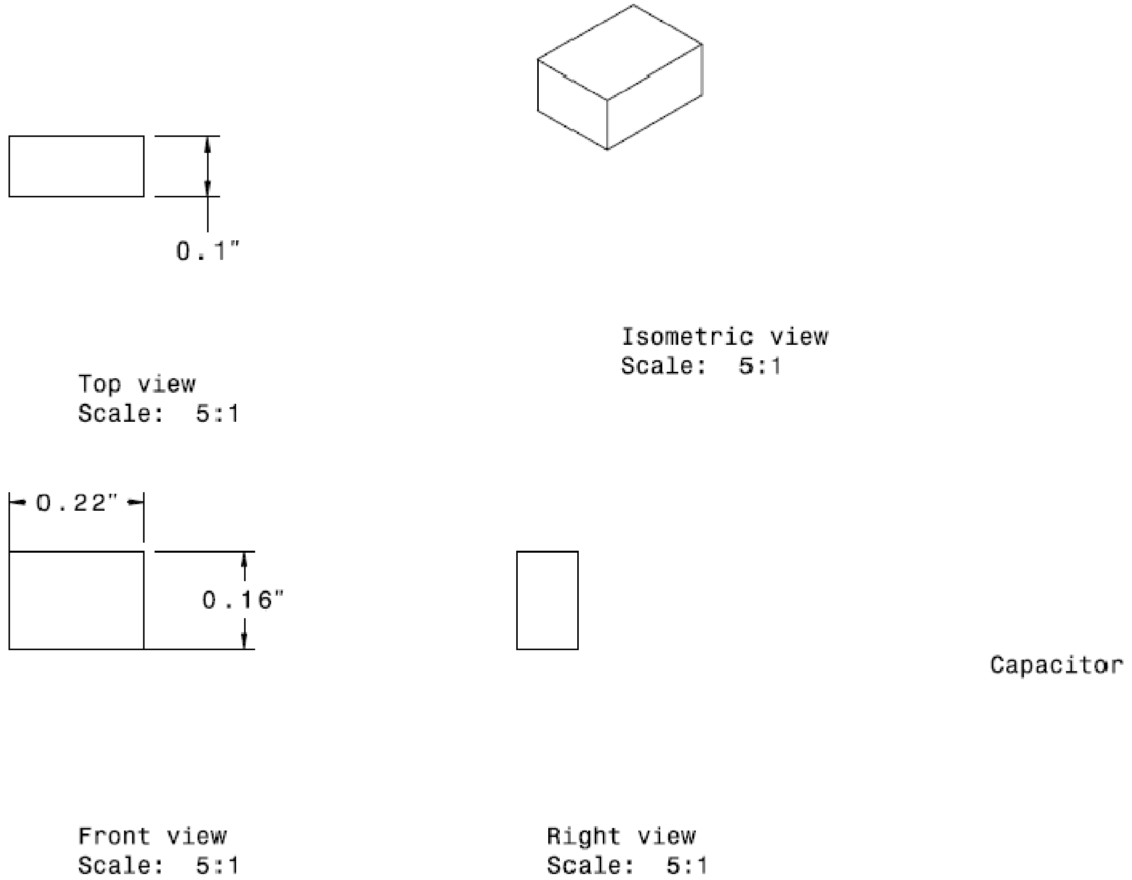
CAD drawing of End Cap



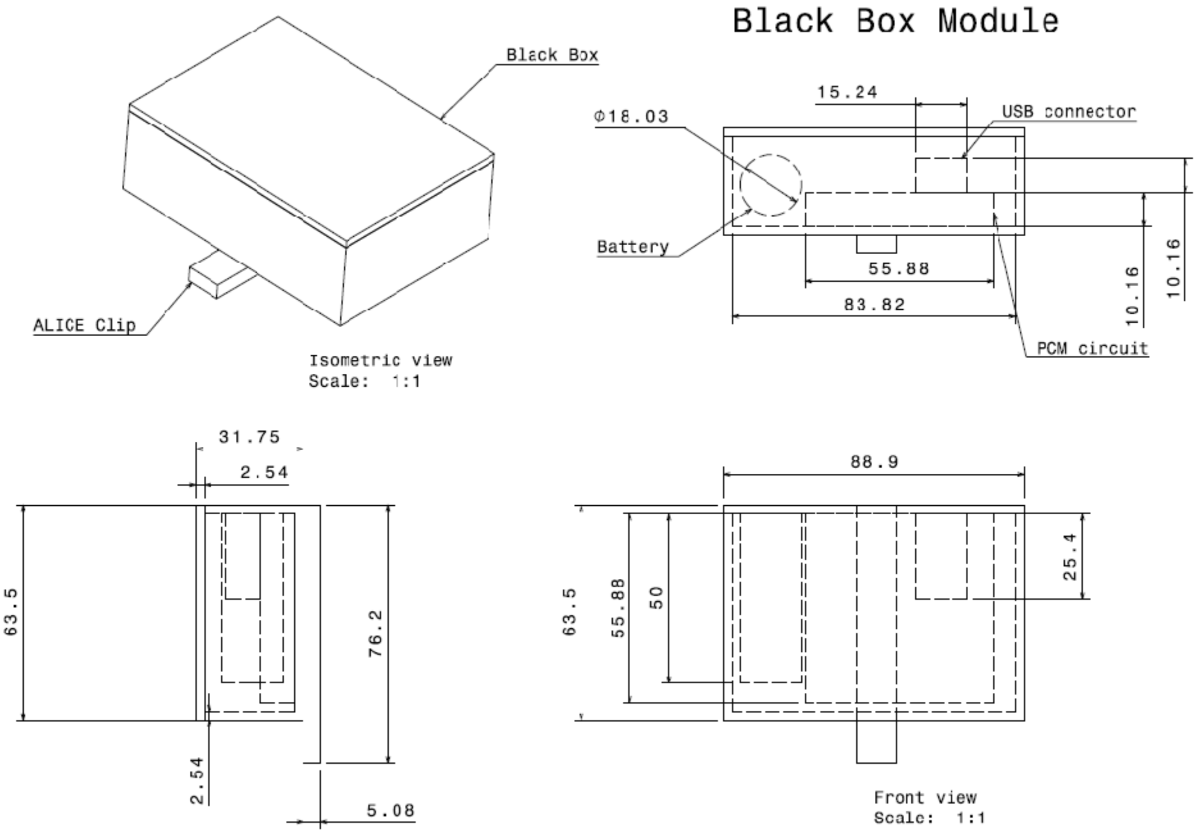
CAD drawing of Rectifier



CAD drawing of Capacitor

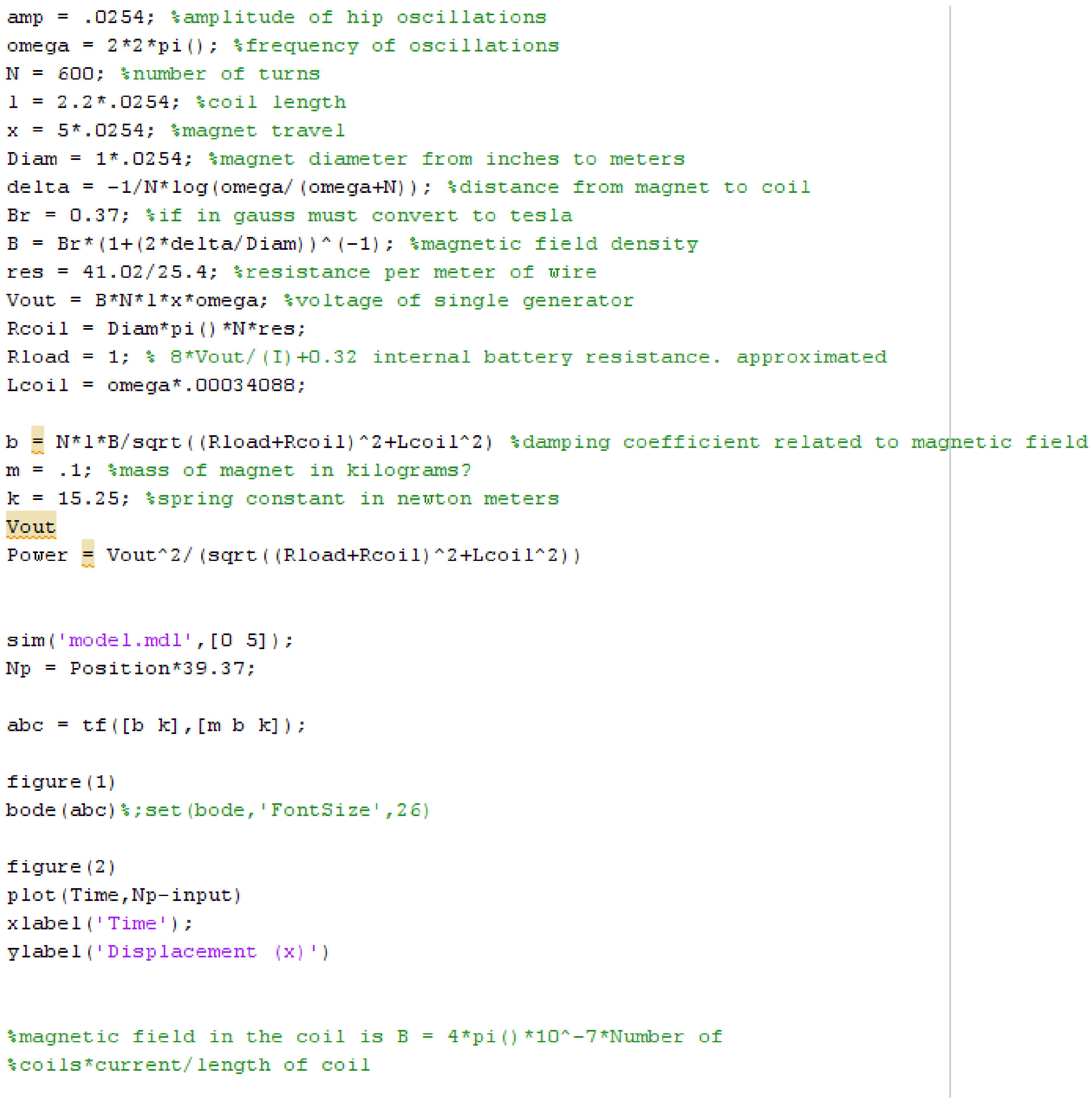


CAD drawing of Battery (“Black Box”) Module



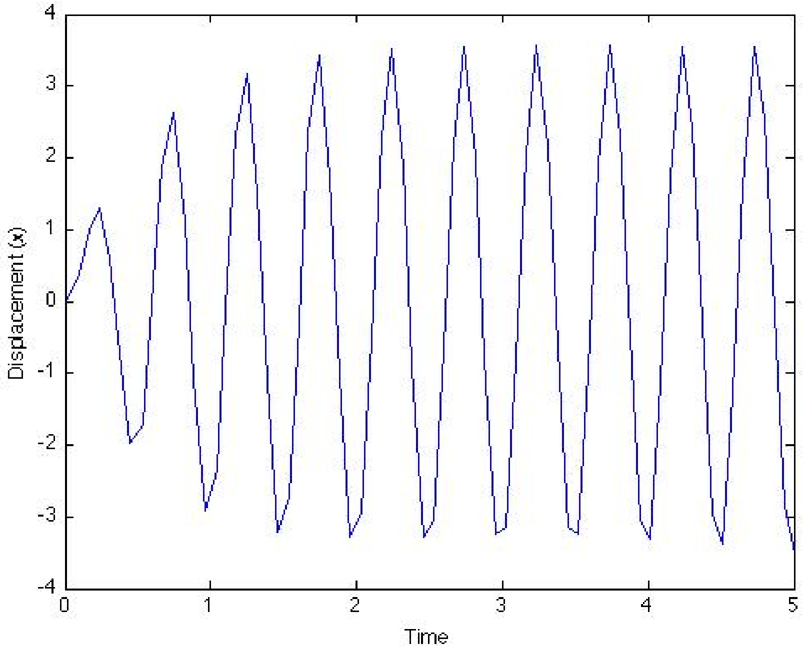
APPENDIX H MATLAB CODE FOR THE MAGNET RESPONSE AND BODE DIAGRAM

MATLAB Code:

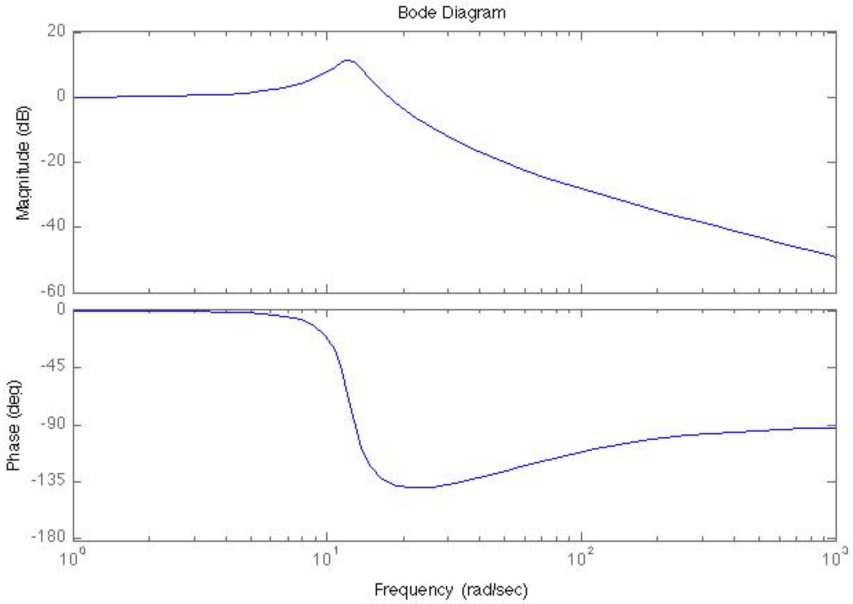


```
amp = .0254; %amplitude of hip oscillations
omega = 2*2*pi(); %frequency of oscillations
N = 600; %number of turns
l = 2.2*.0254; %coil length
x = 5*.0254; %magnet travel
Diam = 1*.0254; %magnet diameter from inches to meters
delta = -1/N*log(omega/(omega+N)); %distance from magnet to coil
Br = 0.37; %if in gauss must convert to tesla
B = Br*(1+(2*delta/Diam))^(-1); %magnetic field density
res = 41.02/25.4; %resistance per meter of wire
Vout = B*N*l*x*omega; %voltage of single generator
Rcoil = Diam*pi()*N*res;
Rload = 1; % 8*Vout/(I)+0.32 internal battery resistance. approximated
Lcoil = omega*.00034088;

b = N*l*B/sqrt((Rload+Rcoil)^2+Lcoil^2) %damping coefficient related to magnetic field
m = .1; %mass of magnet in kilograms?
k = 15.25; %spring constant in newton meters
Vout
Power = Vout^2/(sqrt((Rload+Rcoil)^2+Lcoil^2))


sim('model.mdl',[0 5]);
Np = Position*39.37;

abc = tf([b k],[m b k]);

figure(1)
bode(abc)%;set(bode,'FontSize',26)

figure(2)
plot(Time,Np-input)
xlabel('Time');
ylabel('Displacement (x)')


%magnetic field in the coil is B = 4*pi()*10^-7*Number of
%coils*current/length of coil
```

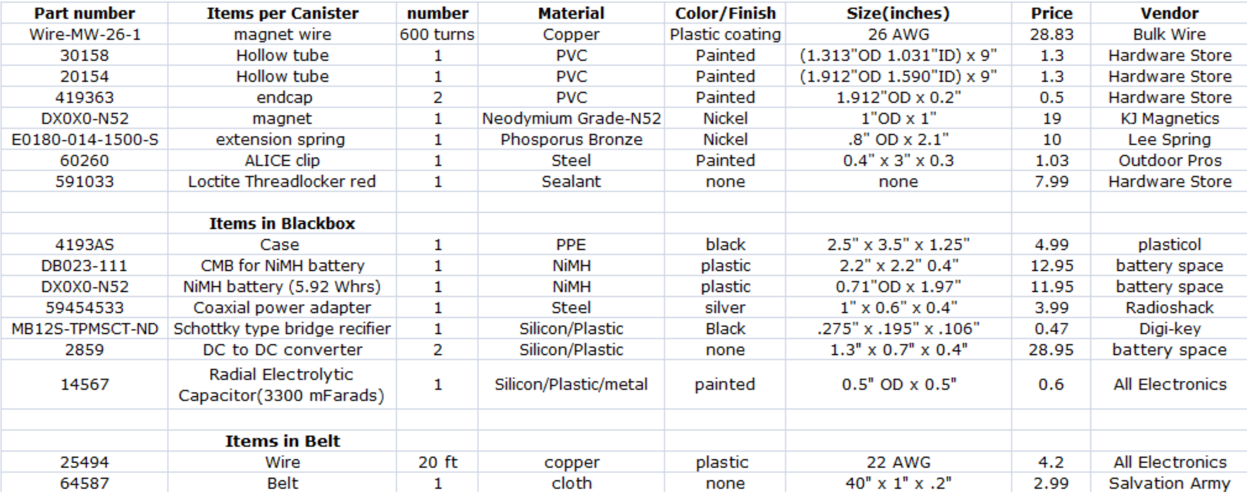
Magnet Response Curve:



Bode Diagram:

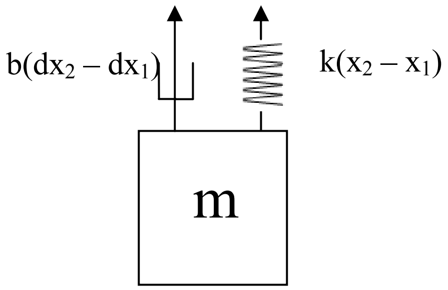


APPENDIX I BILL OF MATERIALS



Part number	Items per Canister	number	Material	Color/Finish	Size(inches)	Price	Vendor
Wire-MW-26-1	magnet wire	600 turns	Copper	Plastic coating	26 AWG	28.83	Bulk Wire
30158	Hollow tube	1	PVC	Painted	(1.313"OD 1.031"ID) x 9"	1.3	Hardware Store
20154	Hollow tube	1	PVC	Painted	(1.912"OD 1.590"ID) x 9"	1.3	Hardware Store
419363	endcap	2	PVC	Painted	1.912"OD x 0.2"	0.5	Hardware Store
DX0X0-N52	magnet	1	Neodymium Grade-N52	Nickel	1"OD x 1"	19	KJ Magnetics
E0180-014-1500-S	extension spring	1	Phosporus Bronze	Nickel	.8" OD x 2.1"	10	Lee Spring
60260	ALICE clip	1	Steel	Painted	0.4" x 3" x 0.3	1.03	Outdoor Pros
591033	Loctite Threadlocker red	1	Sealant	none	none	7.99	Hardware Store
	Items in Blackbox						
4193AS	Case	1	PPE	black	2.5" x 3.5" x 1.25"	4.99	plasticol
DB023-111	CMB for NiMH battery	1	NiMH	plastic	2.2" x 2.2" 0.4"	12.95	battery space
DX0X0-N52	NiMH battery (5.92 Whrs)	1	NiMH	plastic	0.71"OD x 1.97"	11.95	battery space
59454533	Coaxial power adapter	1	Steel	silver	1" x 0.6" x 0.4"	3.99	Radioshack
MB12S-TPMSCT-ND	Schottky type bridge recifier	1	Silicon/Plastic	Black	.275" x .195" x .106"	0.47	Digi-key
2859	DC to DC converter	2	Silicon/Plastic	none	1.3" x 0.7" x 0.4"	28.95	battery space
14567	Radial Electrolytic Capacitor(3300 mFarads)	1	Silicon/Plastic/metal	painted	0.5" OD x 0.5"	0.6	All Electronics
	Items in Belt						
25494	Wire	20 ft	copper	plastic	22 AWG	4.2	All Electronics
64587	Belt	1	cloth	none	40" x 1" x .2"	2.99	Salvation Army

APPENDIX J MASS SPRING DAMPER SYSTEM



Equations of motion

$$\sum F_x = ma$$

$$\sum F_x = -mg + k\left(\Delta x\right) + b(\Delta \dot{x})$$

$$m\ddot{x}_1 = -mg + k(x_2 - x_1) + b(\dot{x}_2 - \dot{x}_1)$$

Magnet displacement

$$x_2 = A\sin(\omega t)$$

$$m\ddot{x}_1 + b\dot{x}_1 + kx_1 = b\dot{x}_2 + kx_2$$

Initial Conditions

$$x(0) = 0$$

$$\dot{x}(0) = 0$$

Laplace Transform

$$ms^2 X_1(s) + bsX_1(s) + kx_1(s) = bsX_2(s) + kX_2(s)$$

Transfer function

$$\frac{X_1(s)}{X_2(s)} = \frac{bs + k}{ms^2 + bs + k}$$

ME 450 Safety Reporting: Winter 2010

Project #: 7 **Date:** 3/22/2010

Report Version #: 1.3

Project Title: Harnessing Waste Energy from Human Motion

Team Member Names: Alex McLane, Gabriel Edgley, Reina Kikuchi, Brian Lerner

Team Member Uniquenames: aamclane, edgleyg, kikuchir, bnlerner

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: ___________________________

Safety Reporting Directions: Please address the following points and questions.

1. **Executive Summary**. Answer the following questions: What activities or designs are covered by this report? What hazards have you identified and eliminated? What analysis have you performed and why do you conclude that the activities/designs are low risk? Be sure you consider all aspects of your project: experimental data collection, component design, system design, manufacturing, assembly, and testing.
2. **Experimentation Plans Prior to Design Completion**. For your experimentation, list what data you will be collecting and why. Are any experiments that might have safety risks unnecessary? Why/Why not?
3. **Purchased Component and Material Inventory**. Provide an inventory of all materials (solid materials such as aluminum/wood/etc.) and purchased components you will be using. Why are these materials and components necessary?

a. Complete an FMEA for any purchased components that have safety risks. Provide the FMEA table as an appendix to this Safety Report and summarize the results in your own words for the main report body.

4. **CAD Drawings and DesignSafe Summary for Designed Parts**. Provide CAD drawings for components you have designed and will manufacture.

a. Conduct a risk assessment using Designsafe software (available on CAEN) for each designed component and for the full assembly of components constituting your design. Provide the Designsafe output as an appendix to this safety report and summarize the results in your own words for the main report body.

5. **Manufacturing**. Provide a list of all fabrication or manufacturing activities you will perform. Where will these activities take place? Why are these processes necessary?

a. CAD drawings for parts to be manufactured are required (per #4 above).

b. For machining or forming processes, list special setup requirements and the operational conditions that will be employed (e.g., speeds, feeds, etc.).

6. **Assembly**. How and where will your components be assembled? On what basis do you conclude that the assembly will not fail before use, during use, or after use?

7. **Design Testing and Validation**. How and where will your final design be tested? Which design specifications are being validated through the testing? Do you plan to test aspects of your design as you manufacture your prototype, or are you going to be validating a finished prototype after most/all manufacturing has been completed?

a. What would you consider to be your first major test of the design?

b. Have you arranged with your Section Instructor to have a cognizant individual present at your first major test? Who will this be? When do you expect this first test to take place?

8. **Additional Appendices**:

a. For every chemical (powder, liquid, gas – distinguished from a “material” defined in step 2 above as a solid) you propose for use in testing or design, you must supply a complete MSDS as an appendix.

b. If relevant safety documentation is provided with a purchased component, include it as an appendix.

9. **Submission**. After addressing points 1-8 above, please do the following:

a. Submit this report to your Section Instructor for signature. Please check with your Section Instructor to learn if a hard copy or an electronic copy is preferred for signature. Regardless, please create an electronic copy for filing and email to Bob Coury and Phil Bonkoski (below).
b. After the report is signed, email a copy to Bob Coury (hornet@umich.edu) and our course GSI Phil Bonkoski (bonkoski@umich.edu)

i. Both Bob and Phil are expected to raise additional safety concerns that will be shared with the students and the Section Instructor. They have the authority to stop any activity they deem unsafe, regardless of whether a safety report has been signed. If this happens, the safety report will be revised and re-signed by the Section Instructor, then emailed with revisions to Bob Coury and Phil Bonkoski.

1. Executive Summary

This report covers the manufacture, assembly and testing of a preliminary prototype of the alpha design. Further revisions of this safety report will be provided before additional manufacturing, assembly and testing is done. However, major revisions of the manufacturing, assembly and testing procedures are not anticipated. This alpha prototype will consist of a magnet attached to springs on each end, which are in turn fixed to the ends of a cylinder, such that the magnet is free to oscillate inside. A coil of magnetic wiring will be wrapped around the center of the canister to form a solenoid. A current will be generated in the solenoid and then pass through a bridge rectifier, which will convert from AC to DC. From the bridge rectifier, the current will pass through a capacitor to smooth out the current before it is dissipated in a resistor. All processes of manufacturing, assembly and testing have been deemed low risk.

Manufacturing Elements: The only part that needs to be manufactured is the PVC cylinder and the processes include: cutting with a band saw and lathing. These processes have inherent to the equipment, and include fast moving equipment, flying debris, and sharp blades. To help reduce these hazards, all members of the team has undergone standard shop training for the equipment. Additionally, safety glasses will be worn at all times.

Assembly Elements: Assembly of the manufactures parts and purchased components was determined to be a low risk process. The magnet, springs, and PVC pipe will be fixed together with epoxy in an area with proper ventilation. The exposed leads of the magnetic wire will be covered with electrical tape to ensure the circuit is left open and prevent electrical shock. The circuit will be assembled in room 2336 of the EECS building.

Testing Elements: The testing has been determined to be a low risk process. There are no pressurized vessels, high forces, or rapidly moving parts in the system. Complete failure due to fracture or fatigue of the PVC canister could lead to electrical shock from the solenoid, however the voltage and current (maximum 4 volts and 2 amps) do not pose a significant safety hazard. Care will be used when handing the device to prevent large impacts, and the device will be monitored to ensure the electrical components are not overheating. Voltage, current, and resistance measurements will be made across the generator, bridge rectifier, and resistor using an oscilloscope (Agilent 3000 series) and recorded using LabView software.

2. Experimentation Plans Prior to Design Completion

To avoid shock we will cover the leads with electrical tape and make sure all other wires are not exposed. The magnet could become separated from the spring during oscillations, but it is contained within the PVC canister with a cap on both sides. The spring could fail by being over extended. This would not cause a safety hazard, however it would prevent the device from performing its primary function of energy harvesting. The mass and velocity of the magnet will not create large enough forces to cause failure of the spring.

3. Materials Inventory

1. Canister
   - Material: Polyvinyl Chloride (PVC)
   - Shape & Dimensions: 6'' x 1.361'' (length x diameter, thickness is 0.361'')

The canister will contain the entire electromagnetic system: magnet with attached springs, and the linear solenoid. The canister will provide an area for the magnet to oscillate as well as separating the solenoid from the environment.

2. Magnetic Wire
   - Material: Enamel-Coated Copper Wire, 26 gauge
   - Shape & Dimensions: 1200' x 0.012'' (length x diameter)

The magnetic wire will be wrapped into a cylinder shape to create a linear solenoid. When the magnet is passed through the center of the solenoid, the changing magnetic field will induce a current in the solenoid. It is important that the copper wire be insulated to insure that the current passes through the wire, rather than across the coils.

Purchased Components

1. Magnet
   - Material: Nickel plated NdFeB, Grade N52
   - Shape & Dimensions: 1.5'' x 1'' (length x diameter)

The magnetic field produced by the oscillating magnet will induce a current in the solenoid, which will act as a current source. We chose a cylindrical rare earth neodymium magnet for use in initial testing because of the high magnetic field strength yet low cost. Initial modeling using a mass spring damper system and Faraday's Law indicate that this magnet will generate 0.5 Watts with the current setup.

2. Spring (extension)
   - Material: Phosphor Bronze
   - Shape & Dimensions: 2.52'' x 0.23'' (length x diameter)

The spring will be used to oscillate the magnet through the solenoid. Moreover, the purpose of the spring is the retain stored energy and ensure the highest point of velocity is while the magnet is in the center of the solenoid, as this will be the highest point of resistance because the solenoid will resist the changing magnetic field. A phosphor bronze spring can be formed into many different shapes and sizes. The main reason we chose to use the phosphor bronze spring is due to its non-magnetic properties and stock availability with our spring provider.

3. Caps
   - Material: Polyvinyl Chloride (PVC)
   - Shape & Dimensions: 1.25'' x 1.625'' (length x diameter)

Standard press fit caps. The caps will be used to enclose the springs and magnet system inside the canister.

4. Capacitor
    - 20 Volt rating

The capacitor is used in the circuit to act as a temporary energy storage and to smooth the current before it enters the battery.

5. Diode
    - Single Phase, low turn on Voltage

A single low turn on voltage will be placed between the battery and the capacitor to ensure the current does not backflow into the capacitor.

6. Bridge Rectifier
    - Single Phase, Schottky Type

A bridge rectifier is used to convert the alternating current generated in the solenoid to direct current. A single phase bridge rectifier is simply an arrangement of four diodes, however, unlike a single diode, the negative current is not lost, instead it is converted to positive.

7. Resistor

A 10 ohm resistor will be used to model the internal resistance of the battery for this testing. By using a resistor, we will be able to acturatey calculate the power dissipated.

8. Proto-board

We will be using a simple proto-board from the EECS labs for soldering and organizing our electrical components.

FMEA Analysis Results

Preliminary risk assessment of the purchased components and materials was performed and can be found in Appendix A. One material, the PVC piping, was identified as the most likely to fail and we performed FMEA analysis on this material. The primary modes of failure are fracture and thermal fatigue of the PVC canister. Complete failure of this component would result in exposure of the electrical components, which could lead to electrical shock. Although such a shock would not be extremely hazardous (maximum of 4 Volts and 2 Amps), the main function, ability to provide power to the user, would be lost. Fracture can be prevented by careful handling and avoiding large impacts. Thermal fatigue can be avoided through careful observation, keeping the system well ventilated, and slowly increasing the current of the magnetic coil.

4. CAD Drawings and DesignSafe Summary for Designed Parts

Device hazards were identified and summarized using DesignSafe and the results are compiled into Table 1. Main hazards were identified to be crushing or impact fragmentation from the magnet, and burns resulting from improper use of the soldering iron. Soldering iron hazards will be avoided by using care with the iron and replacing it in the holder when temporarily not in use. Risks of the high strength magnet will be reduced by ensuring the magnet is separated from the user by the PVC pipe barrier while in the assembly. When the magnet is being handled directly, it will be kept away from all ferrous metals and other magnets; safety gloves will also be worn. Figure 1 shows the engineering drawing of the canister with dimensions.

Table 1. DesignSafe Results

User/ task	Hazard / failure mode	Initial Assessment Severity Exposure Probability	Initial risk Level	Risk reduction methods	Final Assessment Severity Exposure Probability	Final risk level	Status
All	Mechanical: impact, cycling fatigue	Minimal Remote Unlikely	Low		Minimal Remote Unlikely	Low	In-progress
All	Electrical: shorts, water, overload, electromagnetic susceptibility, electrostatic discharge	Slight Frequent Unlikely	Moderate	fixed enclosures / barriers, gloves	Minimal Remote Unlikely	Low	In-progress
All	Heat: burns	Slight Frequent Unlikely	Moderate	Gloves, ventilation	Slight Remote Unlikely	Low	In-progress
All	Magnetic: magnet could be attracted to ferrous metals resulting in crushing of fingers between or fracturing of the magnet	Moderate Remote Unlikely	Moderate	Fixed enclosures / barriers, gloves (magnet will be separated from user with PVC canister. During assembly gloves will be worn)	Slight Remote Unlikely	Low	In-progress
All	Electrical: energized equipment / live parts, shorts, improper wiring, overloading	Minimal Remote Possible	Low	Follow circuit diagrams; not touch electrical components when live	Minimal Remote Unlikely	Low	In-progress
All	Electrical: water, condensation	Minimal Remote Unlikely	Low	Test indoors, avoid water, extreme humidity	Minimal Remote Unlikely	Low	In-progress
All	Heat: burns from solder	Slight Remote Unlikely	Low	Do not touch solder or solder iron; solder training	Minimal Remote Unlikely	Low	In-progress

Figure 1. CAD drawing of inner Canister

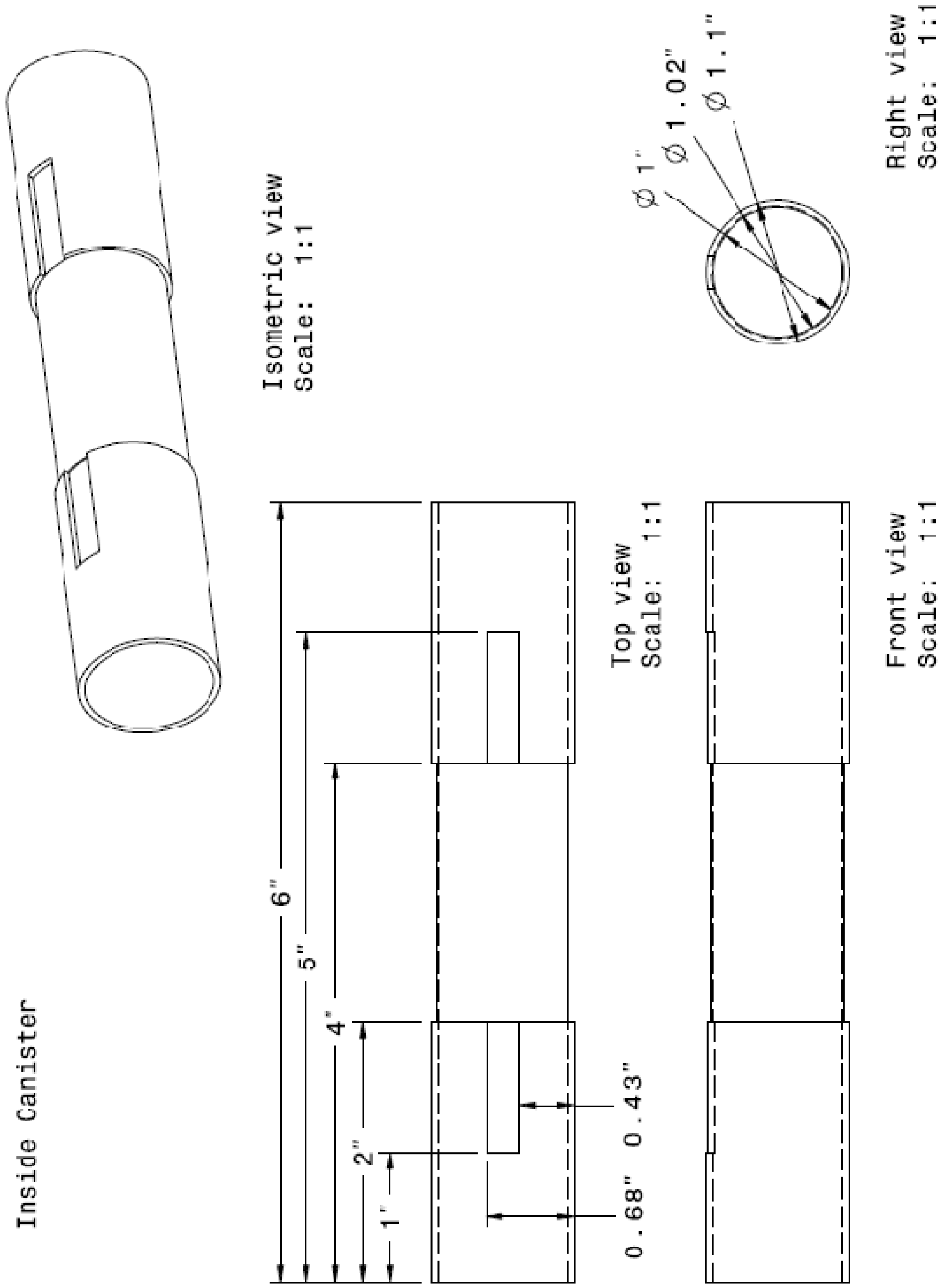


Figure 2. Circuit Diagram for ‘n’ canister devices (modeled as current sources)

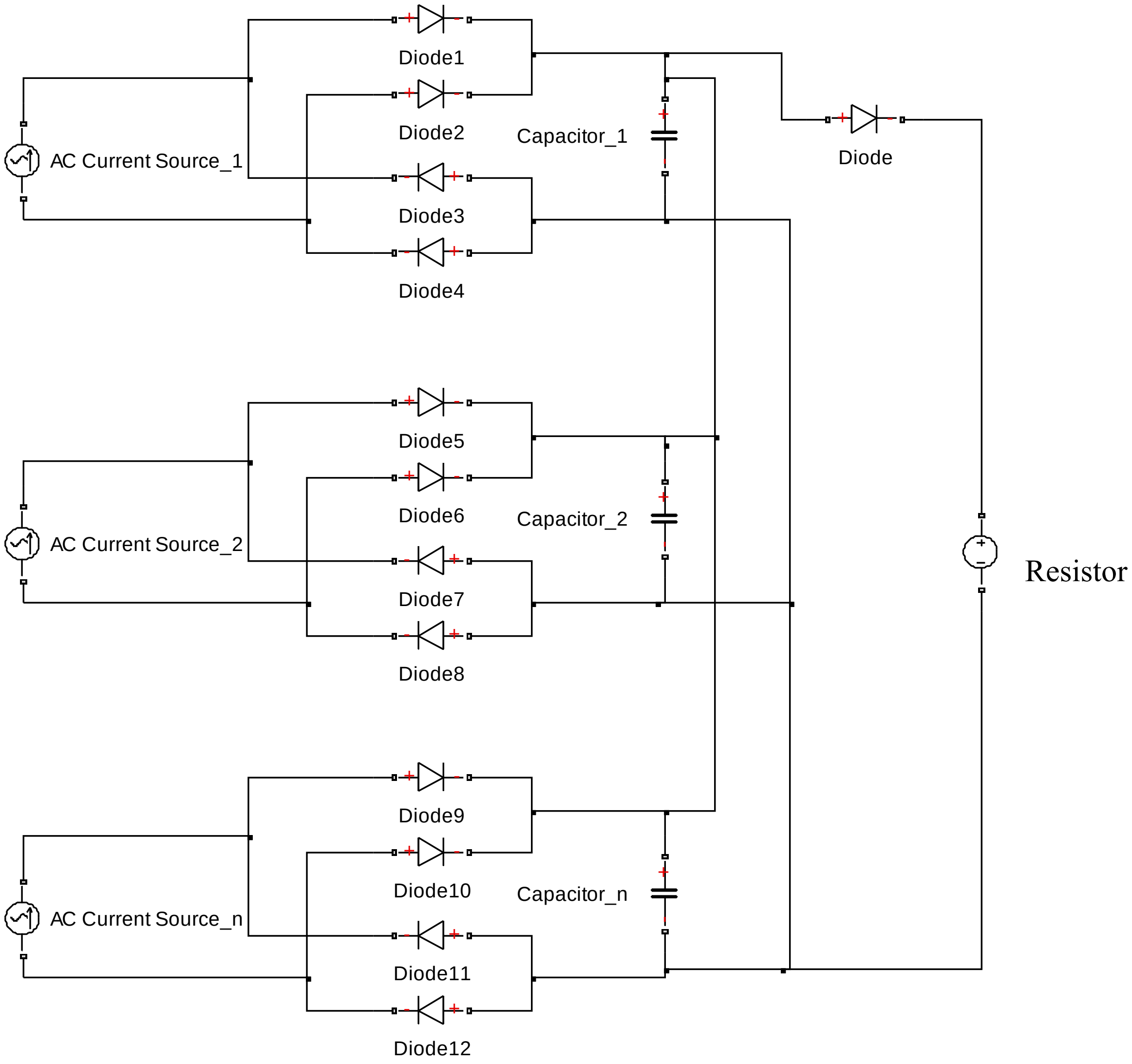
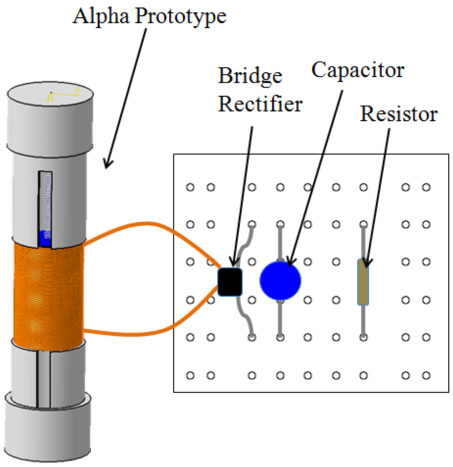


Figure 3. Capacitor and rectifier circuitry system on protoboard



5. Manufacturing

Purchase PVC pipe at 6’’. Lathe a grove in pipe for wrapping wire around and drilling holes in cap to run wires. The risk involved are cutting your hand or having a part of the pipe fly off the band saw and hit you. To avoid this risk we will use proper feeds and speeds settings and reinforce PVC with scrap pipe inside. The machinery’s handbook list 8,000 RPM and 45 FPM for Lathe, and 1,000- 2,000 RPM with a medium feed rate for drilling. Due to machine limitations, we will be running at 650 RPM for the lathe. To protect against projectiles we will use safety glasses. We will follow proper setup procedures when setting up drill press and lathe also. For observation holes, we will put pipe in vice and drill two 3/16’’ holes on a drill press and then connect holes using a file. Windows will be made on each side of the pipe. The caps will be put in vice separately and one 3/16’’ hole will be drilled in each and filed out to edge. Table 2 shows the specifications of the machining steps.

Table 2: Machining specifications

Step	Operation	Machine	Cutting Tool	Cutting Speed
1	Groove slot for solenoid	Lathe	Hardened Steel tooth	650 RPM (due to limitation of machine)
2	Drill observation holes	Drill press	3/16’’ drill	1,000-2,000 RPM
3	Connect holes with a file	N/A	File	N/A

6. Assembly

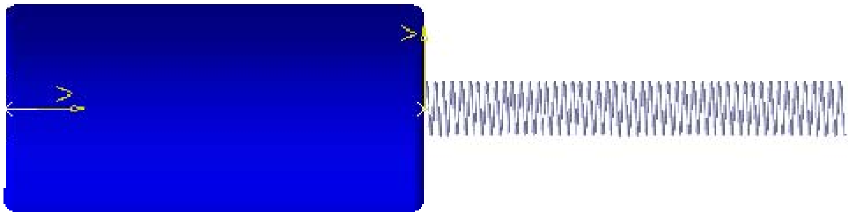
The assembly of the initial prototype will be straightforward and is mostly joining materials with epoxy.

Possible hazards during assembly are:

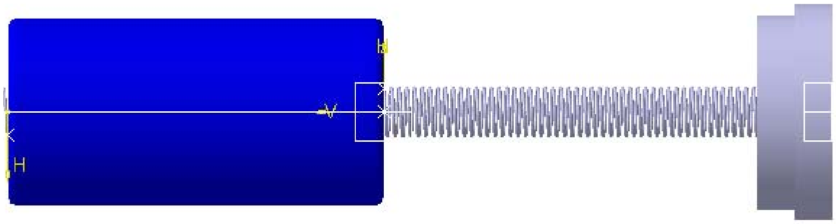
1. Magnet: The magnet produces pulling force of 61 lbs. and this is a potential pinching hazard. In order to avoid such hazards, gloves should be worn and hands will not be placed between magnet and metal surfaces. Also, placements of two or more magnets next to each other should be avoided for potential of impact that could produce projectiles.
2. Springs: Care should be used when compressing springs, for they could become projectiles when released from compression.
3. Epoxy: Epoxy should be applied in ventilated area with gloves. Contact with exposed skin should be avoided.
4. Magnet wire: Ends of magnet wire should be handled with care because they could be sharp.

The steps for assembly are:

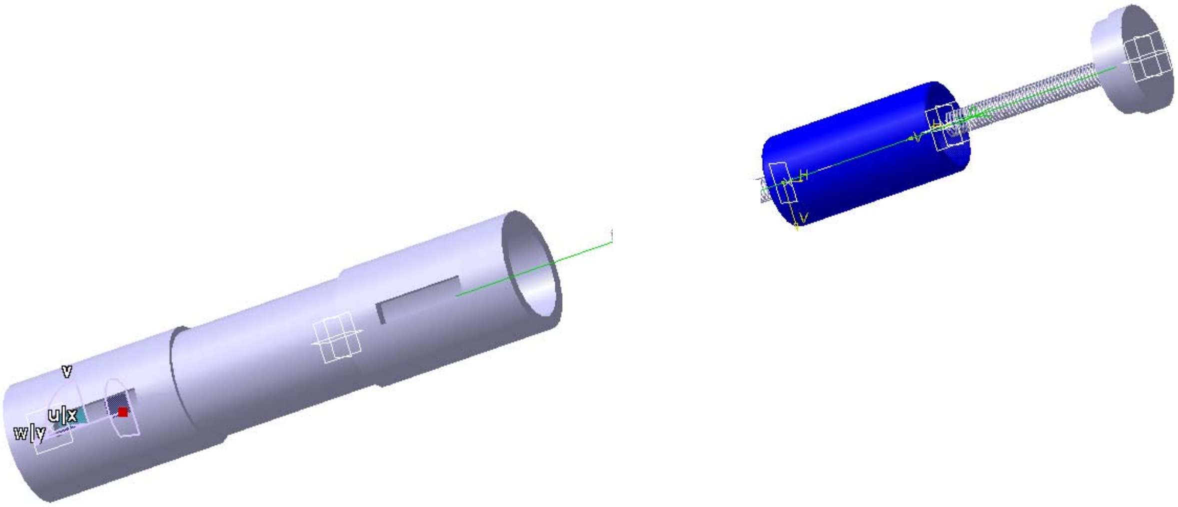
1. Attach spring to magnet with epoxy.



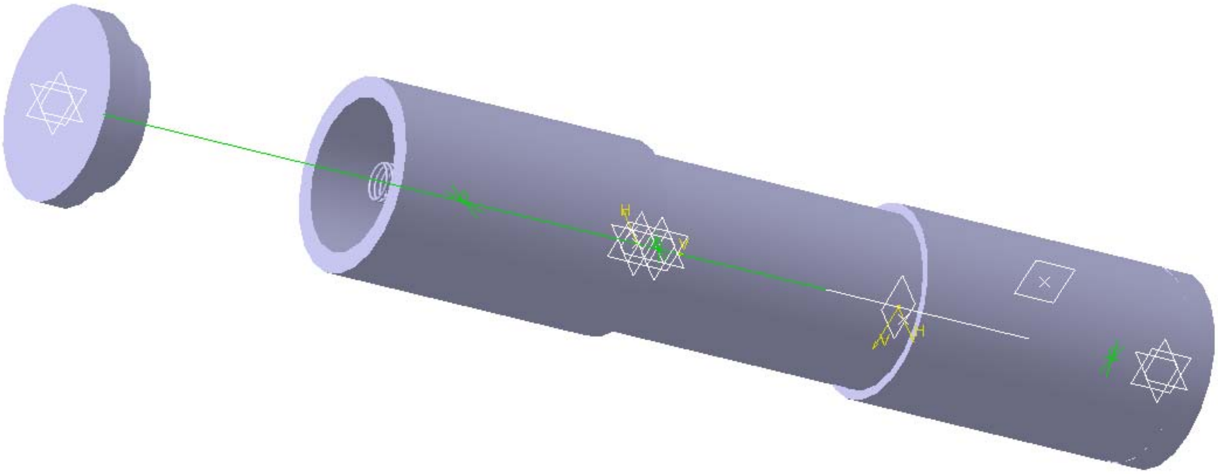
2. Attach one end cap to spring with epoxy.



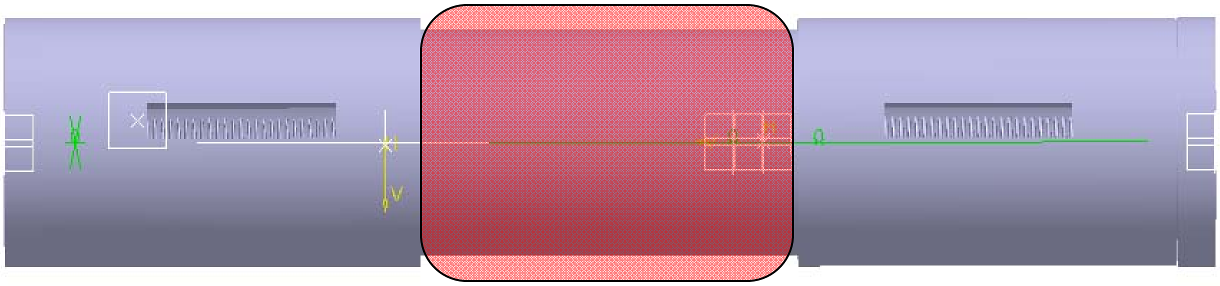
3. Place magnet and spring system into cylinder.



4. Attach other cap to cylinder with press fit.



5. Coil magnetic wire around slot in cylinder.



The assembly of the initial circuit board prototype will be done following the circuit diagram (Figure 2). We will have one diode prior to the battery / load, and for each generator there will be one bridge rectifier and one capacitor on an auxiliary bread board. First the resistor, rectifier and capacitor will be soldered on bread board as shown in Figure 3. We will then make the electrical connections outline in the circuit diagram (Figure 2) with insulated wire and solder each connection. The rectifiers will be attached to the power source, or in our case, the electromagnetic canisters via soldered wire

7. Design Testing

Testing of the initial prototype will be performed in room 2336 of the Electrical Engineering and Computer Science building. The end goal is to achieve a power output of 5 watts with 5-10 canister devices (we will only be testing one device in this instance). We will measure the current and voltage outputs of the system using an Oscilloscope and record the measurements with LabView. Additionally, we will use a Function Generator to determine the effectiveness of the bridge rectifier for converting AC to DC.

Procedure:

- Using the multimeter, record the resistances of the generator (coil), bridge rectifier, and resistor.
- Attach the leads of the function generator to the inputs of the bridge rectifier and attach the oscilloscope to the outputs of the bridge rectifier.
- On the function generator set a sinusoidal input of 1-10 Hz and 0.1 – 2 Volts.
- Run the LabView VI to record the measurements.

Next we test the entire device.

- Disconnect the function generator and oscilloscope leads and reconnect the bridge rectifier as described in the circuit diagram (Figure 2.)
- Attach the leads of the oscilloscope to the resistor.
- Using a displacement of 3-7 cm, oscillate the generator vertically at 1-5 Hz (with the aid of a metronome).
- Run the LabView VI to record the measurements.

8. Additional Appendices

Appendix A: FMEA Analysis

Part #, Name, & Function	Potential Failure Mode	Potential Effects of Failure	Severity (S)	Potential Causes/ Mechanism of Failure	Occurrence (O)	Current Design Controls	Detection (D)	Recommended Action	RPN (=S·O·D)
#1: Canister. PVC pipe containing the electromagnetic generator	Loose	Noise, loss of efficiency	3	Tolerance stack up, assembly error	1	Visual inspecting of connections	1	Inspect the fittings of internal components.	3
	Fracture	Electrical shock	7	Impact loading, overstressing	1	Careful handling, visual inspection.	1	Inspect each purchased part for defects. Avoid impacts.	7
	Thermal Fatigue	Burn	4	Overheating of magnetic coil (due to current)	1	Melting temperature at 180 °F	2	Inspect for visible signs of deformation. Test by slowly increasing current through wiring.	8

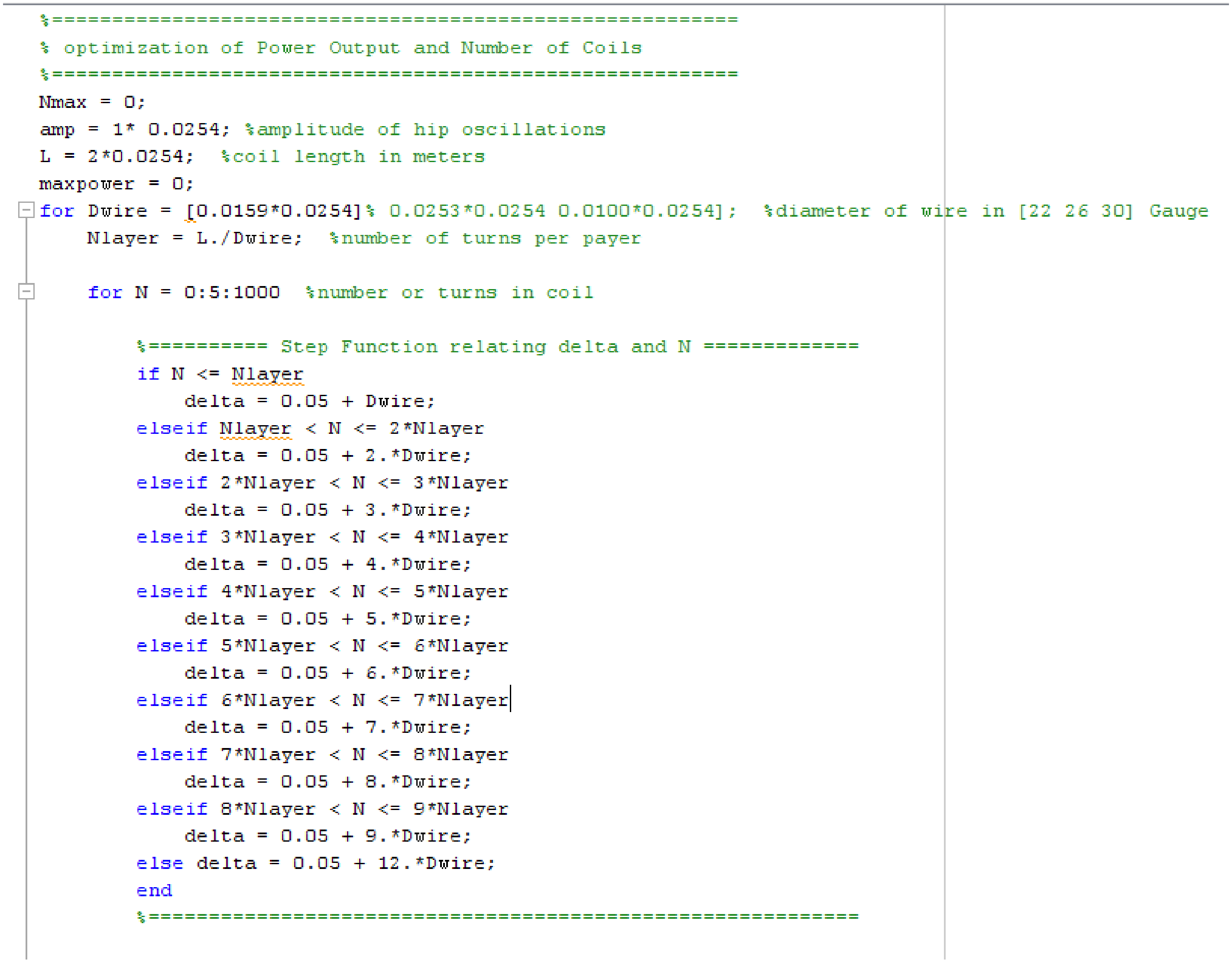
Appendix B: DesignSafe Criteria for Severity

The following definitions for severity levels for risk appear in the ANSI B11 TR#3 system and were used in our DesignSafe classifications:

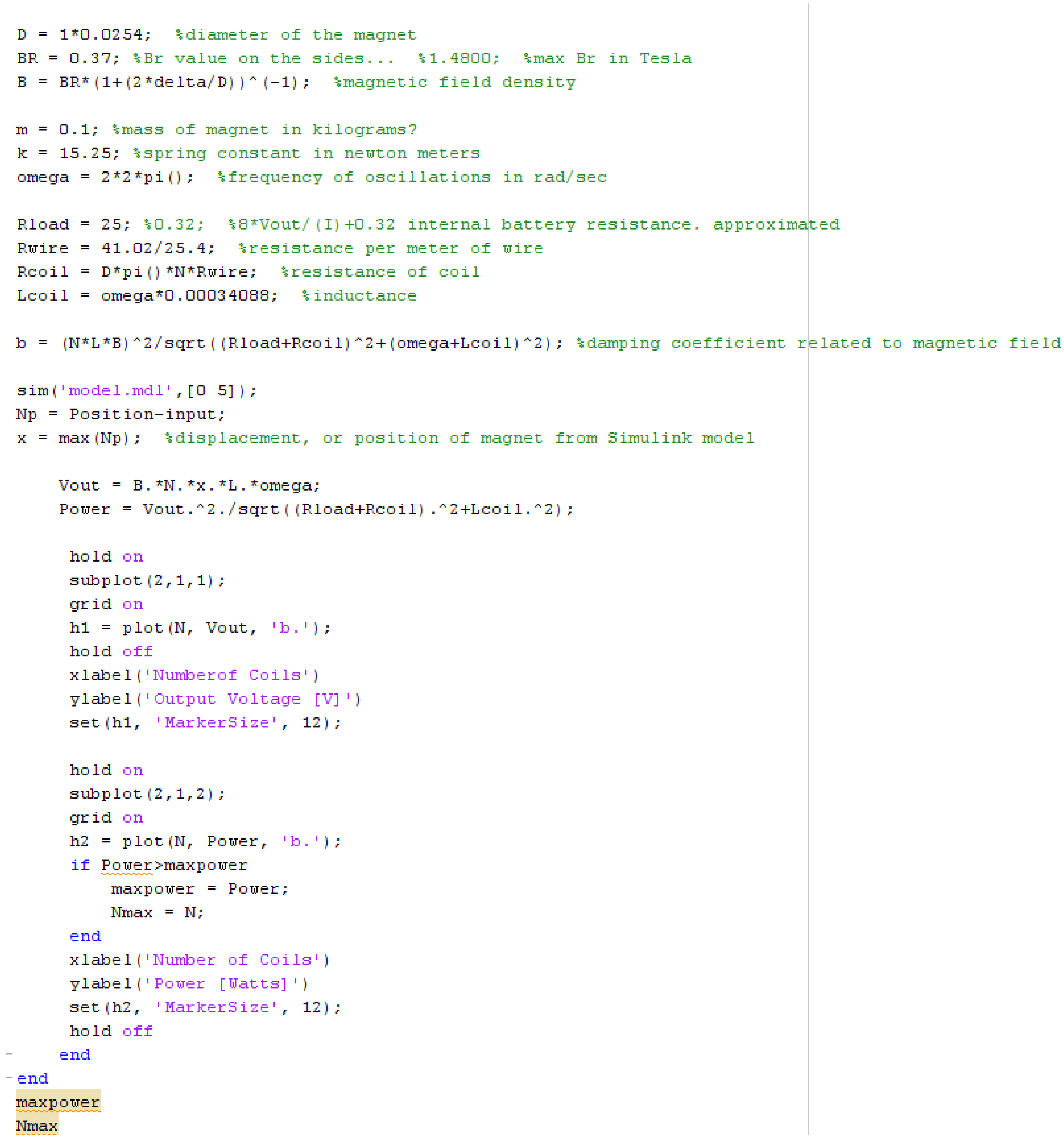
- **Catastrophic**: hazard may cause death or permanent disabling injury, illness or environmental damage; irreversible injury with permanent loss in work capacity.
- **Serious**: hazard may cause severe injury, illness or damage; normally reversible; hospitalization required; no more than one month lost work time.
- **Slight**: hazard may cause slight injury, illness or damage; normally reversible, doctor office visit or emergency room treatment; no more than one week lost work time.
- **Minimal**: hazard will not result in significant injury, illness or damage; first aid treatment; immediate return to work.

APPENDIX L MATLAB CODE FOR OPTIMAL NUMBER OF COILS

MATLAB Code:



```
%==========================================================
% optimization of Power Output and Number of Coils
%==========================================================
Nmax = 0;
amp = 1* 0.0254; %amplitude of hip oscillations
L = 2*0.0254;  %coil length in meters
maxpower = 0;
for Dwire = [0.0159*0.0254]% 0.0253*0.0254 0.0100*0.0254];  %diameter of wire in [22 26 30] Gauge
    Nlayer = L./Dwire;  %number of turns per payer

    for N = 0:5:1000  %number or turns in coil

        %========== Step Function relating delta and N =============
        if N <= Nlayer
            delta = 0.05 + Dwire;
        elseif Nlayer < N <= 2*Nlayer
            delta = 0.05 + 2.*Dwire;
        elseif 2*Nlayer < N <= 3*Nlayer
            delta = 0.05 + 3.*Dwire;
        elseif 3*Nlayer < N <= 4*Nlayer
            delta = 0.05 + 4.*Dwire;
        elseif 4*Nlayer < N <= 5*Nlayer
            delta = 0.05 + 5.*Dwire;
        elseif 5*Nlayer < N <= 6*Nlayer
            delta = 0.05 + 6.*Dwire;
        elseif 6*Nlayer < N <= 7*Nlayer
            delta = 0.05 + 7.*Dwire;
        elseif 7*Nlayer < N <= 8*Nlayer
            delta = 0.05 + 8.*Dwire;
        elseif 8*Nlayer < N <= 9*Nlayer
            delta = 0.05 + 9.*Dwire;
        else delta = 0.05 + 12.*Dwire;
        end
        %==========================================================
```

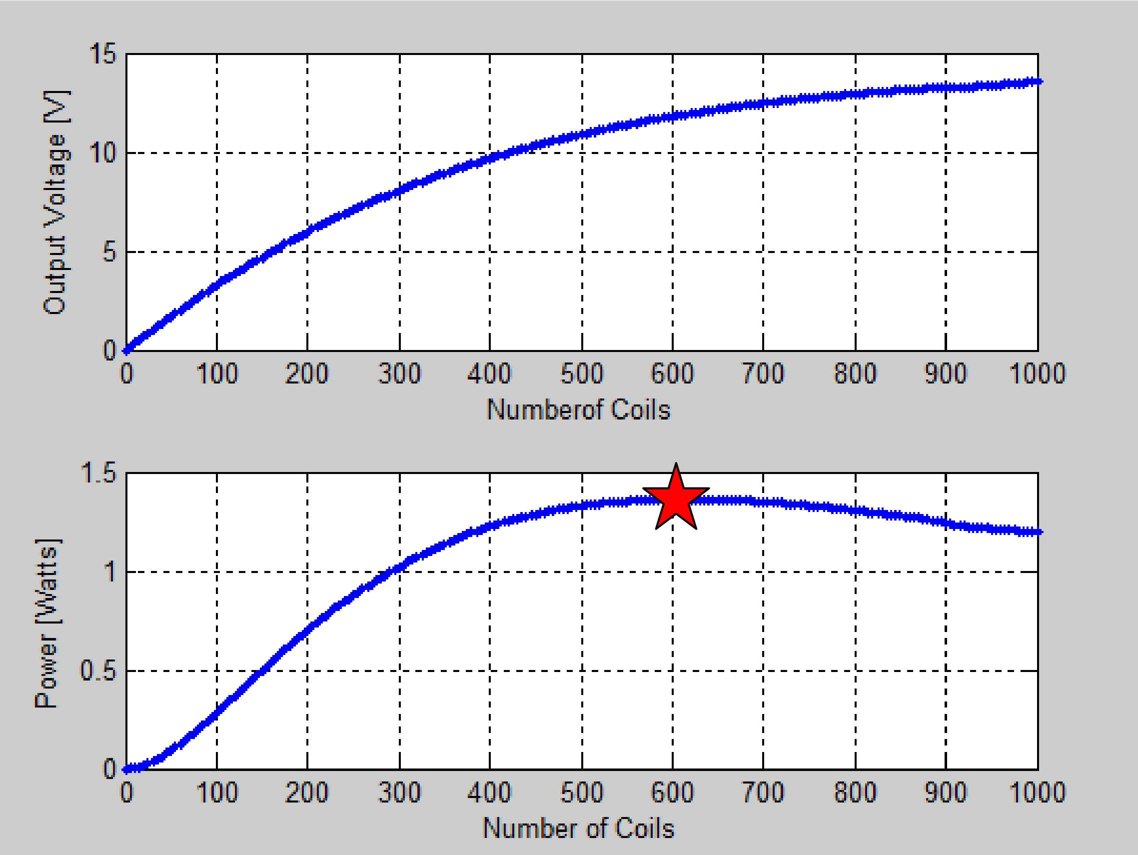


```
D = 1*0.0254;  %diameter of the magnet
BR = 0.37; %Br value on the sides...  %1.4800;  %max Br in Tesla
B = BR*(1+(2*delta/D))^(-1);  %magnetic field density

m = 0.1; %mass of magnet in kilograms?
k = 15.25; %spring constant in newton meters
omega = 2*2*pi();  %frequency of oscillations in rad/sec

Rload = 25; %0.32;  %8*Vout/(I)+0.32 internal battery resistance. approximated
Rwire = 41.02/25.4;  %resistance per meter of wire
Rcoil = D*pi()*N*Rwire;  %resistance of coil
Lcoil = omega*0.00034088;  %inductance

b = (N*L*B)^2/sqrt((Rload+Rcoil)^2+(omega+Lcoil)^2); %damping coefficient related to magnetic field

sim('model.mdl',[0 5]);
Np = Position-input;
x = max(Np);  %displacement, or position of magnet from Simulink model

    Vout = B.*N.*x.*L.*omega;
    Power = Vout.^2./sqrt((Rload+Rcoil).^2+Lcoil.^2);

     hold on
     subplot(2,1,1);
     grid on
     h1 = plot(N, Vout, 'b.');
     hold off
     xlabel('Numberof Coils')
     ylabel('Output Voltage [V]')
     set(h1, 'MarkerSize', 12);

     hold on
     subplot(2,1,2);
     grid on
     h2 = plot(N, Power, 'b.');
     if Power>maxpower
         maxpower = Power;
         Nmax = N;
     end
     xlabel('Number of Coils')
     ylabel('Power [Watts]')
     set(h2, 'MarkerSize', 12);
     hold off
    end
end
maxpower
Nmax
```

Output:

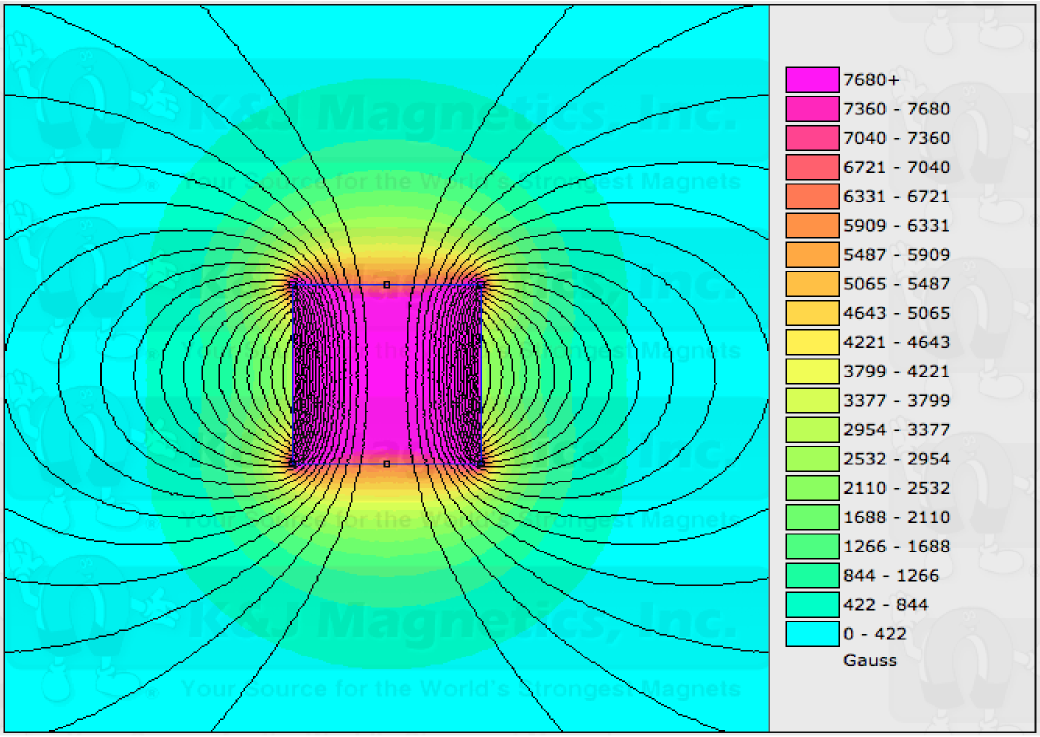
```
maxpower =   1.3606
Nmax =   615
```

Number of Turns vs. Power and Voltage Output:



APPENDIX M MAGNET SPECIFICATIONS

- **Dimensions:** 1’’ dia. X 1’’ thick
- **Tolerances:** ±0.004’’ x ±0.004’’
- **Material:** NdFeB, Grade N52
- **Plating/Coating:** Ni-Cu-Ni (Nickel)
- **Magnetization Direction:** Axial (Poles on Flat Ends)
- **Weight:** 3.41 oz. (96.5 g)
- **Pull Force:** 75.52 lbs
- **Surface Field:** 6619 Gauss
- **Max Operating Temp:** 176°F (80°C)
- **Brmax:** 14,800 Gauss
- **Bhmax:** 52 MGOe



Reference:
K&J Magnetics
http://www.kjmagnetics.com/proddetail.asp?prod=DX0X0%2DN52

APPENDIX N SPRING SPECIFICATION

Cylindrical Extension Spring, Round Wire **Material:**Phospher Bronze

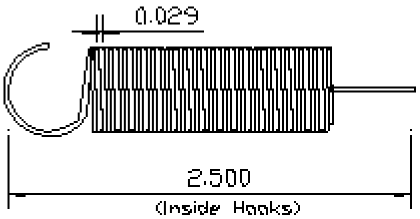
Pitched:	Close Wound (IT>0)	**End Type:**	Crossover	**Grade:**Commercial	
Wire Dia. [in]	**0.0285**	Coil Mean Dia. [in]	0.4865	Active Coils	51.4519
Wire Tolerance [in]	+/- 0.0006	Coil ID [in]	0.458	Total Coils	51.4519
Rate [lbf/in]	**0.087**	Coil OD [in]	**0.515**	Dead Coils	0
Spring Index	17.0702	Diameter Tol. [in]	+/- 0.0206	Pitch [in]	0.0285
Nat. Frequency (Hz)	11.2892	Hook 1 Length [in]	0.5026	Coil Spacing [in]	0
Wire Length [in]	81.7093	Hook 2 Length [in]	0.5026	Additional Feed	0
Wire Weight [lb]	0.01668	Body Length [in]	1.4949	Last Coil Reduction [in]	0
Initial Tension [lbf]	**0.1**	Min. Possible IT [lbf]	0.083415	Max. Possible IT [lbf]	0.125123

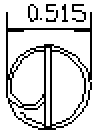
	Free	**Point 1**	**Point 2**	**Set**
Load [lbf]	**0.1**	0.318	0.535	0.957
Load Tolerance [lbf]		+/- 0.2286	+/- 0.2338	
Length [in]	**2.5**	**5**	**7.5**	
Deflection [in]		2.5	5	9.856
Coil Torsion Stress [psi]	5794	18397	30999	
% of Matl. Tensile Stress	4.2	13.3	22.4	
Hook Bending Stress [psi]		36036	60722	
% of Matl. Tensile Stress		26	43.8	
Hook Torsion Stress [psi]		23363	39368	
% of Matl. Tensile Stress		16.8	28.4	

Hook Radius @ Load	0.2433	Hook Bend Radius	0.0428	Free Len. Tol. [in]	+/- 0.1181

Design Status:
Successful

DXF Drawing: **Direction of Coiling:**Optional





Reference:
ANL Springs Manufacturing Co.
http://www.anlspring.com/

APPENDIX O BATTERY SPECIFICATION

- **Cells:** AAA700H
- **Voltage:** 7.2 V
- **Capacity:** 700mAh
- **Weight:** 124 g
- **Connector:** 0
- **Max Current:** 10 C
- **Wire:** 22 ga
- **Shape:** A6

Reference:
http://www.batterieswholesale.com/battery_packs_6_cell.htm

APPENDIX P BATTERY CHARGING MODULE SPECIFICATION

Smart DC Charger Module for NIMH Battery Pack 2.4-7.2 V (0.5 A)

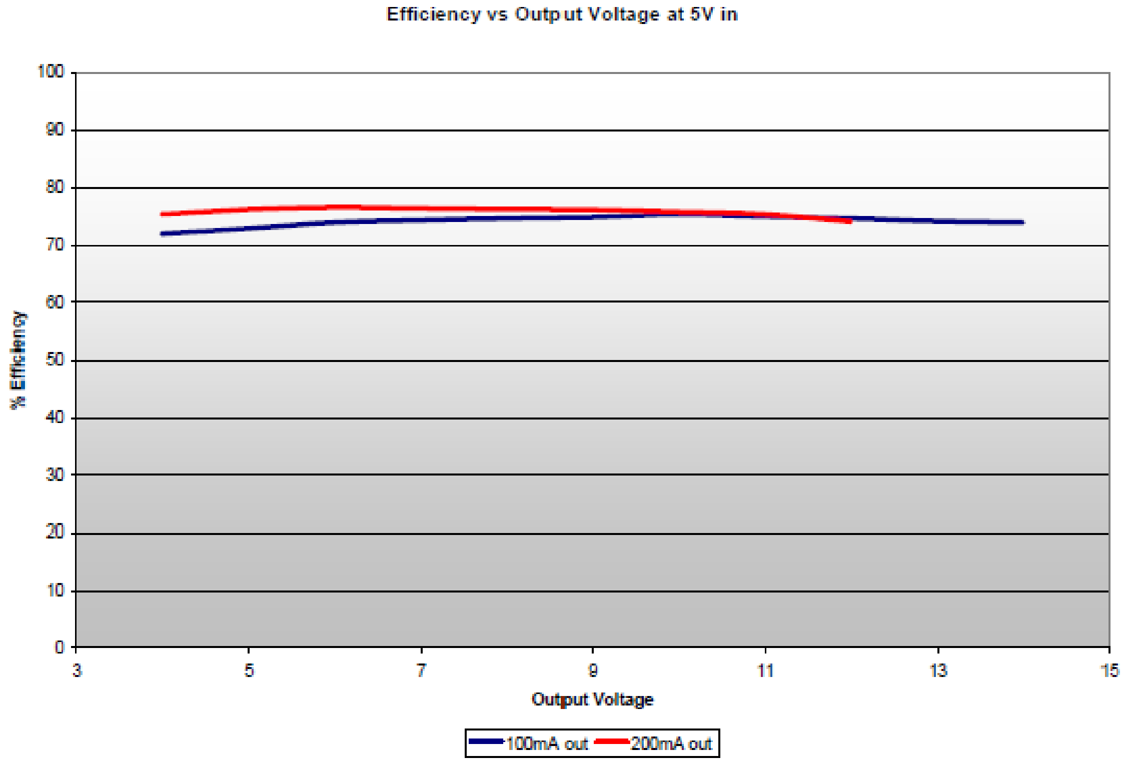
- **Input:** 12-16 V DC
- **Charging:** for 2-6 cells NMH battery pack (2.4-7.2 V)
- **Charging Current:** 500 mA
- **Built in IC with these functions:**
  - Automatically detect battery pack’s voltage and set up correct charging mode
  - Automatically cut-off power by detect minis delta V when battery is full
- **Dimension (LxWxH):** 2’’ x 2’’ x 1’’

Reference:
http://www.batteryspace.com/browseproducts/Smart-DC-Charger-Module-for-NiMH-battery-Pack-2.4V---7.2V--(0.5A).HTML

APPENDIX Q DC TO DC CONVERTER SPECIFICATION

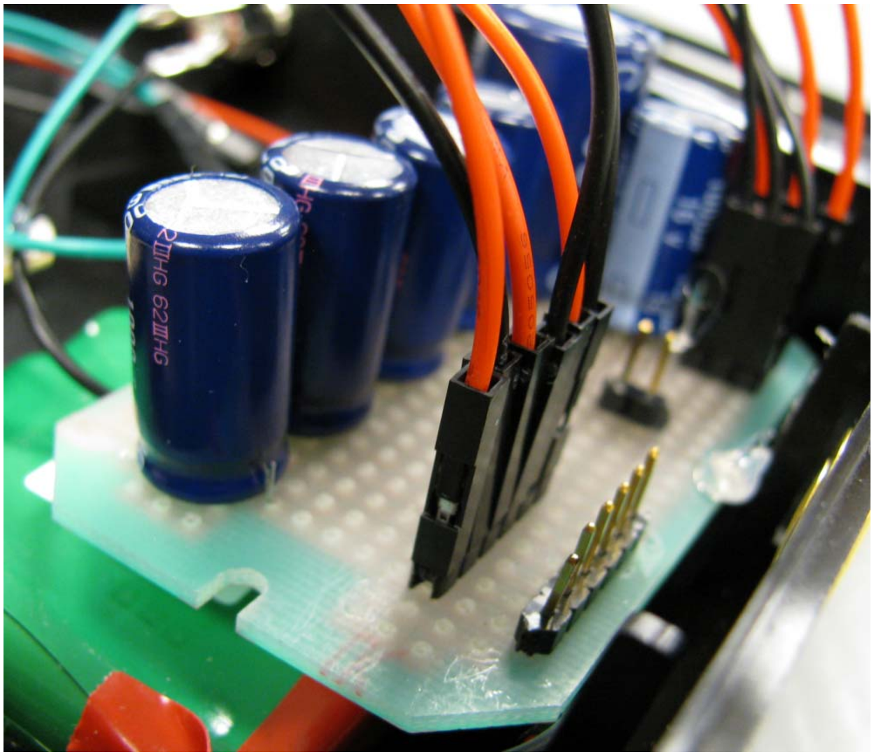
Any Volt Micro Universal DC-DC Converter

- **Input Voltage:** 2.6-12 V
- **Output Voltage:** 2.6-14 V
- **Continuous Input Current:** 0.5 A
- **Continuous Output Current:** 0.5 A
- **Output Ripple (Vp-p):** 40mV
- **Quiescent Current Draw:** 15 mA
- **Efficiency:** 75 %
- **Recommended ambient Temperature:** 25 °C



Reference:
http://www.batteryspace.com/prod-specs/AnyVoltMicro.pdf

APPENDIX R RECTIFIER CAPACITOR SYSTEM



APPENDIX S DESCRIPTION OF ENGINEERING CHANGES SINCE DESIGN REVIEW #3

Since our design review 3, we have made five minor changes to the final design and prototype.

(1) Our final design and prototype all increased in length by about 3 inches. This was due to a modeling error we had in our initial design reviews and was accommodated by increasing the travel distance of the magnet which increased canister length.

(2) Our spring was also changed from a stainless steel compression spring to a phosphor bronze extension spring. This change was necessitated out of the material needing to be non-ferrous and the extension spring giving our design greater total extension length and smaller compressed length.

(3) We modified our modeling code in MATLAB to better simulate the system we created, and this let us optimize the number of coils to 600 while holding wire diameter, coil length, magnet strength, mass, etc. constant.

(4) For our prototype we decided to move the rectifier and capacitor into the black box due to space concerns. However the final design will still incorporate these electrical components into the canister to make our design scalable.

(5) We also moved away from using USB connections to transfer power from the canister to the black box mainly due to space concerns and not wanting to confuse the user into thinking the canister can be directly plugged into a portable devices USB outlet.

APPENDIX T MATERIAL SELECTION: FUNCTIONAL PERFORMANCE

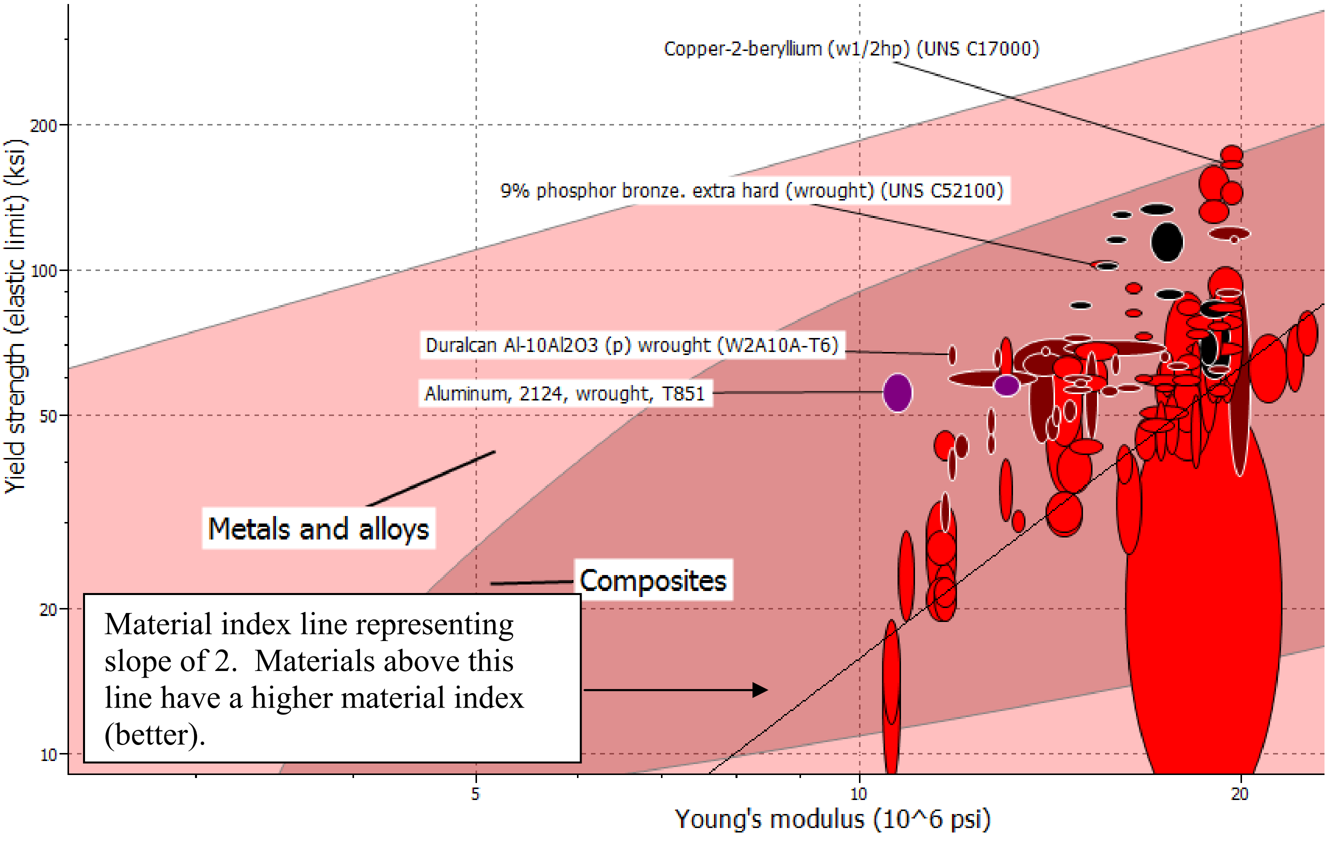
Material selection software, Cambridge Engineering Selector (CES) was used to determine the optimal materials for our spring and canister. We determined the best spring material to be 9% phosphor bronze. Extra hard (wrought) (UNS C52100), and the best canister material to be PPS (30% PAN carbon fiber, conductive – EMI shielding). The following section outlines the procedure used when determining these materials, as well as the other candidate materials.

Spring material selection

Function: The spring should store the kinetic energy of the magnet as it oscillates inside the canister generator. The spring should be able to deform up to three times it's free length.
Objective: Maximize stored elastic energy per unit volume and mass.
Constraints: No failure by yield, fracture or fatigue. Cannot be magnetic. Must resist corrosion.

Material Index:
$M = \sigma_f^2 / E$
Where, σ_f is the yield strength and E is Young's Modulus.

Final Choice: 9% phosphor bronze. Extra hard (wrought) (UNS C52100)
Phosphor bronze has a copper base and is fully nonmagnetic and has a high material index as shown with respect to the diagonal line on the following graph. Phosphor bronze is nearly 10 times cheaper than the other copper based composite, copper beryllium. The other aluminum based composites with slightly higher materials indices were not selected due to their becoming brittle during the cold working spring process.

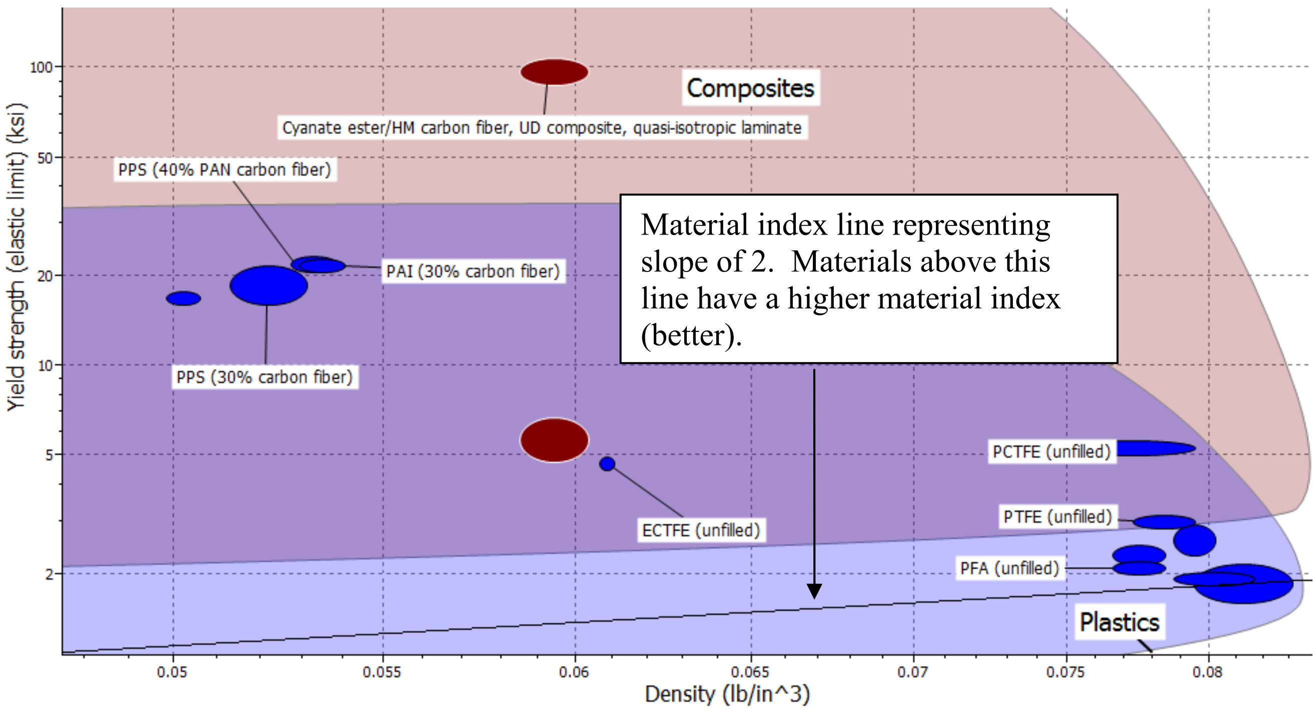


Material index line representing slope of 2. Materials above this line have a higher material index (better).

Canister material selection
Function: The canister should protect the spring, magnet and magnet coiling from the environment.
Objective: Must be as light as possible. Must have high yield strength.
Constraints: No failure by yield, fracture or fatigue. Cannot be magnetic. Should provide magnetic shielding. Must resist corrosion. Must resist UV radiation. Service temperature range of -40 to 180 °F.

Material Index:
$M = \sigma_f / \rho$
Where, σ_f is the yield strength and ρ is density.

Final Choice: PPS (30% PAN carbon fiber, conductive – EMI shielding)
We determined Carbon Fiber reinforced Polyphenylene Sulfide (PPS) to be the optimal material for the canister. Reinforced PPS offers low density while having high yield strength and Young's Modulus. Additionally, reinforced PPS offers magnetic shielding, which will prevent interference with the magnet inside the canister. The material with the highest material index, Cyanate ester/HM carbon fiber UD composite would be much more difficult to obtain and costs nearly 10 times as much. Carbon fiber reinforced Polyamideimide (PAI) has nearly identical mechanical properties as PPS, however has higher costs and does not offer magnetic shielding. The other materials shown on the following graph have significantly lower material indices and do not offer magnetic shielding and therefore were not chosen.



Material index line representing slope of 2. Materials above this line have a higher material index (better).

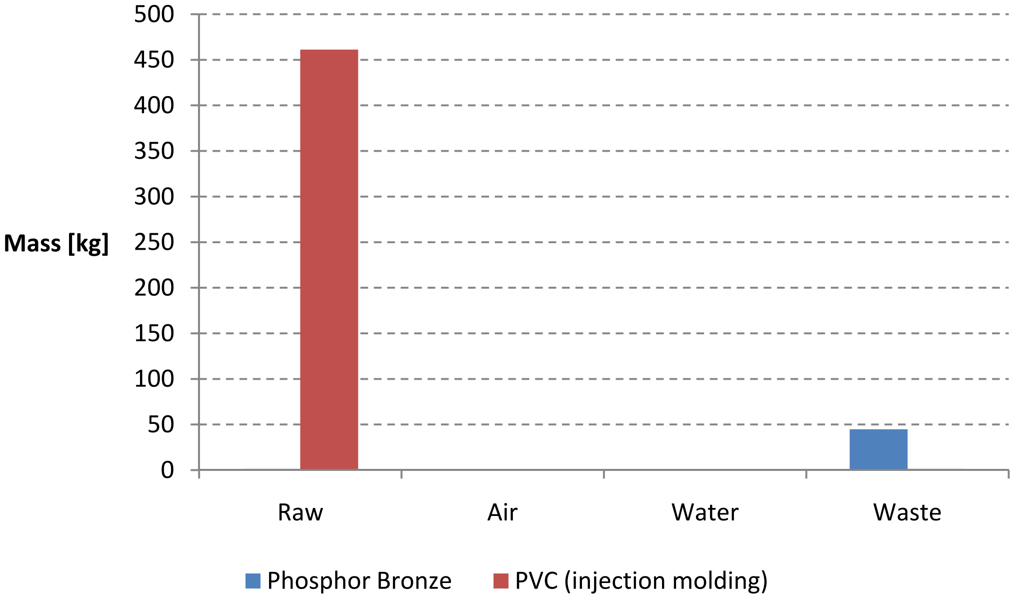
APPENDIX U MATERIAL SELECTION: ENVIRONMENTAL PERFORMANCE

This section presents an environmental analysis of materials used in this design that was performed using Simapro. The method used in all comparisons was the Eco-indicator 99. (*Note that none of the top six canister materials identified using the materials selection software from the previous section were available in Simapro, therefore PVC was chosen instead.*) It was determined that neither Phosphor Bronze (spring materials) nor PVC (canister material) has a large impact on human health or ecosystem quality. The Phosphor Bronze manufacturing process does, however, have a significant impact on resources.

Total Mass / Emissions

The total mass comparison between Phosphor Bronze and PVC injection molding is shown below in figure U.1. The data was acquired using Simapro and then exported into excel for a graphical comparison. It can be seen that PVC injection molding has high raw material consumption but relatively little emissions or waste (according to Simpapro databases, for PVC injection molding, the 'waste' is reused). Conversely, Phosphor Bronze has noticeable waste generation, yet little to no raw material consumption and emissions.

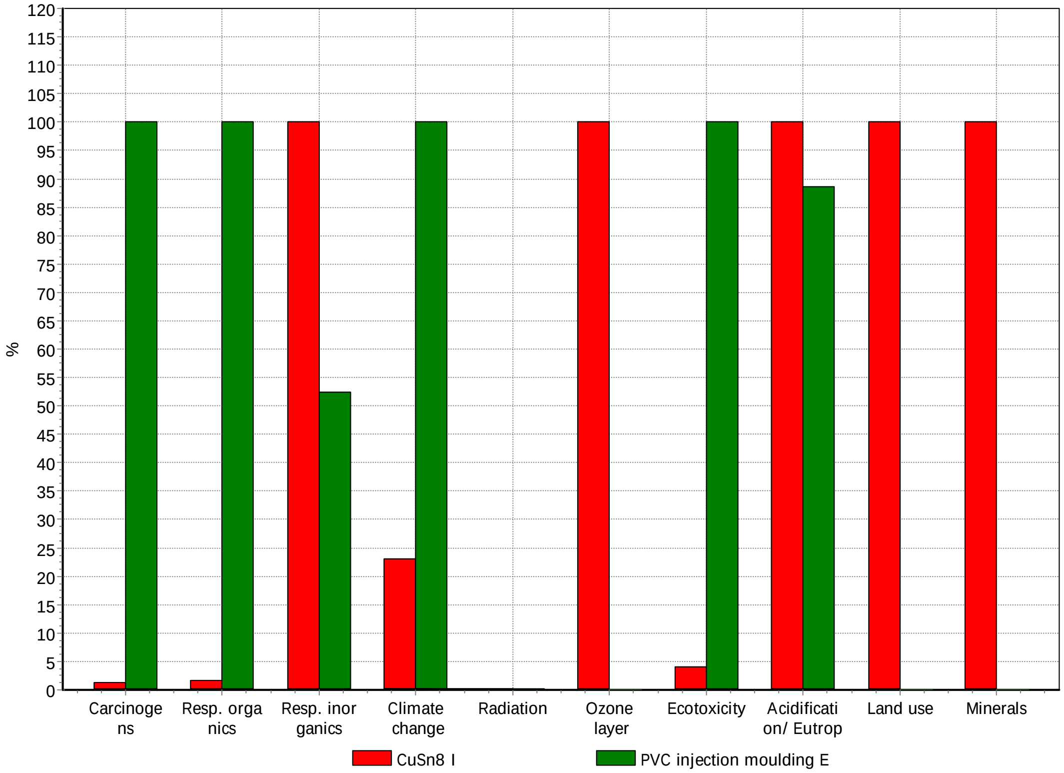
Figure U.1 Shows the total mass comparison



Relative Impacts in Disaggregated Damage Categories

The relative impacts of Phosphor Bronze and PVC are shown below in figure U.2. The total relative impact of each material appears to be fairly even, with each having larger impact in four categories and tying one.

Figure U.2 Shows the Relative Impacts in Disaggregated Damage Categories

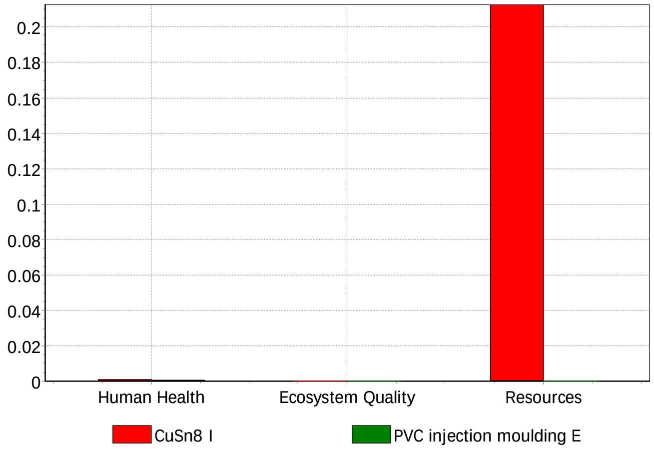


Comparing 0.8 lb 'CuSn8 I' with 10 lb 'PVC injection moulding E'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

Normalized Score in Human Health, Eco-Toxicity, and Resource Categories

The normalized (over one year) impacts of Phosphor Bronze and PVC are shown below in figure U.3. From the normalized data, it can be seen that neither Phosphor Bronze nor PVC poses a significant hazard to human health or ecosystem quality. Phosphor Bronze does, however, impact resources.

Figure U.3 Shows the Normalized Score in Human Health, Eco-Toxicity, and Resource Categories

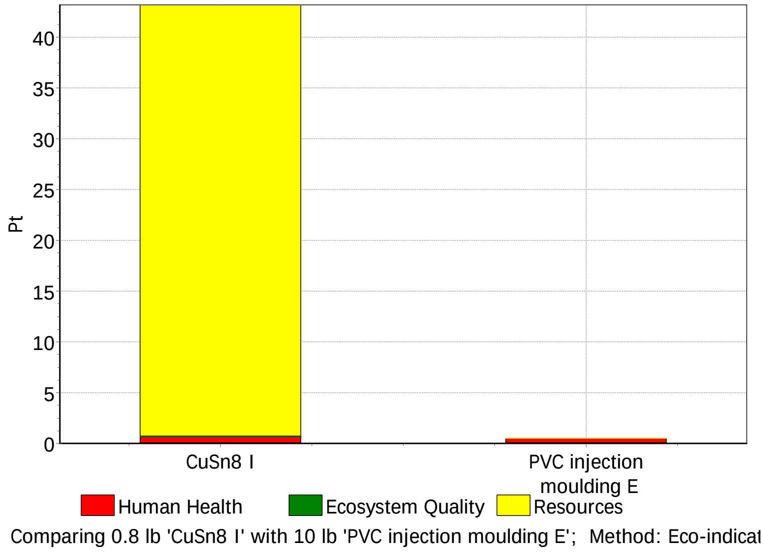


Comparing 0.8 lb 'CuSn8 I' with 10 lb 'PVC injection moulding E'; Method: Eco-indica

Single Score Comparison in "Points"

The normalized scores are weighted and expressed in terms of a single score comparison, shown below in figure U.4. From this rendition of the impacts of Phosphor Bronze and PVC, it can be seen that PVC has a drastically lower impact on resources. The human health and ecosystem impacts of both materials are relatively negligible.

Figure U.4 Shows the Single Score Comparison in "Points"



Comparing 0.8 lb 'CuSn8 I' with 10 lb 'PVC injection moulding E'; Method: Eco-indicat

Based on this analysis, we investigated the possibility of selecting a different material for the spring. The other viable option we determined was Beryllium Copper. Unfortunately, the production of Beryllium Copper poses significant health hazards (from the Beryllium). Based on these finding, we have decided not to select a different material for the springs. We do recommend, however, that a more in-depth database be used in order to determine the environmental impacts of the selected material for the canister (30% carbon fiber reinforced PPS).

APPENDIX V MANUFACTURING PROCESS SELECTION

Assuming our project becomes a viable military tool used by soldier in the field, we could be manufacturing a lot of our devices. This means we won't be able to assemble our device by hand as we have been doing for our prototype and we will have to resort to mass production methods.

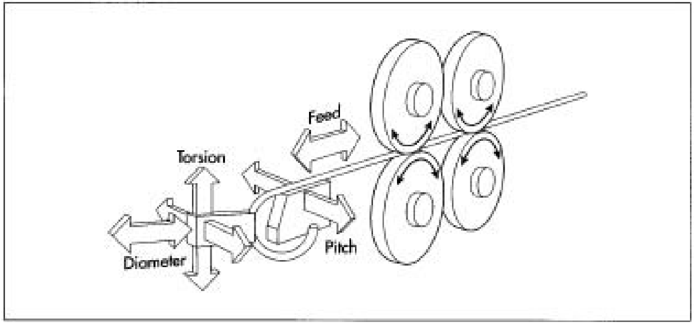
V.1 Production Numbers

Our project is designed for use in the military and if it was widely adopted, it could be used in many different applications for many soldiers. The US army currently has about six hundred thousand active soldiers and the marines have about two hundred thousand. Assuming that only 1 in 20 are issued our energy harvesting device for use in the field that would give a total production number of forty thousand units. Assuming that we need to manufacture ten canisters for every unit and one black box for every unit that would mean we must manufacture four hundred thousand canisters and forty thousand black boxes to satisfy the needs of the US military. We would also need to produce four hundred thousand metal springs to meet the demand. Producing for civilian use could be a spinoff of our design but for this exercise we will just look at selling the product to the military.

V.2 Manufacturing Methods

For the PPS plastic canister, we will need to produce a cylinder shape with relatively tight tolerances and large batch sizes. The manufacturing method will have to be precise and discrete but not too expensive for the volume. The black box can be created in a similar fashion as the canisters the only difference being they are not cylinders. From these parameters, we have decided to use injection molding as the main form of manufacturing for the canisters and blackbox. The economic batch size fits within the injection molding range, $1x10^4$ to $1x10^6$. The mass range, tolerances, section thickness and roughness all fit within the specification of our final design. A cylinder is not a new design to injection molding and should be able to be created with a little creativity on the mold design. This is optimal also due to the multiple diameters necessary for the canister. The black box is an easy design for the injection molding process due to its cupped design with a top. For our surface treatment we have chosen organic solvent-based painting for applying a coating of paint to the canister and black box. This process had good corrosion protection, electrical insulation, texture, and curved surface coverage.

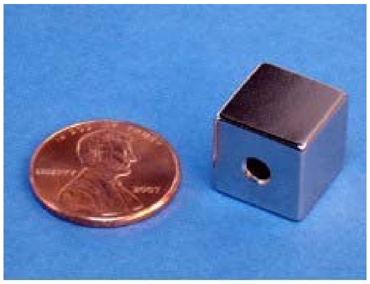
Figure V.1: Spring Manufacturing Machine Schematic



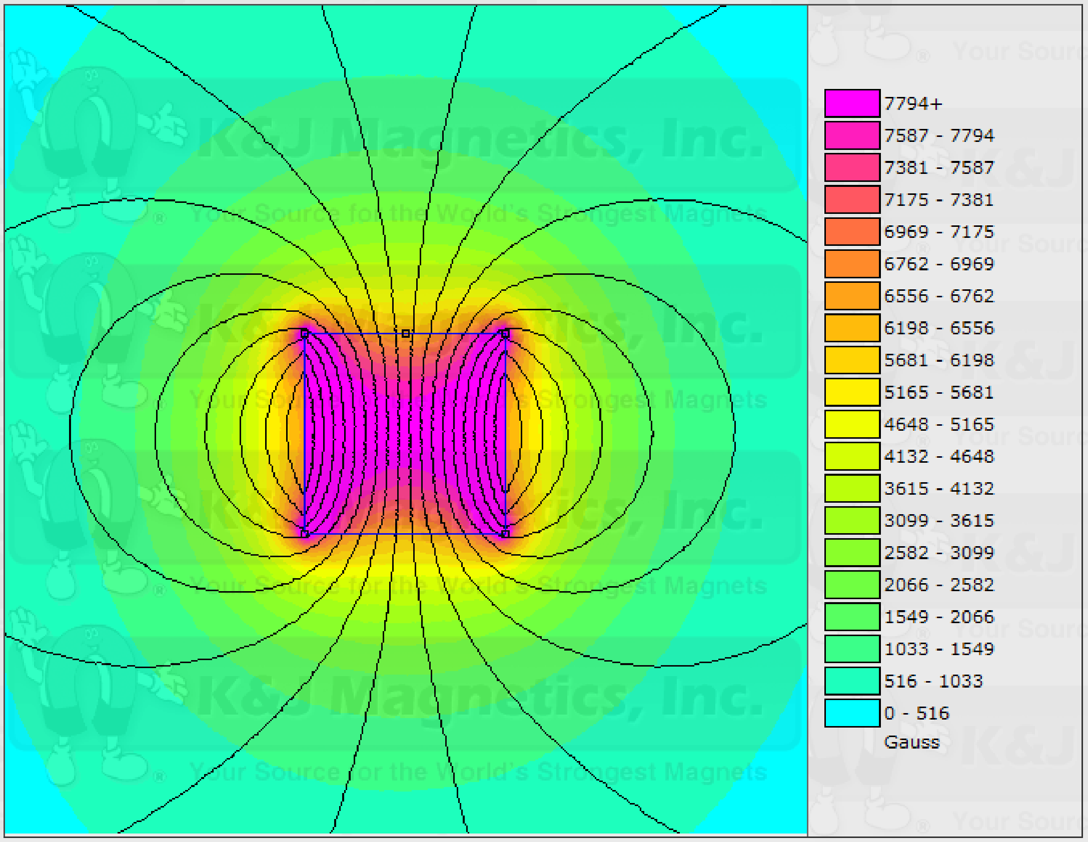
madehow.com

For the Phosphorus Bronze extension spring, we need to have a manufacturing method that is good for mass production of wire of any size and could coil the wire into a spring. In order to make the wire whatever size we want, we will use a drawing manufacturing method to produce a wire of the correct diameter. This process is appropriate because of its mass range, continuous manufacturing process, range of section thickness, and tolerances that match our design specifications. Once the wire is formed we will use a spring making machine that would be similar to the one shown above in figure V.1. This machine takes wire fed into it and coils it to the proper diameter and pitch depending on spring specifications. This machine should be able to mass manufacture springs to our specifications.

APPENDIX W SQUARE MAGNET SPECIFICATION



- **Dimensions:** 1/2" x 1/2" x 1/2" (- 0.127" hole)
  Hole perpendicular to magnetization direction
- **Material:** NdFeB, Grade N52
- **Plating/Coating:** Ni-Cu-Ni (Nickel)
- **Magnetization Direction:** Thru Thickness
- **Weight:** 0.482 oz. (13.67 g)
- **Pull Force:** 21.48 lbs
- **Surface Field:** 6451 Gauss
- **Max Operating Temp:** 176ºF (80ºC)
- **Brmax:** 14,800 Gauss
- **BHmax:** 52 MGOe

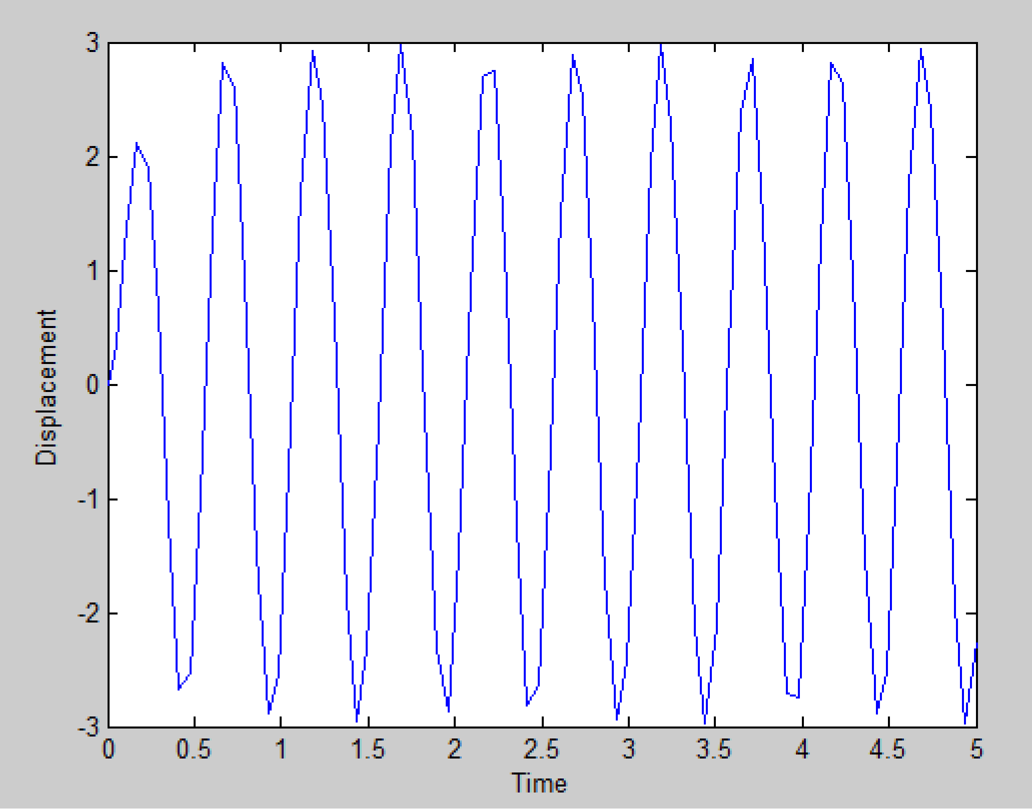


APPENDIX X MATLAB CODE FOR SCALED-DOWN DESIGN

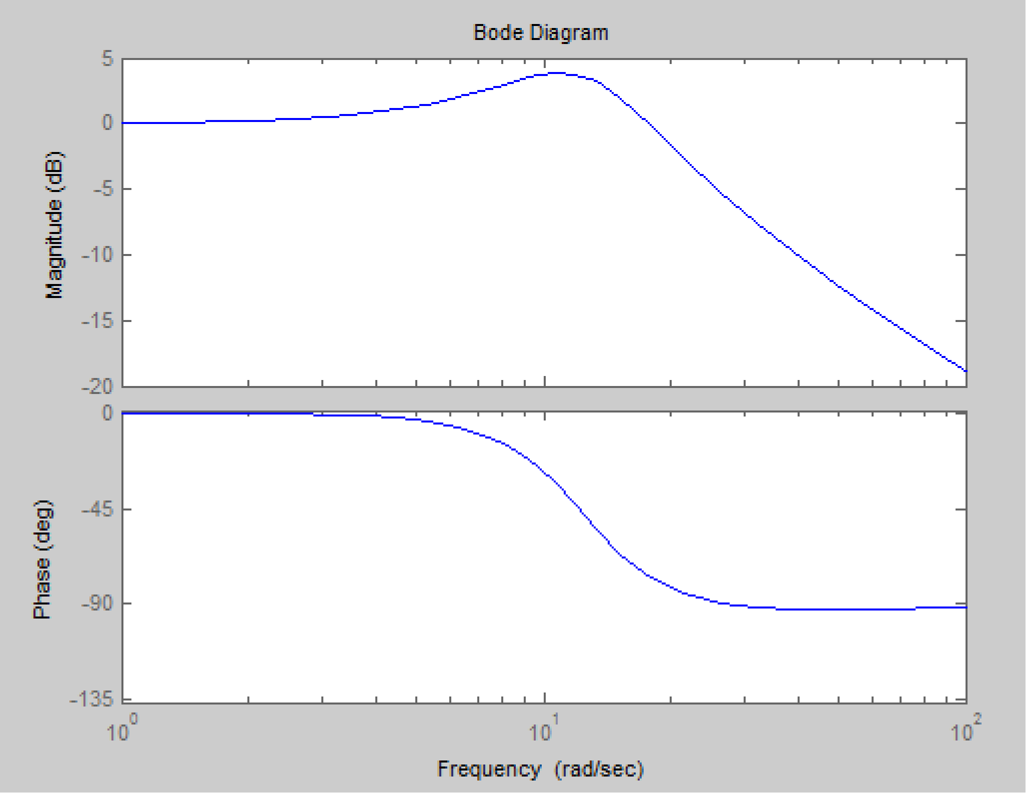
MATLAB Code for Magnet Displacement and Bode Diagram:

```
amp = 2*.0254; %amplitude of hip oscillations
omega = 2*2*pi(); %frequency of oscillations
N = 1000; %number of turns
l = 1.5*.0254; %coil length
x = 3*.0254; %magnet travel
Diam = 1*.0254; %magnet diameter from inches to meters
delta = -1/N*log(omega/(omega+N)); %distance from magnet to coil
Br = 0.7; %if in gauss must convert to tesla
B = Br*(1+(2*delta/Diam))^(-1); %magnetic field density
res = 41.02/25.4; %resistance per meter of wire
Vout = B*N*l*x*omega; %voltage of single generator
Rcoil = Diam*pi()*N*res;
Rload = 1; % 8*Vout/(I)+0.32 internal battery resistance. approximated
Lcoil = omega*.00034088;

b = N*l*B/sqrt((Rload+Rcoil)^2+Lcoil^2) %damping coefficient related to magnetic field
m = 13.67/1000; %mass of magnet in kilograms?
k = 2.16; %spring constant in newton meters
Vout
Power = Vout^2/(sqrt((Rload+Rcoil)^2+Lcoil^2))


sim('model.mdl',[0 5]);
Np = Position*39.37;

abc = tf([b k],[m b k]);

figure(1)
bode(abc)%;set(bode,'FontSize',26)

figure(2)
plot(Time,Np-input)
xlabel('Time')
ylabel('Displacement')


%magnetic field in the coil is B = 4*pi()*10^-7*Number of
%coils*current/length of coil
```

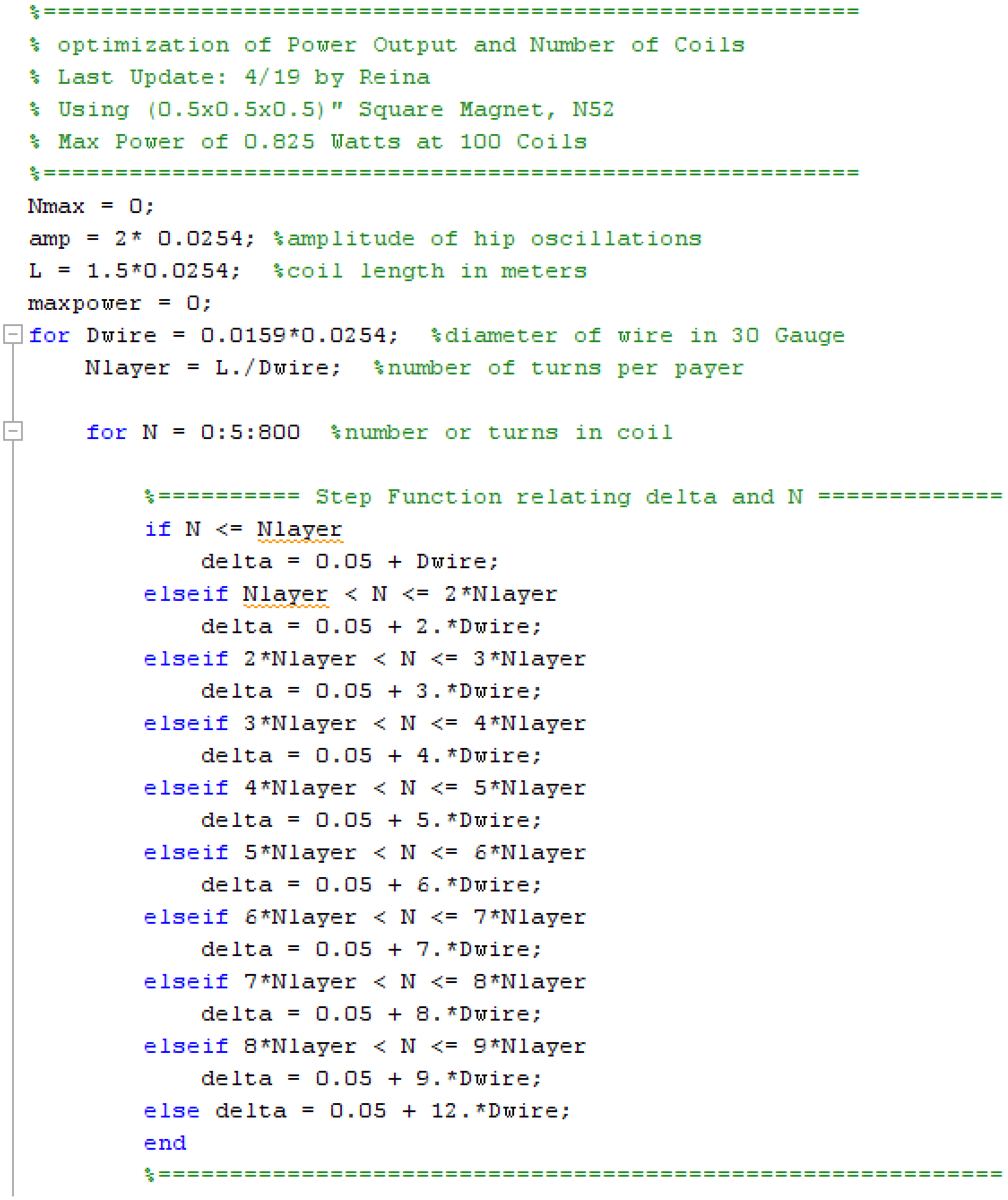
Magnet Displacement Plot:



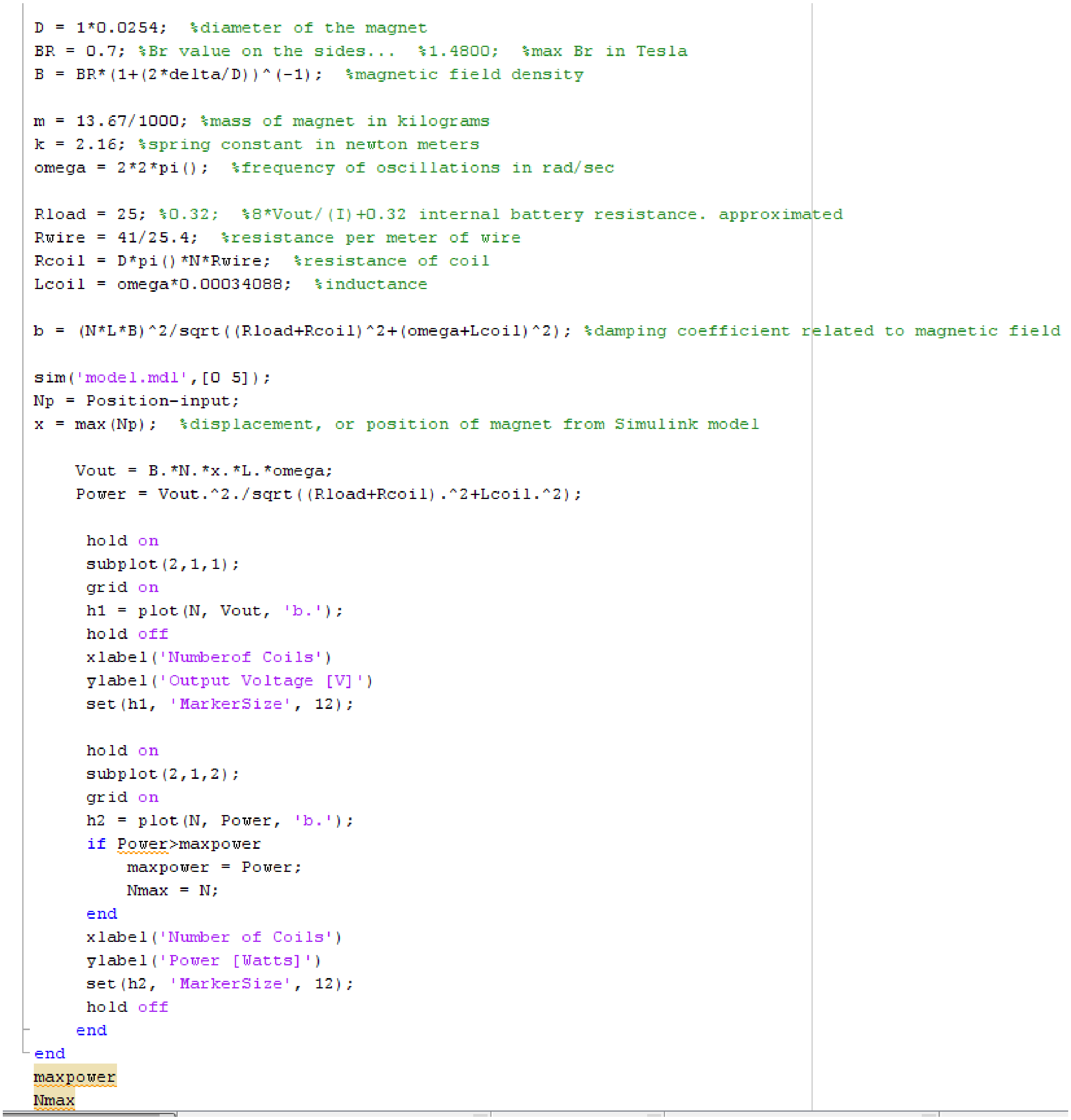
Bode Diagram:



MATLAB Code for Power Output:



```
%==========================================================
% optimization of Power Output and Number of Coils
% Last Update: 4/19 by Reina
% Using (0.5x0.5x0.5)" Square Magnet, N52
% Max Power of 0.825 Watts at 100 Coils
%==========================================================
Nmax = 0;
amp = 2* 0.0254; %amplitude of hip oscillations
L = 1.5*0.0254;  %coil length in meters
maxpower = 0;
for Dwire = 0.0159*0.0254;  %diameter of wire in 30 Gauge
    Nlayer = L./Dwire;  %number of turns per payer

    for N = 0:5:800  %number or turns in coil

        %========== Step Function relating delta and N =============
        if N <= Nlayer
            delta = 0.05 + Dwire;
        elseif Nlayer < N <= 2*Nlayer
            delta = 0.05 + 2.*Dwire;
        elseif 2*Nlayer < N <= 3*Nlayer
            delta = 0.05 + 3.*Dwire;
        elseif 3*Nlayer < N <= 4*Nlayer
            delta = 0.05 + 4.*Dwire;
        elseif 4*Nlayer < N <= 5*Nlayer
            delta = 0.05 + 5.*Dwire;
        elseif 5*Nlayer < N <= 6*Nlayer
            delta = 0.05 + 6.*Dwire;
        elseif 6*Nlayer < N <= 7*Nlayer
            delta = 0.05 + 7.*Dwire;
        elseif 7*Nlayer < N <= 8*Nlayer
            delta = 0.05 + 8.*Dwire;
        elseif 8*Nlayer < N <= 9*Nlayer
            delta = 0.05 + 9.*Dwire;
        else delta = 0.05 + 12.*Dwire;
        end
        %============================================================
```



```
D = 1*0.0254;  %diameter of the magnet
BR = 0.7; %Br value on the sides...  %1.4800;  %max Br in Tesla
B = BR*(1+(2*delta/D))^(-1);  %magnetic field density

m = 13.67/1000; %mass of magnet in kilograms
k = 2.16; %spring constant in newton meters
omega = 2*2*pi();  %frequency of oscillations in rad/sec

Rload = 25; %0.32;  %8*Vout/(I)+0.32 internal battery resistance. approximated
Rwire = 41/25.4;  %resistance per meter of wire
Rcoil = D*pi()*N*Rwire;  %resistance of coil
Lcoil = omega*0.00034088;  %inductance

b = (N*L*B)^2/sqrt((Rload+Rcoil)^2+(omega+Lcoil)^2); %damping coefficient related to magnetic field

sim('model.mdl',[0 5]);
Np = Position-input;
x = max(Np);  %displacement, or position of magnet from Simulink model

    Vout = B.*N.*x.*L.*omega;
    Power = Vout.^2./sqrt((Rload+Rcoil).^2+Lcoil.^2);

     hold on
     subplot(2,1,1);
     grid on
     h1 = plot(N, Vout, 'b.');
     hold off
     xlabel('Numberof Coils')
     ylabel('Output Voltage [V]')
     set(h1, 'MarkerSize', 12);

     hold on
     subplot(2,1,2);
     grid on
     h2 = plot(N, Power, 'b.');
     if Power>maxpower
         maxpower = Power;
         Nmax = N;
     end
     xlabel('Number of Coils')
     ylabel('Power [Watts]')
     set(h2, 'MarkerSize', 12);
     hold off
    end
end
maxpower
Nmax
```

Output:
maxpower =   0.8250 Watts
Nmax =   100 turns

Plot of Power Output: