An Investigation of Didactic Energy Transfer Systems

by

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

BACHELOR OF SCIENCE
AT THE
MASSACHUSETTS INSTITITE OF TECHNOLOGY

JUNE 2007

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Submitted to the Department of Mechanical Engineering on May 11, 2007 in partial fulfillment of the requirements for the Degree of Bachelor of Science in Mechanical Engineering

ABSTRACT

New experiments were developed for the freshmen seminar Physics of Energy. The class covers electricity generation and dissipation, and provides experience in analysis and design of electrical and mechanical engineering systems. There was interest in developing a series of new laboratory experiments that would demonstrate methods of energy conversion to students. The experiments are focused on the topic of energy conversion and they introduce topics from electromagnetism to mechanical engineering. The new systems developed include a DC motor kit for learning about motor design and use, a linear synchronous motor for learning about electromagnetism, classical mechanics and ballistics, and an end to end power plant energy conversion laboratory to introduce the topics of heat transfer and process efficiencies.

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Acknowledgements:

I would like to thank Prof. Seven B. Leeb for guidance, Salome Morales for keeping me on task, and Cameron Lewis for magnet-car project management.

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Introduction

Educational Context

Undergraduate freshmen at MIT have the choice of taking a class taught on energy conversion by a multidisciplinary group of professors, including Prof. Steven Leeb, Prof. James Kirtley, and Prof. Les Norford. The class was designed to provide experience in various fields before the freshmen choose their majors, while at the same time teaching the importance of energy conversion issues in today's society. Power conversion is a rising issue of concern as the health of the environment is coming into question and eyes fall on methods for reducing energy usage. MIT is taking the lead by introducing a suite of new classes on the subject of energy, this class being one of them.

The class covers electricity generation and dissipation, and provides experience in analysis and design of electrical and mechanical engineering systems. For next school year, there was interest in developing a series of new laboratory experiments that would demonstrate methods of energy conversion to students. Ideally they would be both educational and entertaining. Three types of demonstrations were desired:

- Electrical Potential to Mechanical Movement – (DC Motor)
- Mechanical Movement to Electrical Potential – (Generator)
- Temperature Difference to Electrical Potential through Mechanical Movement – (Power Plant)

The goals were met by creating a series of demonstrations that can be modeled with equations based on fundamental principles. The work was divided into two main thrusts, electromagnetic actuators, including DC motors, linear synchronous motors, and solenoids, and an end to end power plant laboratory which features a Stirling Engine and a generator.

Electromagnetic Actuators

Introduction to Electromagnetism

In the presence of a magnetic field, a current carrying wire feels a force; this force, the Lorentz force, is what makes most motors and generators work. Coiling the wire concentrates the magnetic field in the core, which is the principle used in most electromechanical applications like the common mechanical solenoid or DC motor. Several things affect the strength of the magnetic field. From Maxwell's equations we can derive the simplified formula for the magnetic field in the center of a coil of wire.

$$B = \frac{\mu_0 N i}{d}$$

Simplified Magnetic Field in a Coil of Wire

Where the strength of the magnetic field depends on the number of turns, ***N***, the current through the wire in Amperes, ***I***, the height of the coil in meters, ***d***, and the permeability in Heneries per meter, μ_0.

We will attempt to create models that teach students the physics involved and show them how people have harnessed the power in everyday objects like DC motors and solenoids. Experiments that the students can interact with firsthand may deepen their interest in the subject, cement their understanding, and allow them to explore potential extensions to the theory. The electromagnetic experiments are meant to encourage the use and design of solenoid actuators, DC motors, and linear synchronous motors.

Solenoid Actuators:

Solenoids are typically used to pull on a rod with a relatively small throw. A ferrous rod is placed approximately halfway into the coil and upon excitation of the coil the rod is pulled to the far end of the coil. Solenoids are commonly used in vending machines, valves, and door locks.

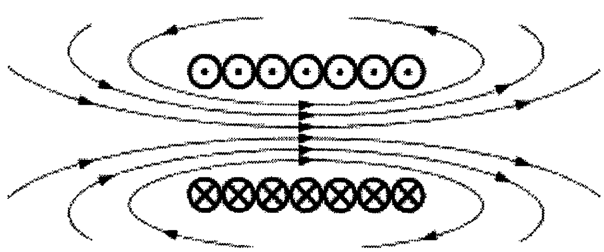


Figure 1: Magnetic Field Lines Through a Coil of Wire

The solenoid can be made more exciting for students by placing a magnet inside of the coil. If the magnet experiences a gradient in magnetic field, which can be accomplished by allowing the magnet to protrude slightly out of the top of the coil, when current is applied, the magnet may jump completely out of the coil. With a 20AWG 1.14"X0.6" copper coil (Part #255-028 from Parts Express), a 0.5 inch diameter by 0.75 inch neodymium magnet and two motorcycle batteries in series the magnet has been known to jump six feet into the air.

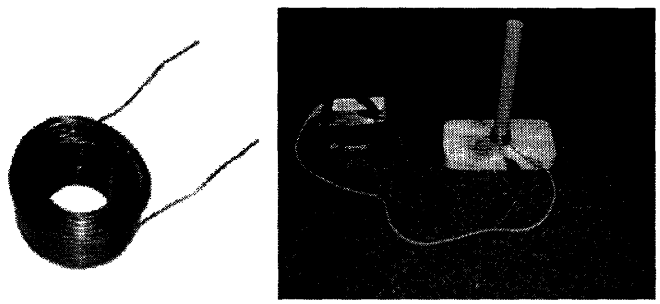


Figure 2: Sample Magnet Launcher Device

For a given volume, a larger wire size reduces the resistance of the coil enabling larger currents but reducing the number of turns one can achieve. There is a trade-off situation which is present in the design not only of solenoids but DC motors and many other electromechanical actuators that use coils of wire as a force transmitting element. There exists an optimum coil design given functional parameters such as maximum current and voltage requirements, and a contest can be administered in the classroom to find the solenoid that will launch the magnet the highest. A sample experiment would fix the voltage at 24 volts, current limit the supply at 20 amperes, and establish a maximum coil size of 1.5 inch diameter by 0.75 inches tall.

Motor Demo:

There are countless types of motors: DC/AC, Brush/Brushless, PWM controlled/Voltage controlled, etc. Several types of motors discussed in this section. DC permanent magnet motors are the simplest to model from basic electromagnetism, and these are the primary type of motor intended to be demonstrated in the power conversion class. Two DC motor kits have been put into use prior to my arrival, the "bipolar" motor and the "shop-day" motor. In going over the various types of simple educational motors advantages and disadvantages of each type will be discussed. The two new projects being developed are the DC Motor Kit, and the Linear Synchronous Motor.

The bipolar wire motor is a simple demonstration which one would find hard pressed to analyze the performance of. The DC motor kits which were designed as a part of this thesis, on the other hand, are versatile machines that can operate not only as DC motors but as generators. A student may delve into experiments and calculations and find the motor constant, efficiency and many other performance characteristics. In the past both the bipolar wire motor and the shop-day motor have been used in classes such as the energy conversion class. The intent of the new DC motor kit is to bridge the gap and possibly supplant the bipolar motor and the shop-day motor in favor of the quick, easy and high performance kit.

How a Motor Works:

A permanent magnet DC motor works by driving current through a coil of wire that is in the presence of a magnetic field. Current passing through a wire in a magnetic field creates a force on the wire.

$$\boldsymbol{F} = \boldsymbol{L}\,(\boldsymbol{i} \times \boldsymbol{B})$$

Force on a Current Carrying Wire in a Magnetic Field

Where ***i*** is the current in Amperes, ***B*** the magnetic field strength in Teslas, ***L*** is the length of the wire, and ***F*** is the resultant force in Newtons. Current on one side of the coil flows one direction, and current on the other side of the coil flows the other; one side of the coil experiences a force directly opposite in direction to the other.

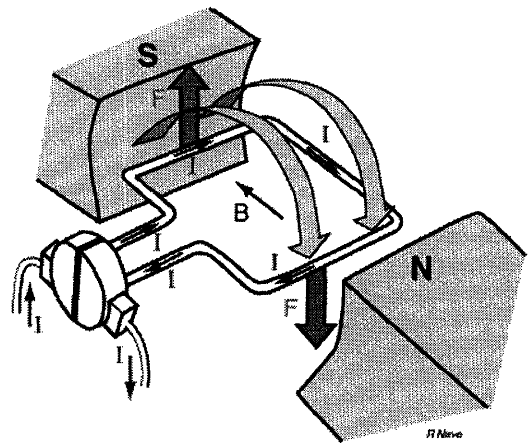


Figure 3 - Forces on a Winding of a Simple DC motor (Nave)

This coupling of forces creates a toque about the center of the coil which, multiplied by the number of turns in the coil, creates the total torque on the rotor. In the case of Figure 3, N would equal one as there is only one turn on the coil.

$$\boldsymbol{T} = \boldsymbol{L}\,\boldsymbol{N}\,[\boldsymbol{r} \times (\boldsymbol{i} \times \boldsymbol{B})]$$

Torque on the Rotor when the Windings are Aligned with Magnetic Field

Where ***N*** is the number of turns of the coil, ***L*** is the active length (two times the length of the coil) and ***r*** is the radius of the motor windings radially out from the axis of the coil. The value of the torque changes through the rotation approaching zero in the case of a single coil as the coil becomes perpendicular to the magnetic field and the Lorentz Force is pointing radially outward. If we were to split up the commutator into additional segments and add more coils, we can approximate that there will always be a coil in the position parallel to the magnetic field and approximate the torque as being constant and eliminate the cross products.

$$\boldsymbol{T} = \boldsymbol{L}\,\boldsymbol{N}\,\boldsymbol{r}\,\boldsymbol{B}\,\boldsymbol{i}$$

Torque Approximated for Many Poles

It is often not necessary for end-users of a DC motor to be familiar with the physical aspects of the motor they are dealing with, such as the number of turns or the strength of the magnetic field, etc. The physical parameters are often grouped together to form the motor constant ***K***.

$$\boldsymbol{K} = \boldsymbol{L}\,\boldsymbol{N}\,\boldsymbol{r}\,\boldsymbol{B}$$

Motor Constant

Simple DC Motor:

One experiment that has been used extensively in the lab for quick demonstrations to people of all ages is the "rotating bipolar" motor, sometimes called the "Beakman Motor" after the children's television show that popularized the experiment in the mid 1990s *Beakman's World*.

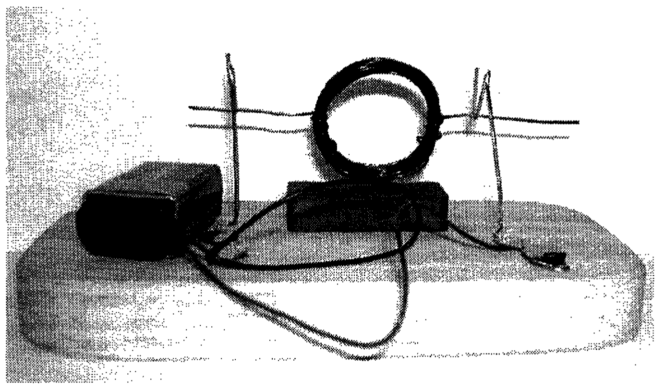


Figure 4: Rotating Bipolar Motor (Leeb, 2007)

Simply coiling magnet wire, 18 gauge works well in our experience, around a D cell battery approximately ten times has been demonstrated to shape a coil that works surprisingly well. Extending the ends of the coil outward completes the structure of the rotor. Stripping off all of the insulation from one leg of the coil and stripping off the top half of the other leg while holding the coil in the vertical orientation forms a simple commutator. As the coil rotates, the conductive supports intermittently activate the coil at the appropriate times to keep the coil spinning. Ceramic magnets are typically used as they are less expensive and adequately powerful. A 9volt battery connects to the supports as they get the motors going to an impressive speed and the 9 volt battery clips provide convenient attachment leads to the motor supports. This experiment can be used to explain the Lorentz force, but lacks the design aspect desired to fully understand the motor constant and DC motor performance.

Shop-day Motor

The bipolar motor is an experiment that demonstrates the principle of electromagnetism, but is pales in comparison to a DC motor you might find in a consumer product. With the shop-day motor, students would spend two days in the machine shop creating a motor of their own design. This serves as great introduction to machine tools and spurs creativity, however, it takes a great amount more time than necessary if the teaching goal is to learn about electromagnetism.

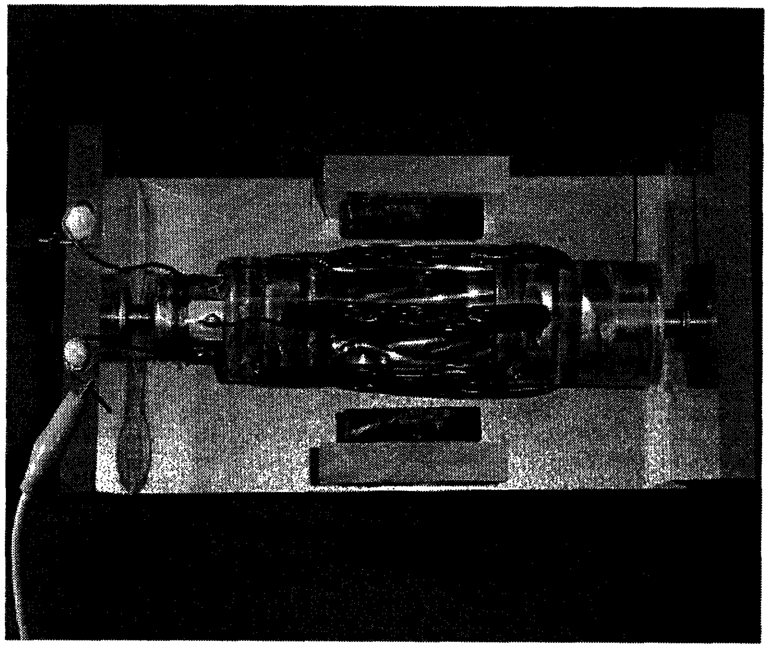


Figure 5: Shop Motor (Leeb, 2007)

There were some good take away lessons learned from the example shop-day motors. Paperclips work well enough as commutator brushes to create a very fast motor. The scale of the motors, with approximately eight inch long rotors, was a good size to hold in the hands when wrapping. Ball bearings serve exceptionally well as low friction and vibration machine elements in the DC motors. The variation from one machine to the next demands a lot of the customizability from a kit that serves to replace it.

To reiterate, the main problem with the current shop-day method was that amount machining required was excessive for an electrical engineering lesson plan, which distracted the students from the physics was intended to be addressed.

DC Motor Kit

The new DC motor kit was our opportunity to design something new that had the configurability of a shop day motor with the assembly time of the bipolar motor. We wished to be able to vary as many parameters as possible while still being able to construct the motor within a couple of hours. Many designs were considered, and the best are illustrated here to shed light on why we settled on the design that we did. It was decided early on to use the chassis from the robots from a separate laboratory experiment as the foundation for the DC motor kit. The chassis has a cone inch grid quarter inch diameter hole pattern across the top and is raised off the table to which allows us to secure items to the top with bolts without worrying about clearance for nuts on the underside.

The first design considered consisted used a hex rotor shaft, two pillow blocks to support the shaft, and two to four magnet supports. Although fairly simple, this design was passed over because of the lack of configurability. Although it was possible to vary the intensity of the magnetic field and the number of turns in the coils, you could not change the rotor cross-sectional area or add additional poles.

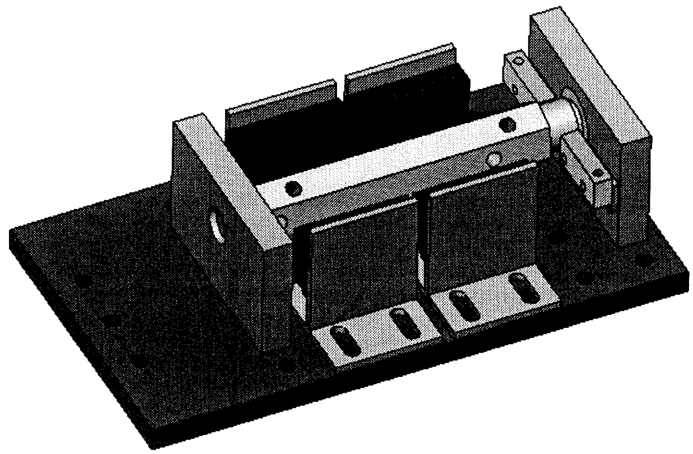


Figure 6: Simple DC Motor Kit

A similar motor was developed made out of sheet metal with one part that served both as the pillow block and the magnet holder (Figure 7).

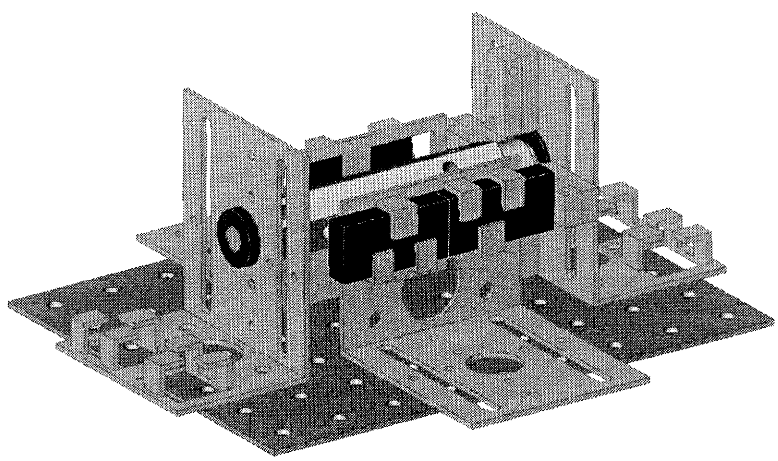


Figure 7: One Piece Sheet Metal Design

Although it was a great design in terms of part cost, the motor would be harder to assemble, look less aesthetically pleasing, and would be less configurable.

The next design consisted of 30-60-90 degree triangular wedges that held the magnets and were then attached to vertical supports coming up from the base. Rotating the triangular pieces allowed for either a square of hexagonal configuration (Figure 8).

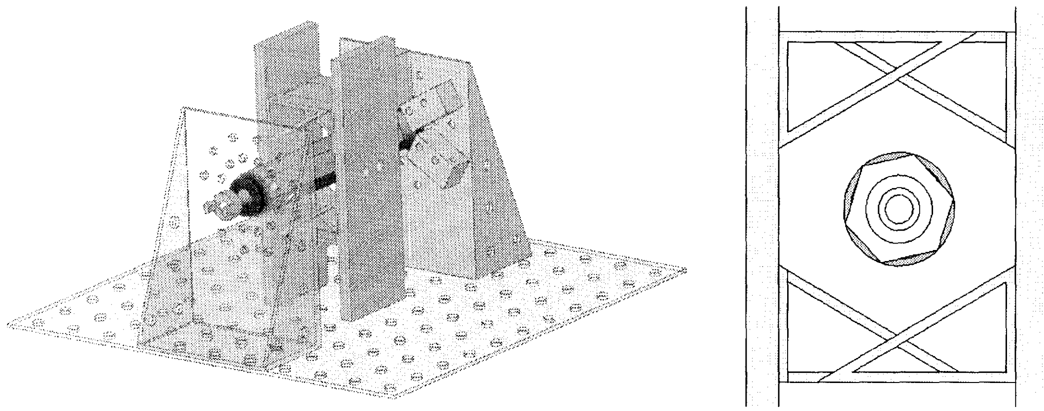


Figure 8: Dual Tower Design

It would be possible to flip the components around and use 2, 4, or 6 magnets at a time. For 3 types of magnet configurations, it used three types of sheet metal parts. It allowed for different rotor diameters, magnet distances, number of windings, number of poles, and active lengths – all of the configurability that we desired. However, it was not as straightforward as desired to assemble the motor without direction, and it would take more time than necessary to get a simple motor running.

Next, I looked at attaching the magnets to the ends or rods for maximum configurability and possible advances in usability (Figure 9). This design suffered in terms of part cost and ease of use. It could use 2, 4, or 6 magnets and like the previous design required 3 types of custom parts to accomplish that.

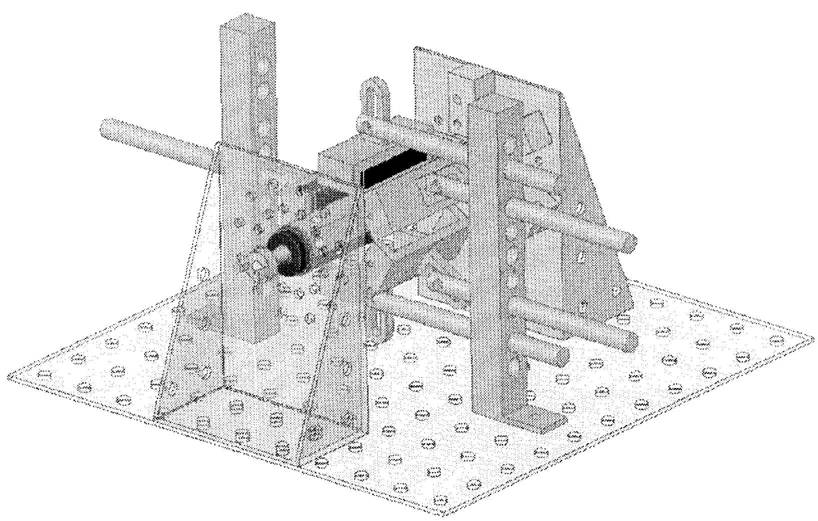


Figure 9: Bar Extension Design

Going for simplicity, I decided to toy with the idea of dropping the ability to use 6 magnets in favor of ease of assembly and configurability (Figure 10). This design was worked well in theory in terms of adjusting distance from the magnet to the rotor, but the activation energy to get a basic motor setup still required 12 bolts to assemble. It suffered in terms of ease of installation and on top of that, it was not able to handle six magnets.

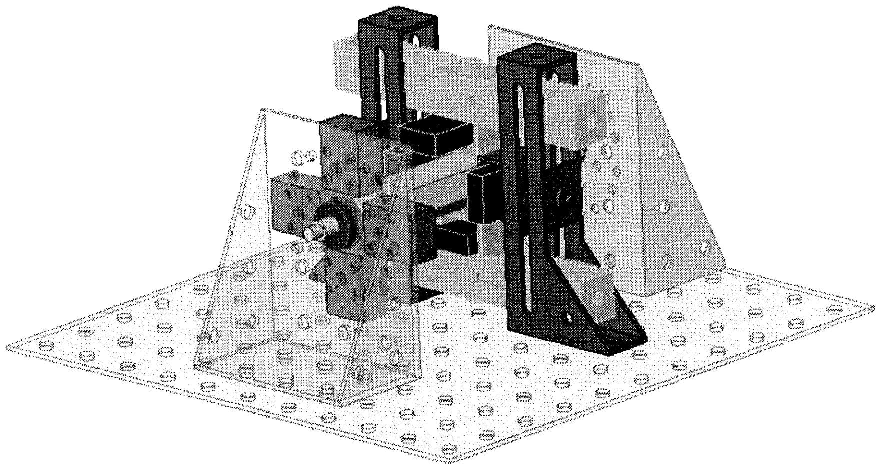


Figure 10: Four Way Adjustment Design

Most of the assemblies investigated used as many parts to hold the magnets as magnet configurations available, it made sense to simplify the parts and create one specialized part for each configuration. The default magnet position would leave room for the largest coils that could be wound on the rotors.

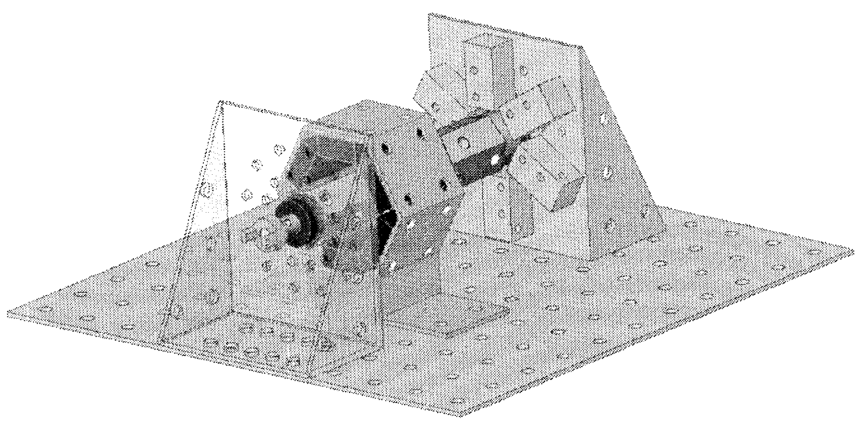


Figure 11: Sample Configuration with a Selection from the Final Design

It was a balance of setup time, configurability, and cost that allowed us to settle on the final design. The fixed shape magnet holders were designed to be easy to install in the base, cheap to manufacture out of aluminum, and the distance from the magnet to the rotor may still be changed by sliding the magnet mounts toward the rotor or with shims. It is possible to use one or two magnet holder wide configurations which allow the user to vary the active length. Four types of magnet holders were manufactured; a sample configuration with the bracket type is shown in Figure 12. The magnets may be attached to the brackets with nylon ties or hot melt for quick assembly.

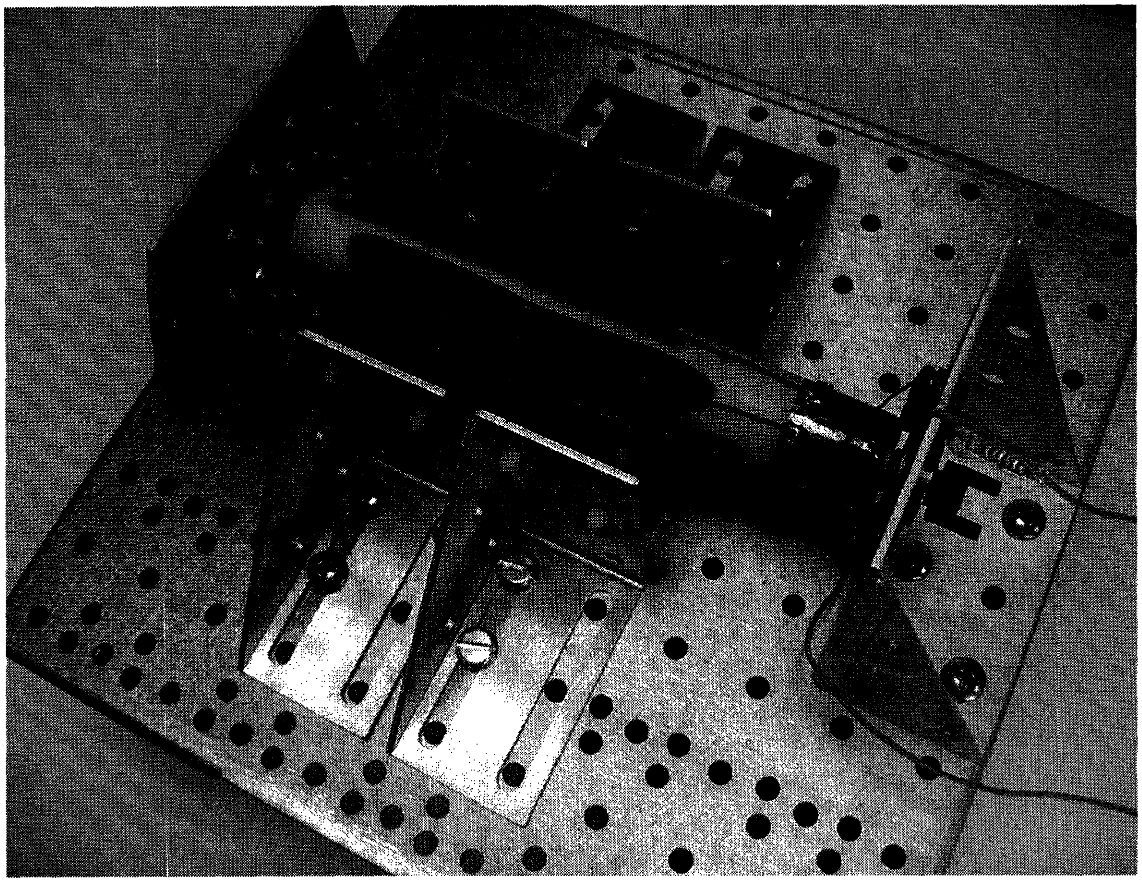


Figure 12 - Final Design, with Bipolar Magnet Mounts and 18 Gauge Magnet Wire

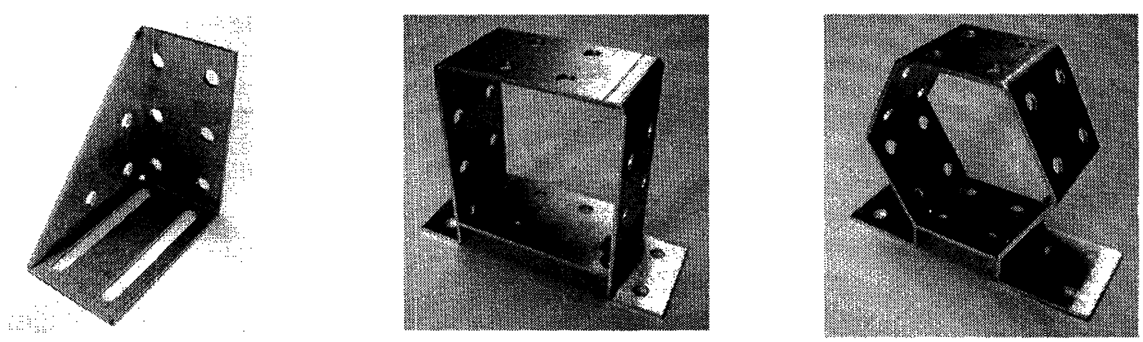


Figure 13: Final Design Magnet Mounts – Bracket, Four Magnet and Six Magnet

Three styles of motor rotors were developed (Figure 14) which stove to allow variations in motor design. Two once inch diameter rotors were developed: one which two orthogonal coils and another with three coils spaced 60 degrees apart. It is faster to wind two coils than three, however, the three coil design allows three coils to be active at one time (which can be achieved with the six magnet mount) and theoretically achieve higher performance. A two inch diameter rotor was also developed, which is one of the design parameters incorporated into the motor constant, which should allow for greater torque at a given current. Once receiving a rotor, students may choose what gauge wire to use and how many turns to wrap for each coil. These decisions may affect the current passing through the coil and the motor constant.

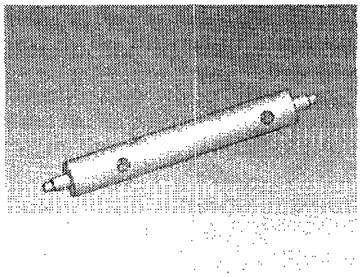
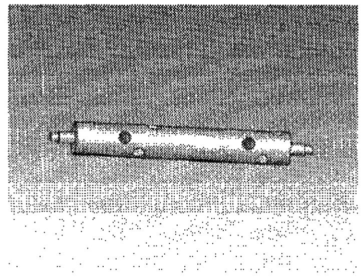
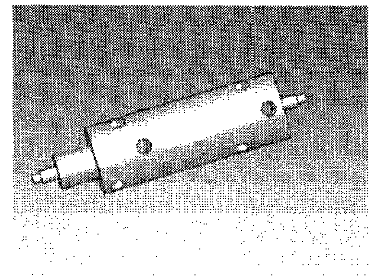
  

Figure 14: Final Design Rotors - Two Coil One Inch, Three Coil One Inch and Three Coil Two Inch

The rotor is held in the air by two flanged ball bearings that fit into the "pillow block" module (Figure 15). The axis is set far enough above the base plate to allow adequate room for either one inch or two inch diameter rotors. There is a hole pattern on this module which assists in mounting contacts to brush on the motor's commutator.

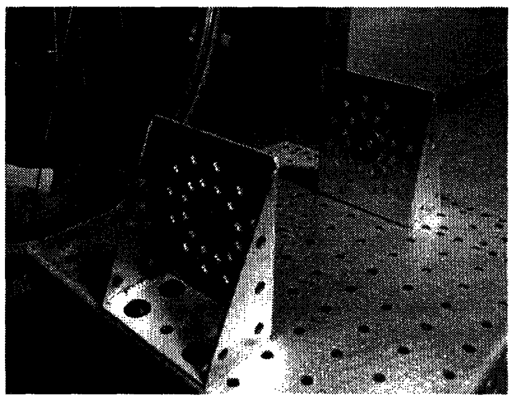


Figure 15: Bearing Blocks with Bearings

The best temporary commutator solution found involves both heat protection for the acetal copolymer rotor and electrical connections to the motor brushes and coils. To prevent against heat damage to the rotor, a piece of heat shrink tubing must be first applied to the commutator section of the rotor. Next, wrapping copper tape around the end of the rotor forms the base of the commutator. Thin strips in the copper are made with a utility knife and removed to form independent copper plates on a heat shrink backing. It has been found that the heat shrink distributes the heat enough to not damage the rotor and provides an easy mechanism for removing or replacing damaged commutators by simply sliding off the heat shrink section.

A carbon brush contact system to the commutator was attempted, but difficulties were encountered and no solid solution found. However, like the shop-day motor, we have found paper clips work very well as contacts at medium speeds (Figure 16).

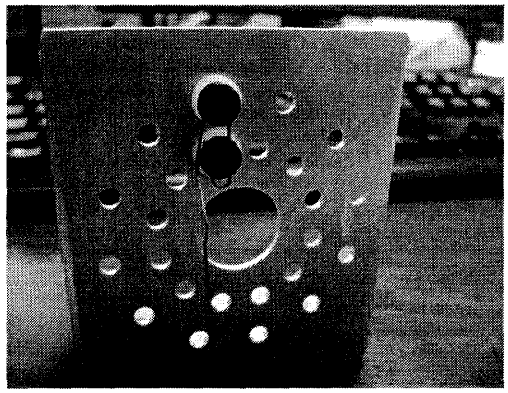


Figure 16: Method of Mounting Paper Clip Contact with Plastic Bolts

At high speeds the sparks generated by breaking contact on the commutator as the rotor turns break down the copper tape quite quickly. A more permanent commutator solution consisting of sections of copper pipe glued with epoxy to the rotor may be investigated to prevent against deterioration, but this would reduce the customizability and "home built" feel to the machine.

Linear Synchronous Motor:

Another application of electromagnetic coils is that in the linear synchronous motor. After becoming inspired by riding the theme park ride "Superman: The Escape" at Six Flags Magic Mountain which uses a linear synchronous motor to accelerate the ride vehicle quickly to 100 miles an hour, it was decided to make a electromagnetic launcher on the small scale as a classroom demonstration. The goal will be to be able to calculate the distance the projectile should go based on calculations involving electromagnetism and classical mechanics and test the apparatus by firing it across the classroom and into a trashcan or other receptacle (Figure 17).

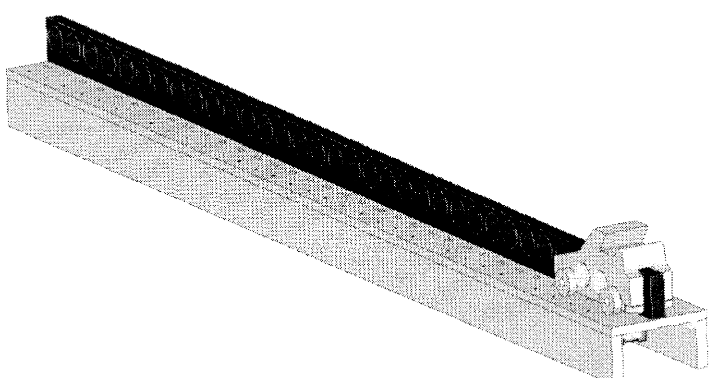


Figure 17: The Magnet-car

To keep things safe the input limits will be set at a maximum of 40 Volts and 25 Amperes. The coils are designed to be closely packed, spaced 1.39 inches apart. The coils were sized appropriately so that at maximum velocity, an optimistic 25 miles per hour, the coil's turn on time would be fast enough to reach a decent current to keep the car accelerating even at high speed.

As the car passes a coil a photodetector receives a signal reflected from the passing car which turns on the coil and pulls the car forward to the next coil, and so on. A prototype featuring a five stage accelerator has been built, and it works as intended (Figure 19). The final design is still in development and features a 30 stage segment and should accelerate the car to a speed fast enough to make an impressive jump potentially across the room.

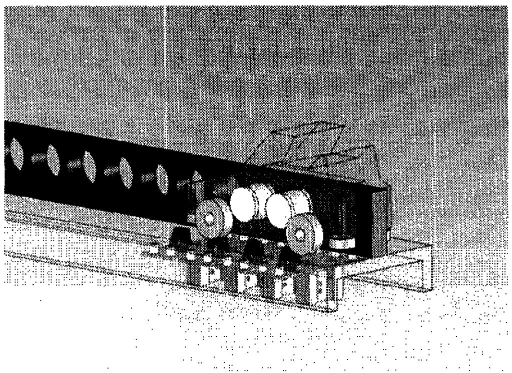


Figure 18: Magnet-Car in CAD

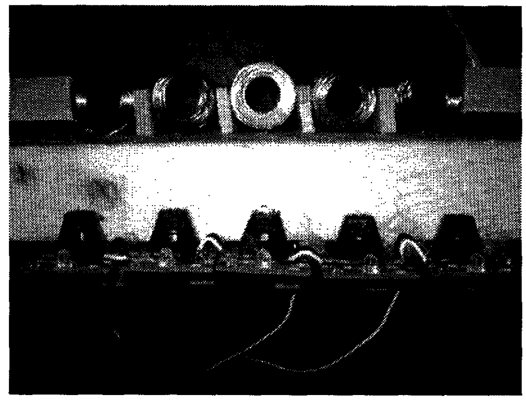


Figure 19: Magnet-Car Test Rig (Lewis, 2007)

There are many possible educational lessons that can be taught with the magnet car demonstration. Electromagnetic attraction, force measurement, RL time constant calculations, classical mechanics and ballistic motion.

The Power Plant

Introduction

The freshman seminar Physics of Energy desires to teach students the various stages of generating power and how efficient the conversion process typically is. The lecturers wished for a new lab experiment for the students to get an end to end view of power generation in a method that was not all too different than what may go on at the electric utility. An engine would generate mechanical movement from a stored fuel and a generator would convert the mechanical energy into electrical energy that could be used to power electronic devices.

System Overview

Stirling Engines were chosen as the working end of the power plant. In comparison to other types of engines, Stirling engines are remarkably efficient at turning a temperature difference into work reaching efficiencies close to the Carnot limit. In a system where efficiency in power conversion is important Stirling engines are a good choice.

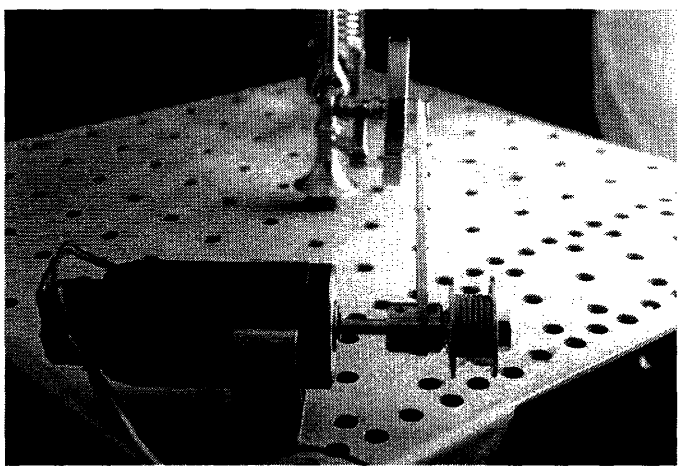


Figure 20: Maxon Motor/Generator (Leeb, 2007)

Several fuels were considered, but gelled ethanol fuel in the form of Sterno "Canned Cooking Fuel" was selected as it is inexpensive, produces low levels of toxic fumes when burned, and is harder than liquid fuels to spill all over the bench to accidently set the lab on fire.

The Sterno will power the Stirling Engine which will turn a DC motor that will be used to power an electrical load. It will be possible to calculate the power dissipated from burning the Sterno and follow the efficiency through to the electrical power dissipated at the electrical load.

Sterno Cooking Fuel:

In order to calculate the end to end efficiency it is necessary to know the energy coming out of the system and the energy going in. Calling Sterno Technical Information, (903)-223-3450, yielded the energy density of Sterno, 4,517 BTU/8oz can, which means it packs 21,087 Joules/g. It is possible to measure the time it takes to burn through any amount of Sterno and calculate the average number of

Watts of energy expelled for that batch. From the MSDS sheet, the consumer brand of Sterno is 67% ethanol and 3% methanol.

The Engine

The choice of engine was made prior to my arrival. The model used was the $200 Hog Stirling Engine which is about has about a 1" long glass chamber that makes it easy for the students to see the displacer piston and get an image of the inside of the engine.

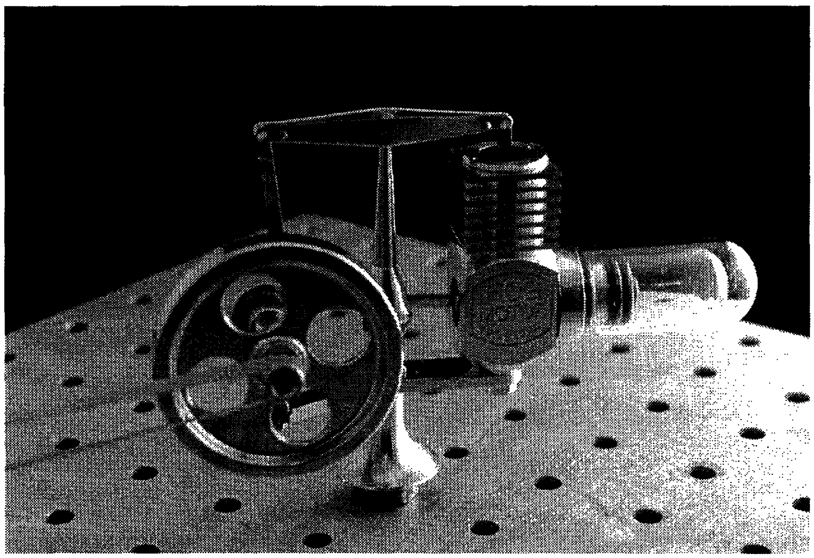


Figure 21: The Hog Stirling Engine, Approx $200 (Leeb, 2007)

Several options were considered for transferring power from the Stirling Engine. The first option we considered was interfacing an adapter to the threaded nut protruding from the flywheel. The thread on the nut was measured to be M5x0.5, otherwise known as M5 fine thread. Although the possibility of a solid connection to the flywheel had promise, it would require machining custom linkages, as the thread was so uncommon no bolts of that thread could be found on the market. Instead, we opted to belt the engine to the motor from the outside of the nut, which is grooved and supplies an adequate place for the belt to ride, to the motor shaft. Common rubber bands were chosen as the belt material, as they were extremely inexpensive, of the correct length, and provided a nice limited slip connection due to the rubbery texture.

The Generator

Small Maxon motors were used as the generator end in our power plant laboratory, as they performed admirably in simple tests of the generated voltage versus angular velocity and were readily available in the lab.

The Class Experience:

Build a Combustion Chamber:

The first task in the Power Plant Laboratory is to construct a "combustion chamber." This chamber will eventually be used to surround the hot end of the Stirling Engine help increase the efficiency of the transmission of heat from the Sterno to the Stirling Engine. In our experiment small paint cans were used as the combustion chamber. Holes were punched in the cans by placing them on wood blocks with a "v" shaped section removed to constrain the can, and then holes punched by hammering a scratch awl into the side of the can.

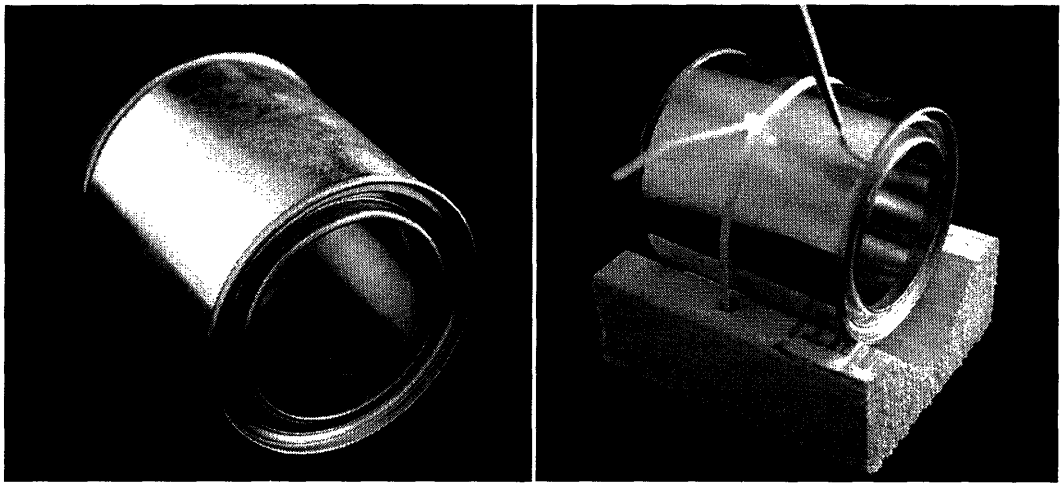
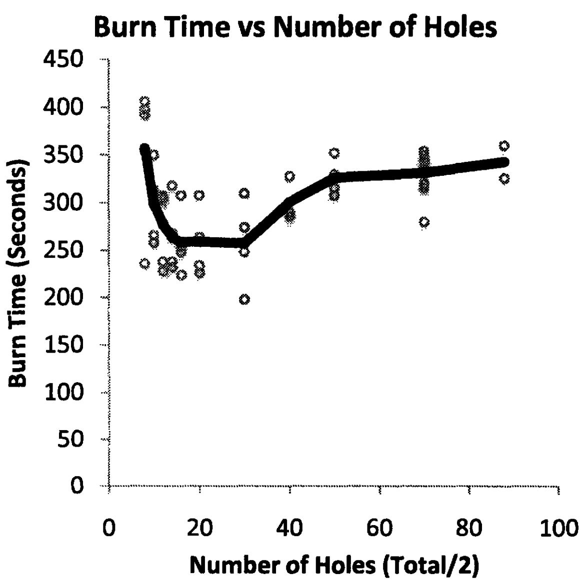


Figure 22: Combustion Chamber Pain Can, Creating Holes with an Awl (Leeb, 2007)

The number of holes in the can affects the burn time and the average can temperature. The students were presented with the data in

Figure 23. It was left up to the student to decide what plan of action to take in the design of the can. Although there was a measured difference in having the combustion chamber around the flame and not having the combustion chamber at all, it is unclear whether any benefit was received from optimizing the number of holes in the can, save for having enough to keep the flame burning and not too many as to lose the windscreen effect.



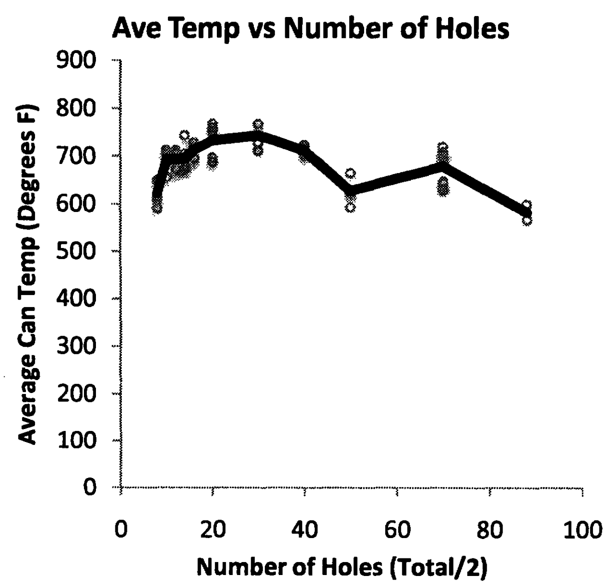


Figure 23: Burn Time and Ave Temp Versus Number of Holes in Can

The challenge was then thrown at the students to see whose combustion chamber could heat a beaker of water to the greatest temperature with a measured amount of water and Sterno fuel (Figure 24). It was the student's choice as to which containment vessel they used and how the interface was handled. This activity introduced heat conduction and capacitance. A thin layer of water between a beaker and the can with a foil cap on the beaker appeared to work best.

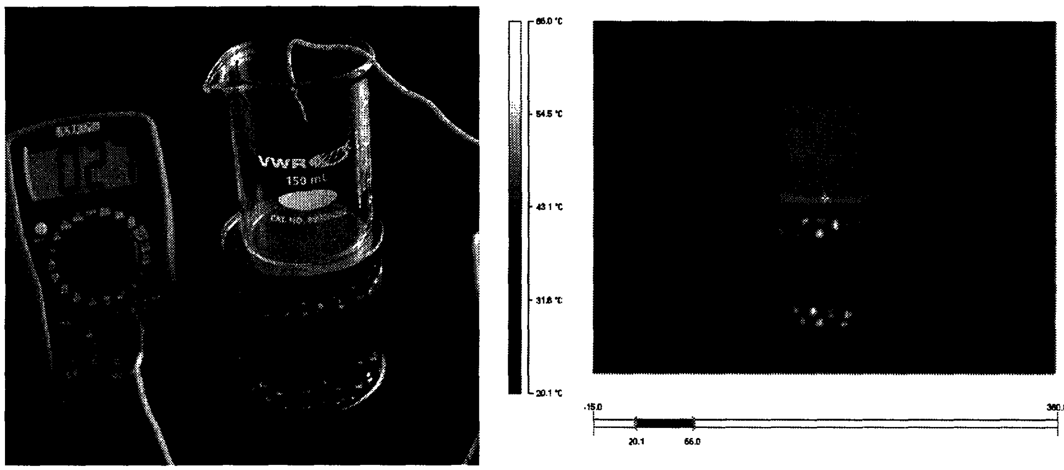


Figure 24: Combustion Chamber Apparatus, Thermal Image of Combustion Chamber Water Heating Test (Leeb, 2007)

It is interesting to note that the water in the thermal image of Figure 24 is warmer than the side of the combustion chamber can. This is possible because of the interesting temperature distribution in the top of the combustion chamber can due to the concentrated flame coming into direct contact with can (Figure 25).

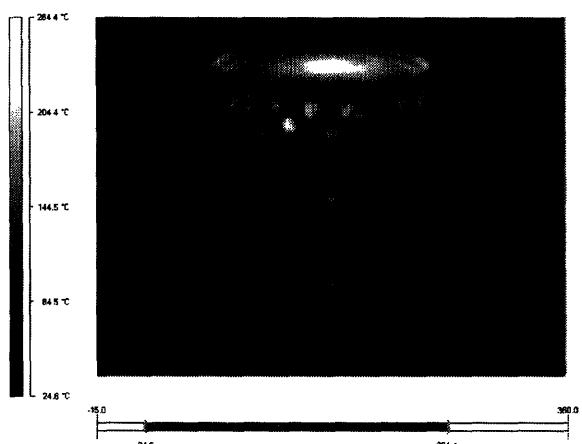


Figure 25: Thermal Image of Combustion Chamber

Connect the Generator:

The torque speed curve of the Stirling Engine was determined by belting the engine to a DC motor with known K and measuring the shaft speed for a given load determined by the resistance between the motor terminals (Figure 26).

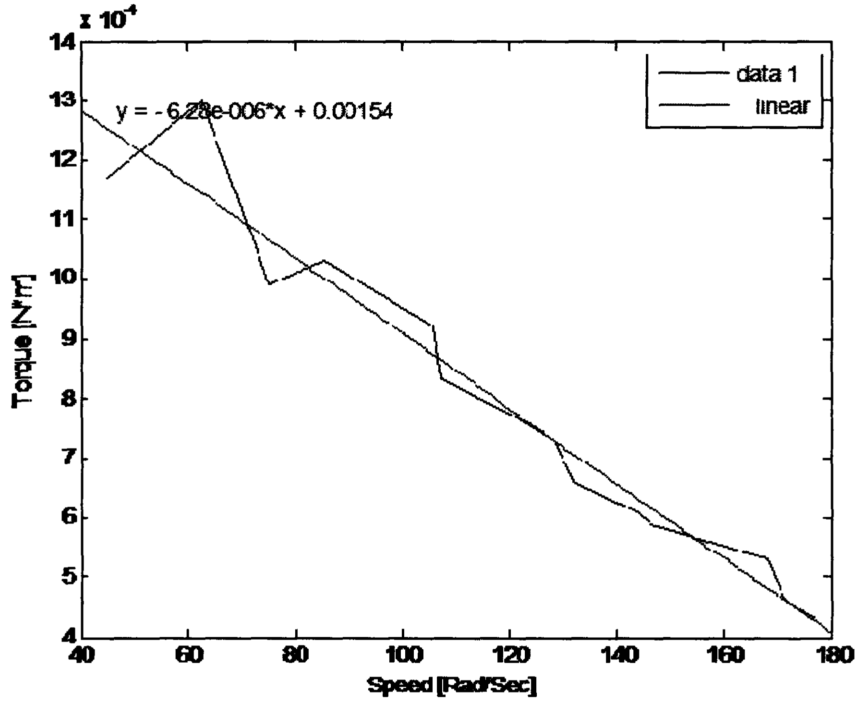


Figure 26: Stirling Engine Torque vs. Speed

The max power output of the Stirling Engine was found to be 0.0944 Watts at an output shaft speed 123 radians per second. In order to run at maximum power, the Stirling Engine must be running at 123 radians per second. This means we must match the load such that the power being dissipated in the motor equals, or is very close to 0.0944 Watts. The DC motor has lower losses due to the armature resistance if the voltage being generated is higher and the current is lower for the same power output. This means that analytically, the faster the motor spins the more efficient the motor will be at generating power. However, if the same power is being transferred to the generator and the speed is increasing, the torque delivered to the generator is decreasing. At extremely high speeds the motor receives extremely low torque. This becomes a major problem as frictional forces end up consuming a significant amount of the power. The ideal speed is in fact high, but not too high. It can be seen in the graph of power generated versus generator rotational speed that the actual data differs from the theoretical in that at higher speeds the power output of the generator goes down (Figure 27). This could easily be due to the frictional losses.

It looks as though the ideal gear ratio between our Stirling Engine and generator was around 2:1. However, even far from this gear ratio teams were able to light an LED and see the product of the Stirling Engine power plant. The efficiency of the entire system ran at best around 0.1%.

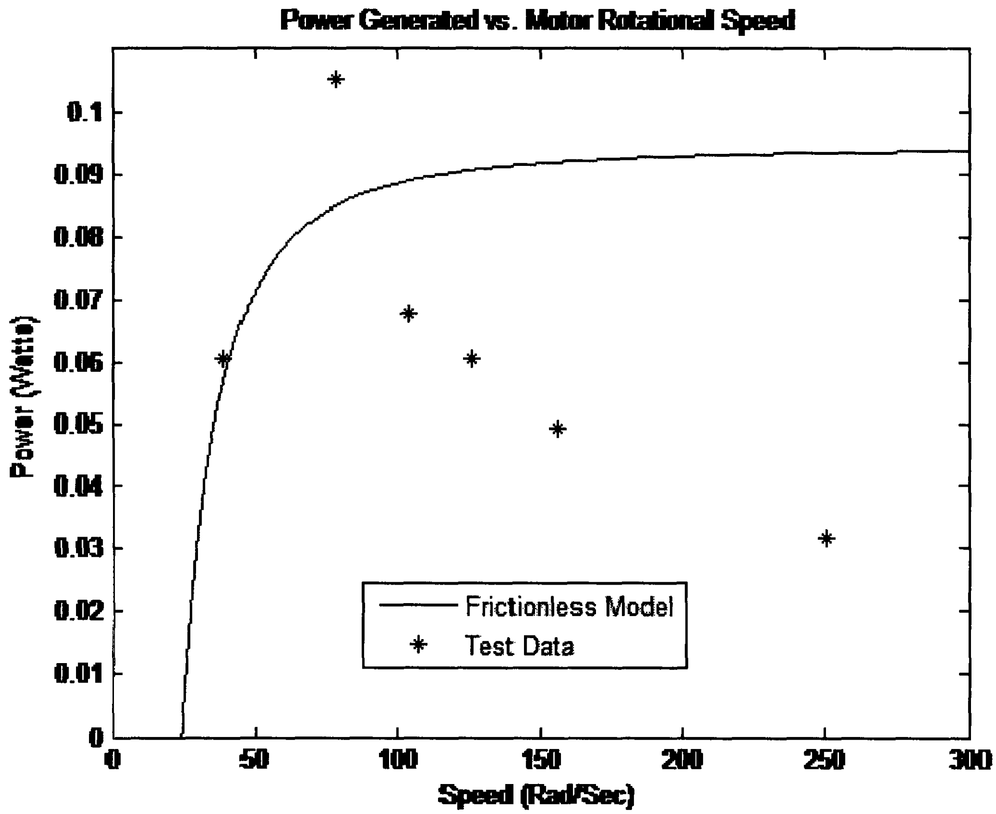


Figure 27: Power Generated vs. Motor Rotational Speed

In the future, it would be a wise choice to choose a more powerful engine as the power source for the demonstration. Significant time has been spent searching for a low cost alternative, both in Stirling Engine and Steam Engine form, but no deals have been found on the market as the more powerful engines quickly rise in cost. It is interesting to note that 6.5 HP gasoline engines can be found new for $150 due to the large market for them, whereas even the 0.0001 HP Stirling Engines used in this laboratory cost $200. Perhaps it would be a wise choice to abandon the hobby market in search of a mainstream commonly used alternative.

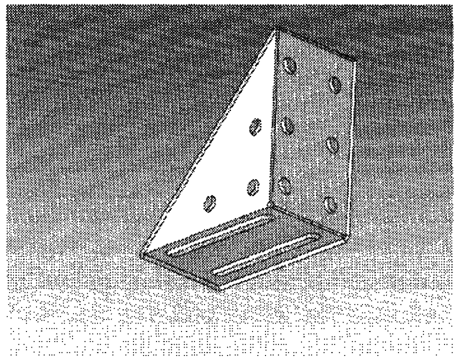
Works Cited

Leeb, S. B. (2007, 05 07). Cambridge, MA, USA.

Lewis, C. (2007, 05 10). Cambridge, MA, USA.

Nave, R. (n.d.). *DC Motor Image*. Retrieved 05 09, 2007, from HyperPhysics: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/imgmag/dcmop.gif

Appendix



Bipolar Magnet Mount

These pieces are meant for quickly assembling a simple two pole motor. The pieces hold the magnets at right angles and can be slid forwards and backwards to adjust the magnetic field strength. It can be made by bending and welding one piece of sheet metal.

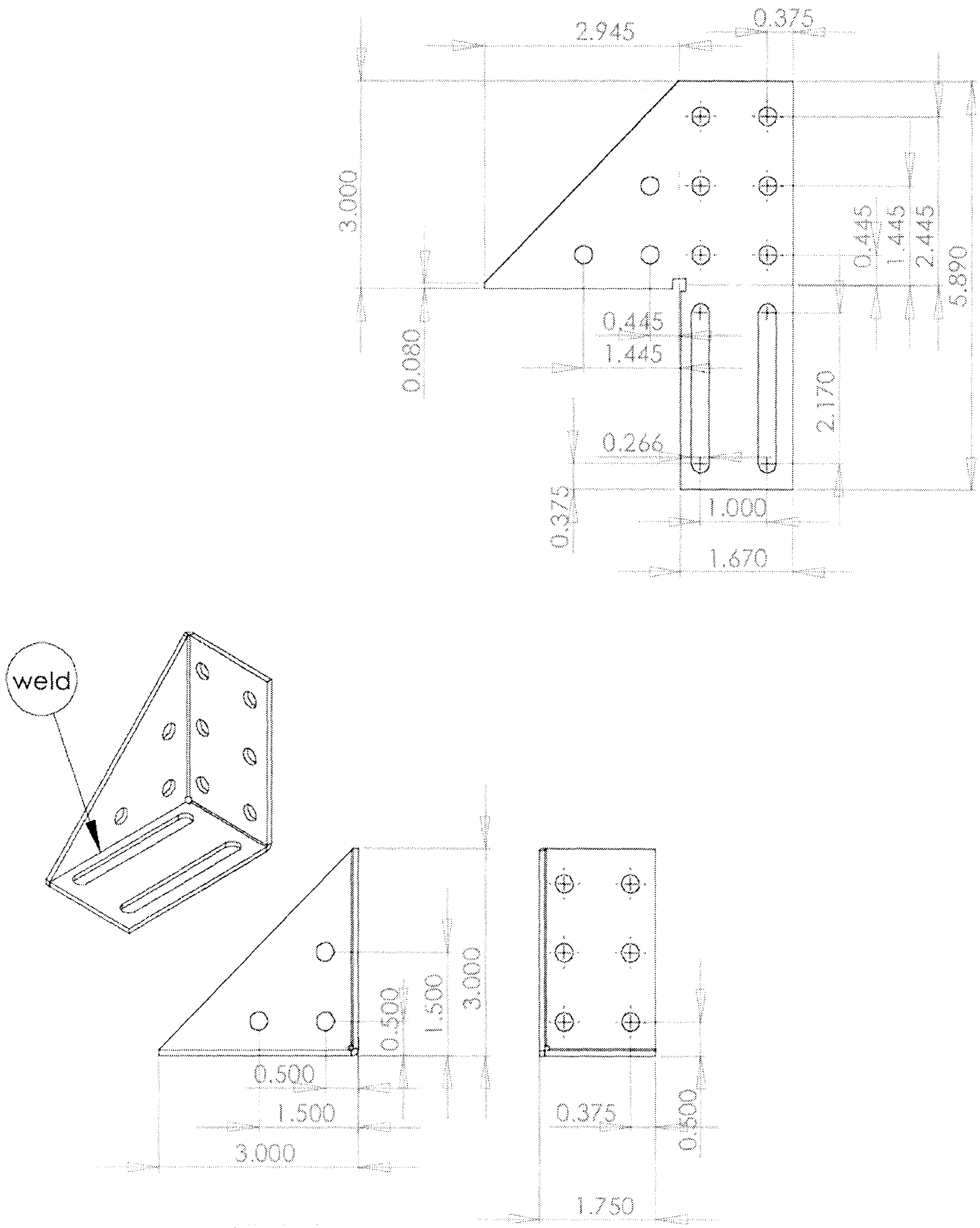
Message Sent To Supplier:

0.08in ± 0.005in brushed 5052 H32 aluminum sheet metal.

All bend radii are 0.029in.

Unless otherwise marked, all holes are 0.2656" +0.006/-0.001 diameter.

All seams should be welded together.



Steven Leeb

Motor Kit Project

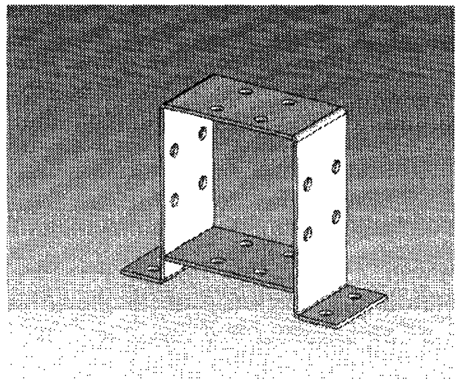
MATERIAL: Al 5052

FINISH: Brushed

COMMENTS:

SIZE: A DWG. NO.: Bracket

SCALE: 1:2



4 Pole Magnet Mount, For 1 Inch Rotor

This piece can hold four magnets around the one inch rotor. It is also possible to use this piece as a substitute for the two pole magnet mount, although the two magnet brackets would be prefered as it is easier to see and access the rotor when using them. This piece can be made by bending one piece of sheet metal and welding it to an additional sheet metal segment.

Message Sent To Supplier:

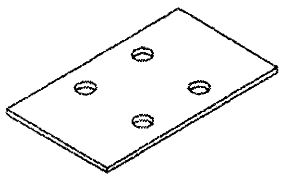
0.08in ± 0.005in brushed 5052 H32 aluminum sheet metal.

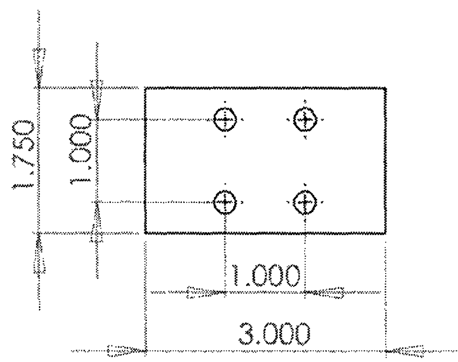
All bend radii are 0.029in.

Holes marked "A" are mounts, and their position relative to each other after folding is critical, requiring dimensional tolerances between "A" holes of ± 0.02", while all other lengths require ± 0.03".

Unless otherwise marked, all holes are 0.2656" +0.006/-0.001 diameter.

All seams should be welded together.





Steven Leeb

Motor Kit Project

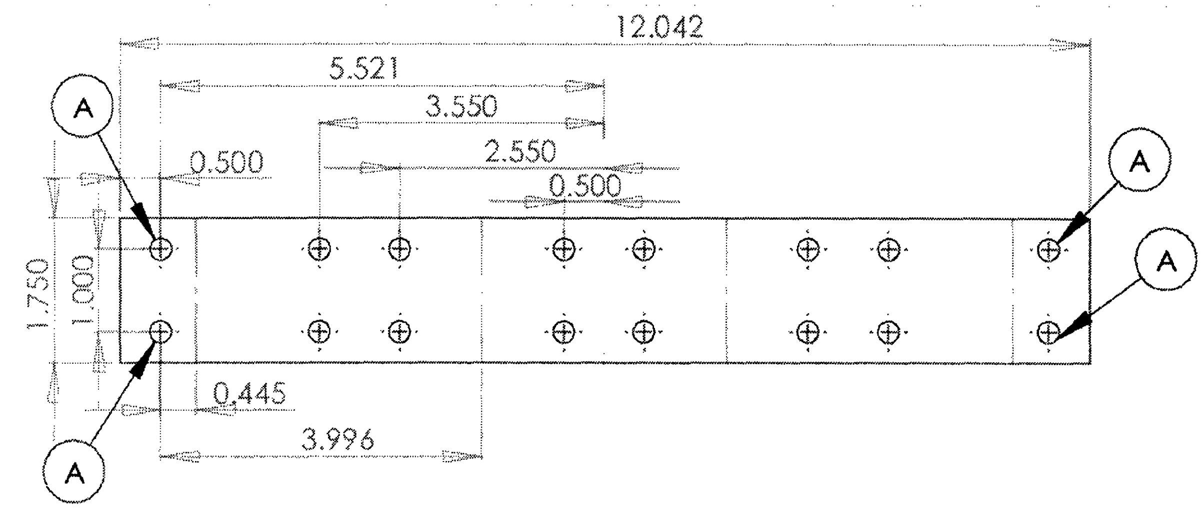
MATERIAL Al 5052

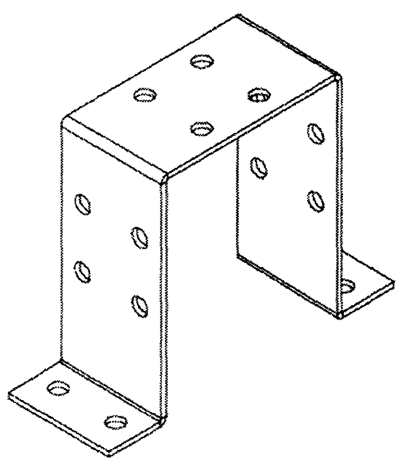
FINISH Brushed

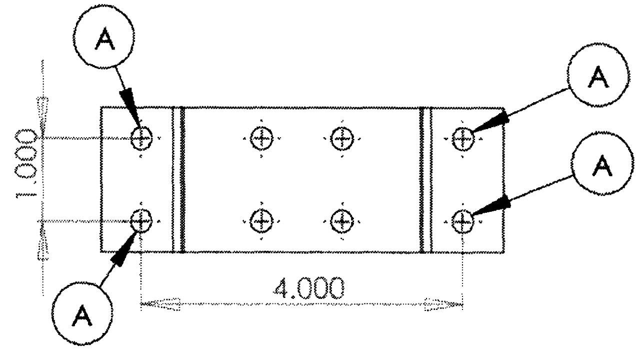
COMMENTS:

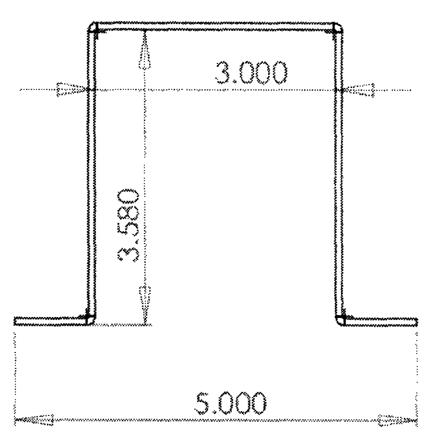
SIZE A DWG. NO. square3inch - (SmallPart)

SCALE: 1:2









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Steven Leeb

Motor Kit Project

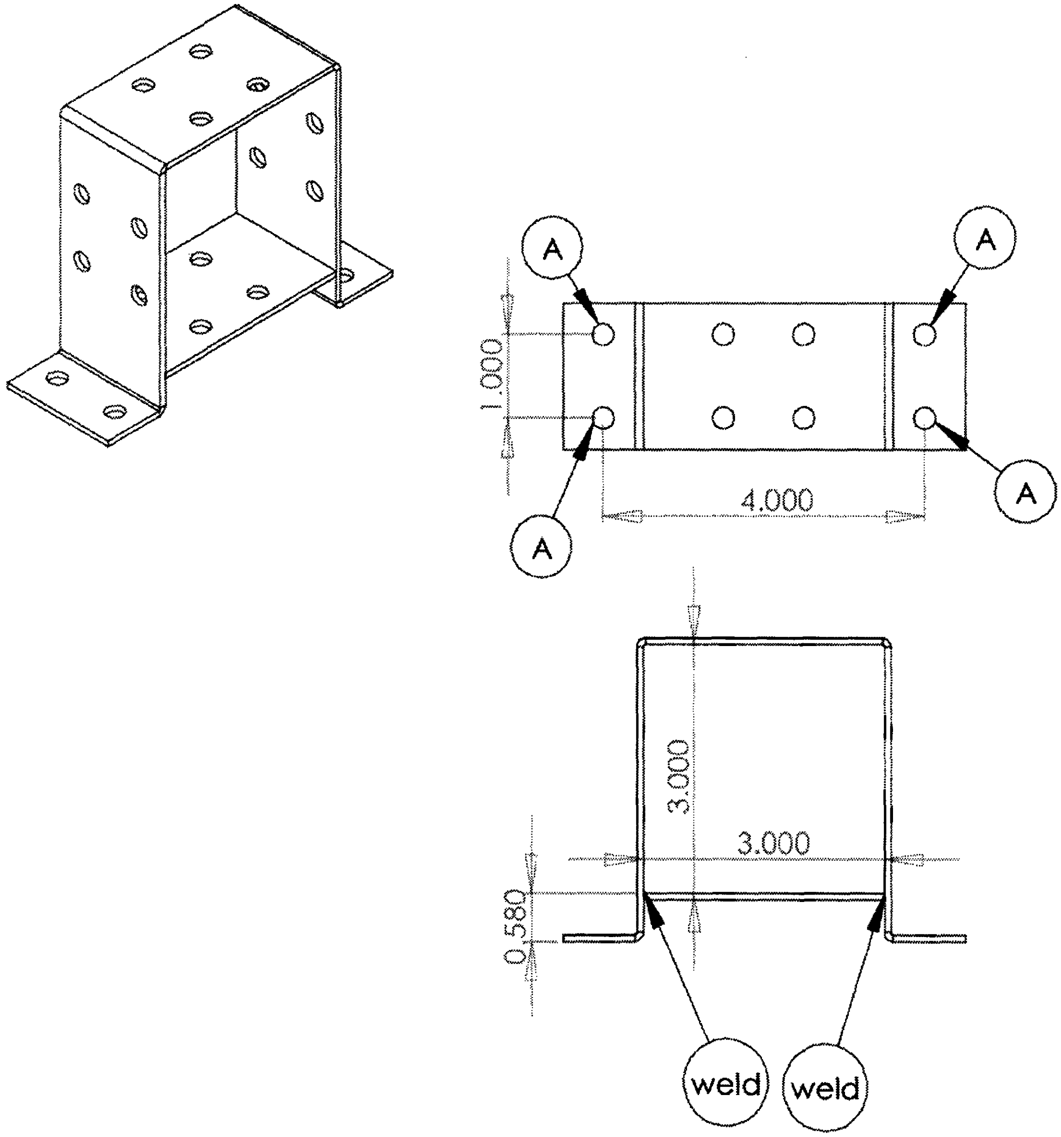
MATERIAL Al 5052

FINISH Brushed

COMMENTS:

SIZE A DWG. NO. square3inch - (LargePart)

SCALE: 1:2



Steven Leeb

Motor Kit Project

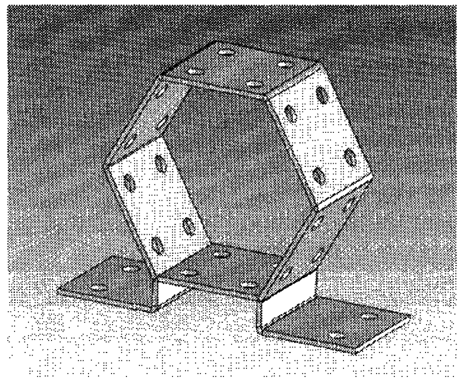
MATERIAL Al 5052

FINISH Brushed

COMMENTS:

SIZE A DWG. NO. square3inch - (Assembly)

SCALE: 1:2



6 Pole Magnet Mount, For 1 Inch Rotor

This design easily accepts six magnets around a the one inch rotor. It can be made by bending one piece of sheet metal and welding it to an additional sheet metal segment.

Message Sent To Supplier:

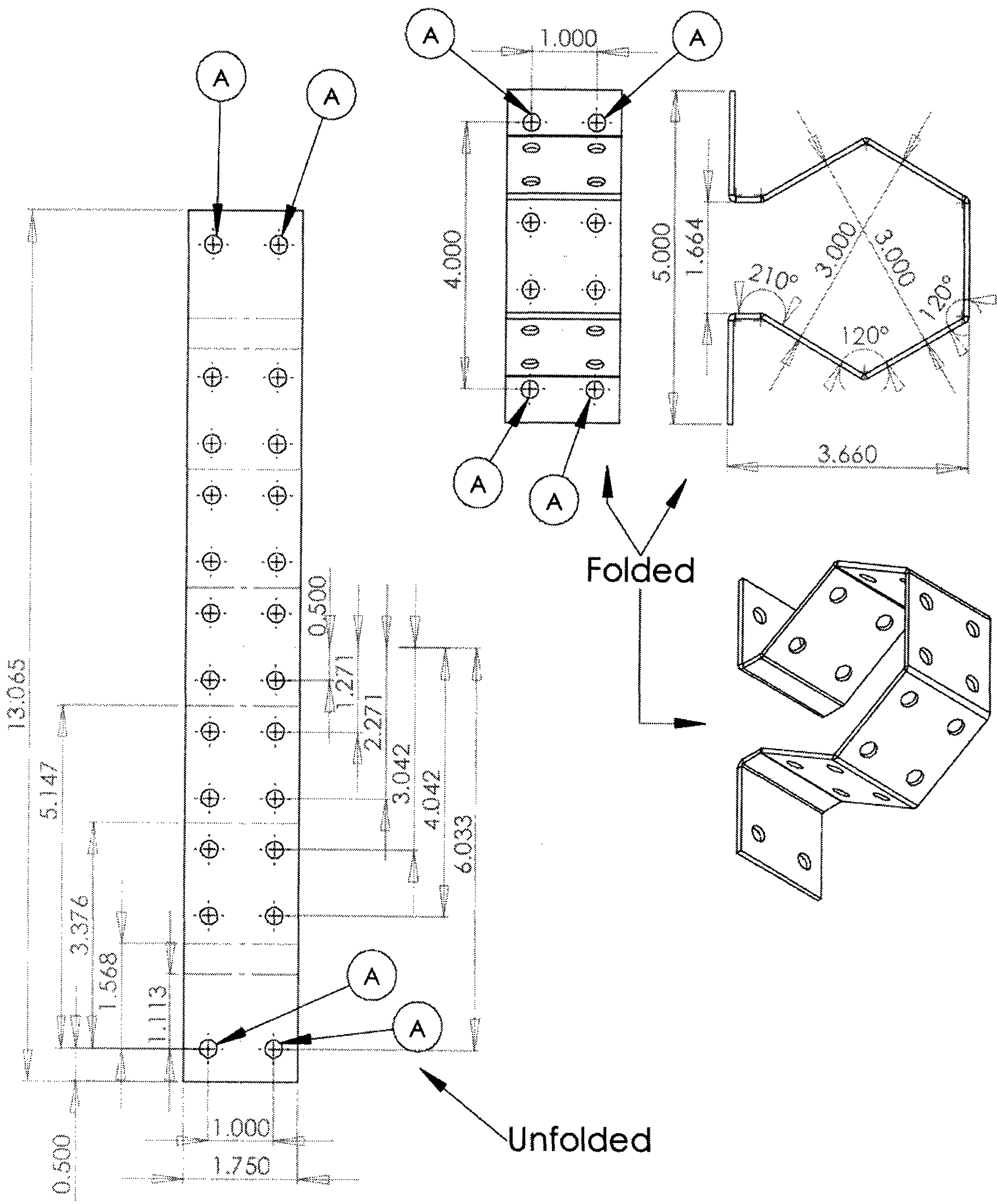
0.08in ± 0.005in brushed 5052 H32 aluminum sheet metal.

All bend radii are 0.029in.

Holes marked "A" are mounts, and their position relative to each other after folding is critical, requiring dimensional tolerances between "A" holes of ± 0.02", while all other lengths require ± 0.03".

Unless otherwise marked, all holes are 0.2656" +0.006/-0.001 diameter.

All seams should be welded together.



Steven Leeb

Motor Kit Project

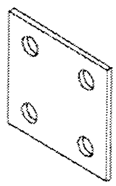
MATERIAL: Al 5052

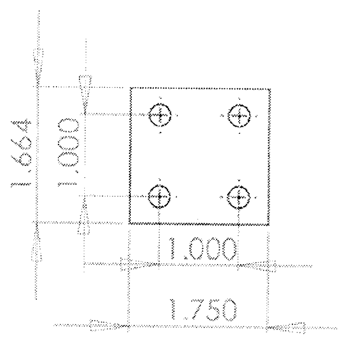
FINISH: Brushed

COMMENTS:

SIZE: A DWG. NO. 3 inch hex - (largepart)

SCALE: 1:2





Steven Leeb

Motor Kit Project

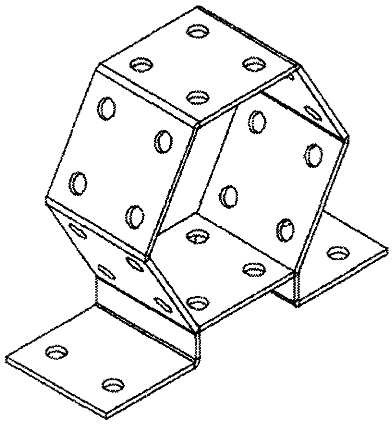
MATERIAL Al 5052

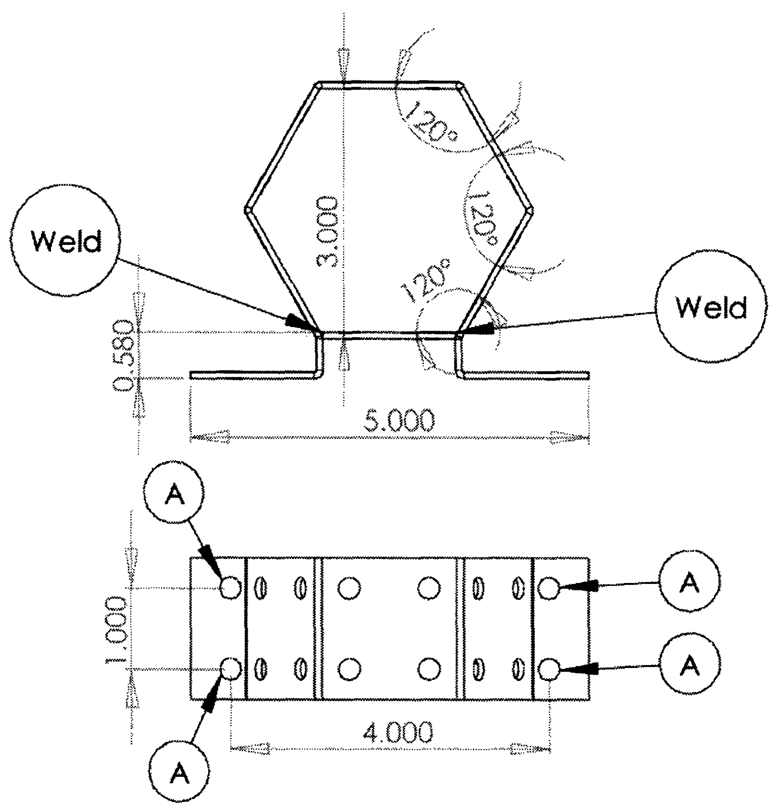
FINISH Brushed

COMMENTS:

SIZE A DWG. NO. 3 inch hex - (small part)

SCALE: 1:2





Steven Leeb

Motor Kit Project

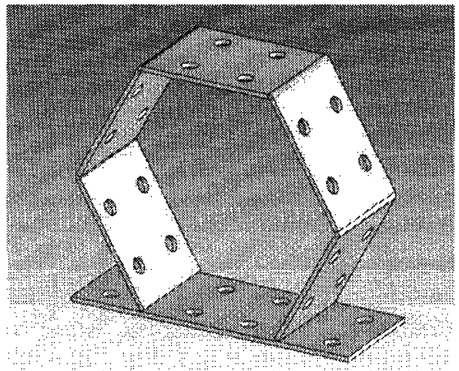
MATERIAL Al 5052

FINISH Brushed

COMMENTS:

SIZE A DWG. NO. hex3inch - (assembly)

SCALE 1:2



6 Pole Magnet Mount, For 2 Inch Rotor

This design easily accepts six magnets around a the two inch rotor. It can be made by bending one piece of sheet metal and welding it to an additional sheet metal segment.

Message Sent To Supplier:

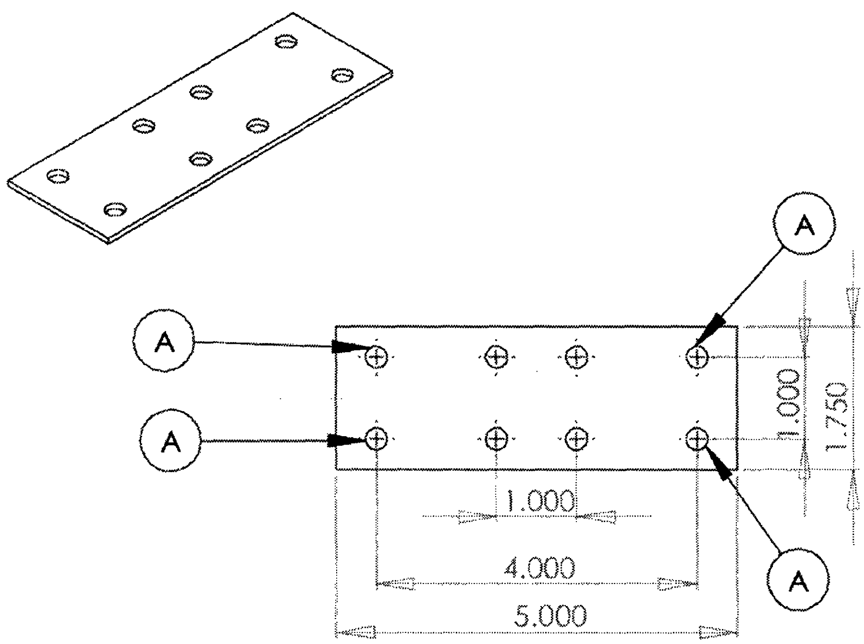
0.08in ± 0.005in brushed 5052 H32 aluminum sheet metal.

All bend radii are 0.029in.

Holes marked "A" are mounts, and their position relative to each other after folding is critical, requiring dimensional tolerances between "A" holes of ± 0.02", while all other lengths require ± 0.03".

Unless otherwise marked, all holes are 0.2656" +0.006/-0.001 diameter.

All seams should be welded together.



Steven Leeb

Motor Kit Project

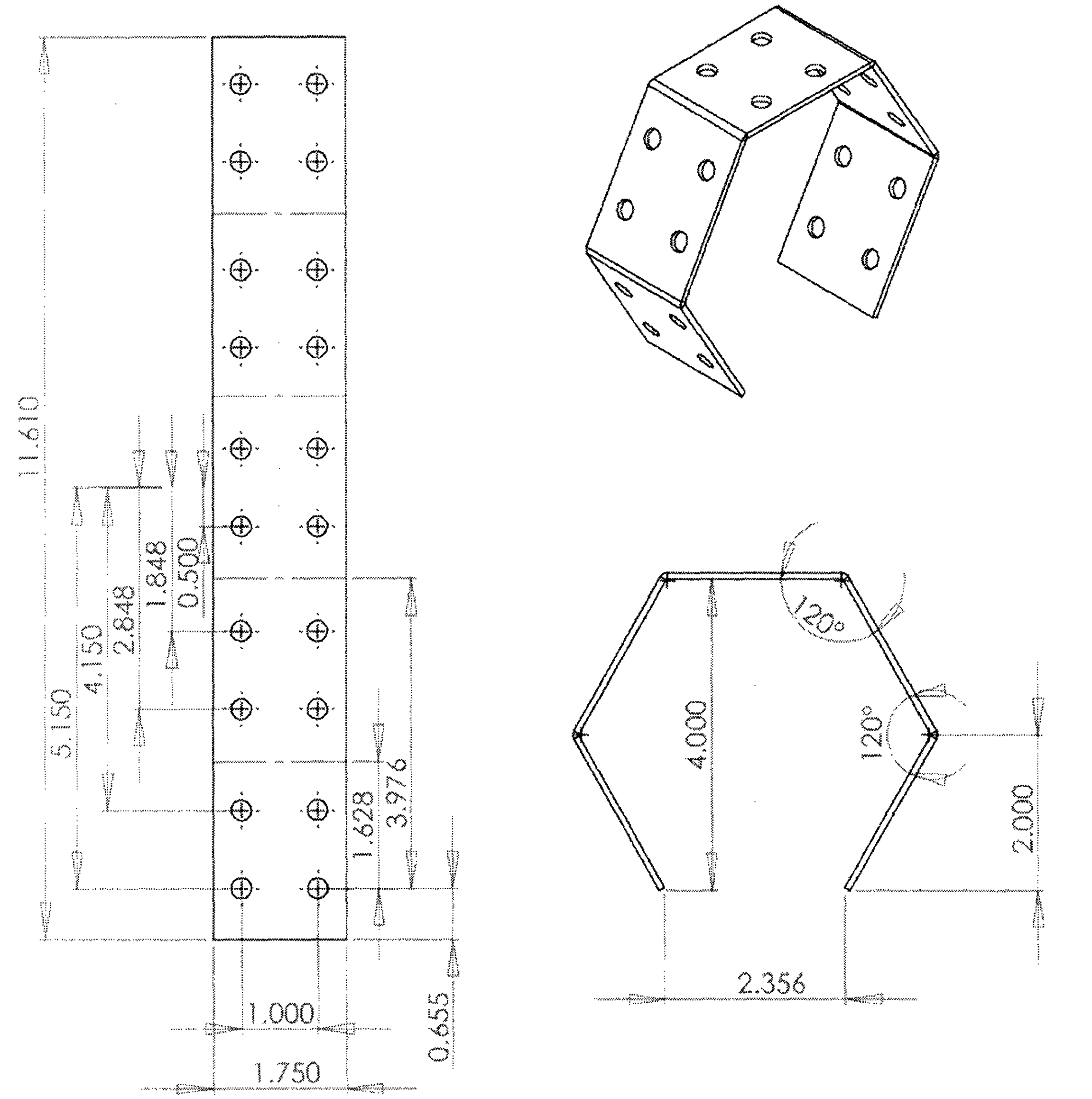
MATERIAL Al 5052

FINISH Brushed

COMMENTS:

SIZE A DWG. NO. hex4inch - (SmallPart)

SCALE: 1:2



Steven Leeb

Motor Kit Project

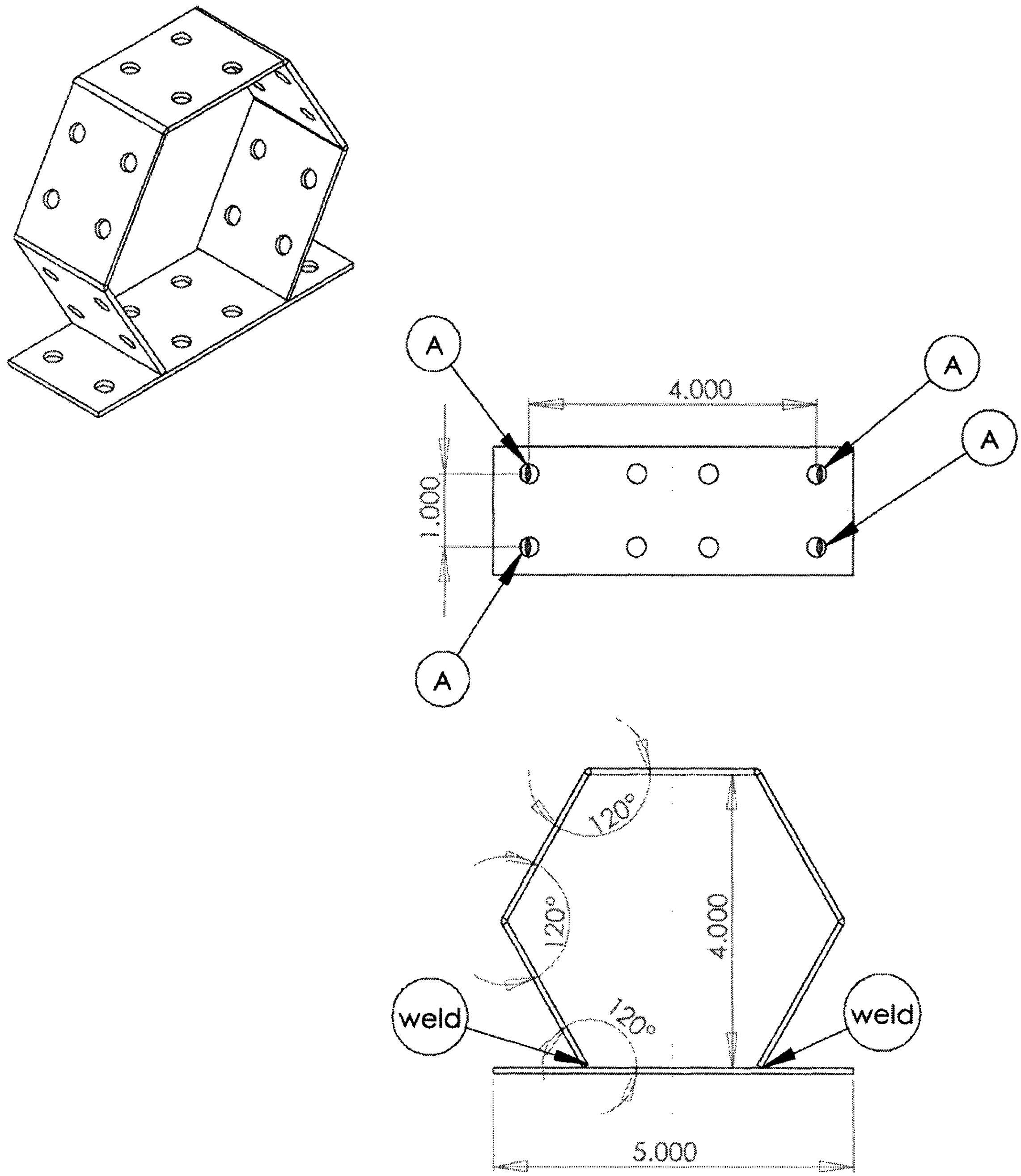
MATERIAL Al 5052

FINISH Brushed

COMMENTS:

SIZE A DWG. NO. hex4inch - (largepart)

SCALE: 1:2



Steven Leeb

Motor Kit Project

MATERIAL Al 5052

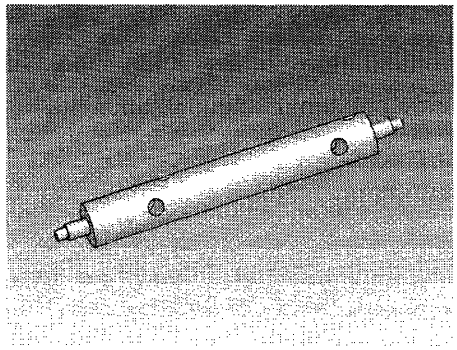
FINISH Brushed

COMMENTS:

SIZE A

DWG. NO. hex4inch - (Assembly)

SCALE: 1:2



1 Inch Diameter Rotor, 2 Coils

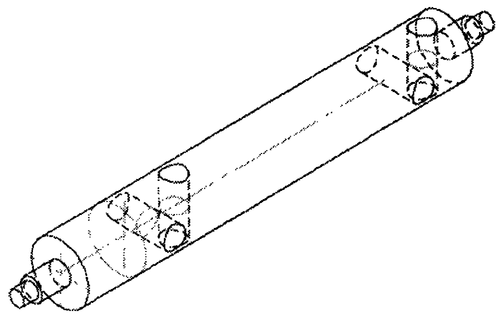
This part is made from acetal copolymer and has holes for two perpendicular windings.

Message Sent To Supplier:

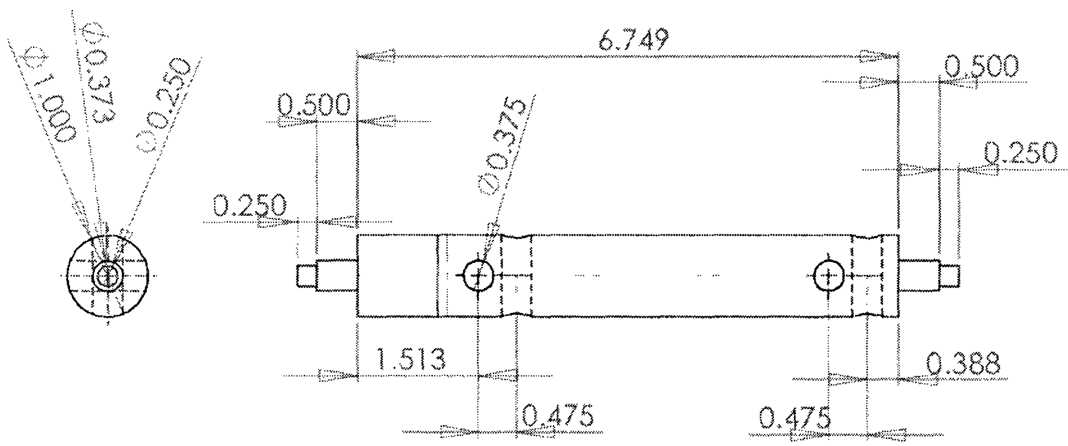
Notes For Supplier:

Production of a motor rotor. Approximately 1.00" OD x 8.249" long.

All linear and hole tolerances are +/- 0.01 inches, while all cylindrical radii are + 0.00/ -0.01 inches.



Holes are drilled 90 degrees apart



Steven Leeb

MATERIAL Acetal

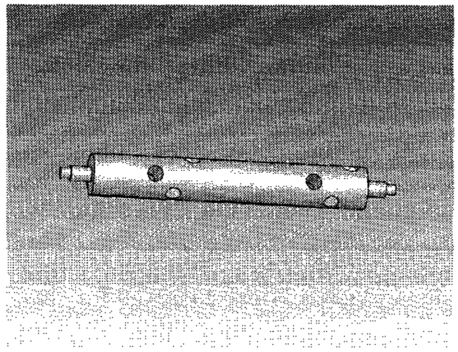
FINISH

COMMENTS:

DO NOT SCALE DRAWING

SIZE A DWG. NO. longoneinchsquare

SCALE: 1:2



1 Inch Diameter Rotor, 3 Coils

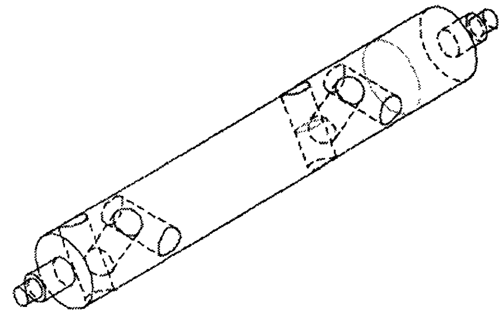
This part is made from acetal copolymer and has holes for three windings 60 degrees apart.

Message Sent To Supplier:

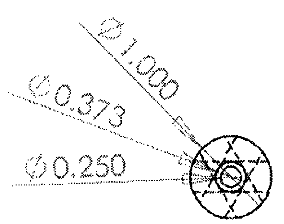
Notes For Supplier:

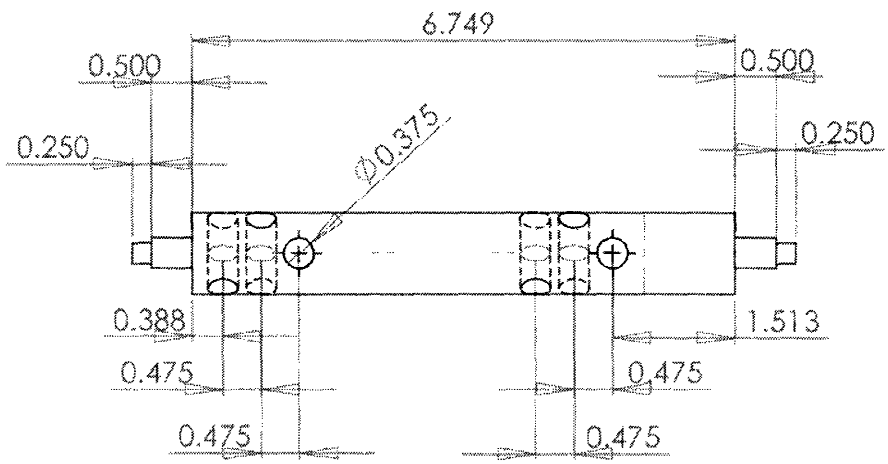
Production of a motor rotor. Approximately 1.00" OD x 8.249" long.

All linear and hole tolerances are +/- 0.01 inches, while all cylindrical radii are + 0.00/ -0.01 inches.



Holes are drilled 60 degrees apart and are sized 3/8".





Steven Leeb

MATERIAL Acetal

COMMENTS:

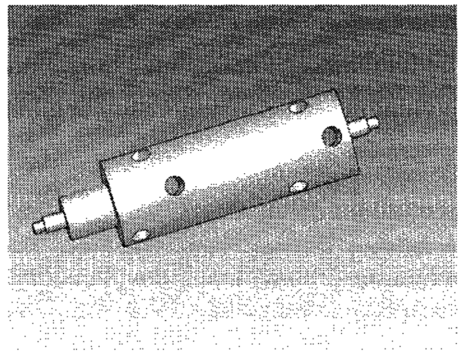
Motor Kit Project

FINISH

DO NOT SCALE DRAWING

SIZE DWG. NO.
A 1 Inch Rotor (Long)

SCALE: 1:2



2 Inch Diameter Rotor, 3 Coils

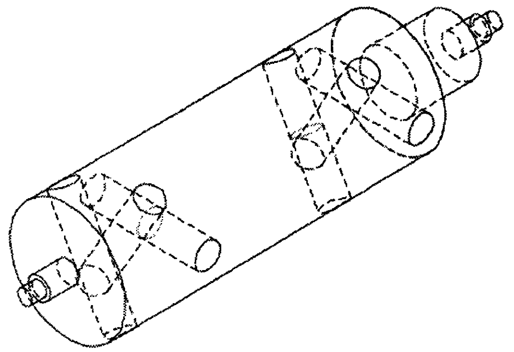
This part is made from acetal copolymer and has holes for three windings 60 degrees apart.

Message Sent To Supplier:

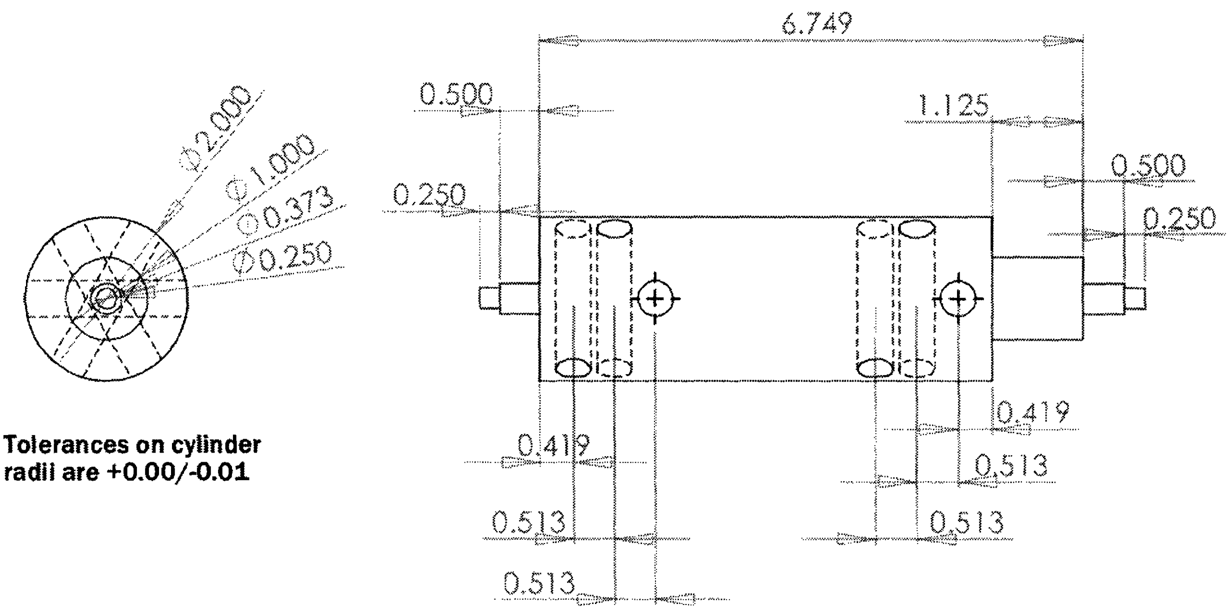
Notes For Supplier:

Production of a motor rotor. Approximately 1.00" OD x 8.249" long.

All linear and hole tolerances are +/- 0.01 inches, while all cylindrical radii are + 0.00/ -0.01 inches.



Holes are drilled 60 degrees apart and are sized 7/16".



Tolerances on cylinder radii are +0.00/-0.01

Steven Leeb

Motor Kit Project

MATERIAL Acetal

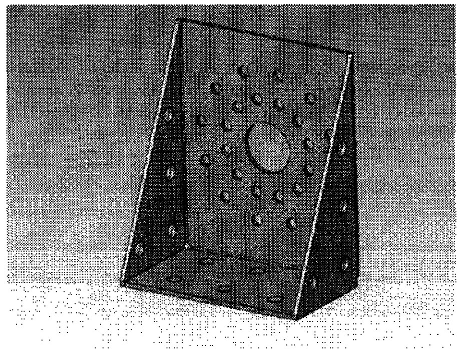
FINISH

DO NOT SCALE DRAWING

COMMENTS:

SIZE A DWG. NO. 2 Inch Rotor

SCALE: 1:2



Bearing Mount/Brush Holder

This piece may supports either the large or small rotors. A flanged ball bearing sits in the large hole, and the rotor slips in the ball bearing. This piece can be made by bending and welding one piece of sheet metal.

Message Sent To Supplier:

0.08in ± 0.005in brushed 5052 H32 aluminum sheet metal.

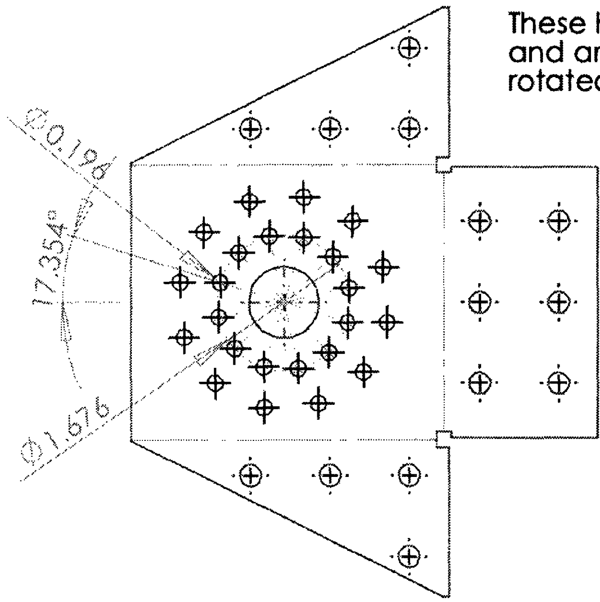
All bend radii are 0.029in.

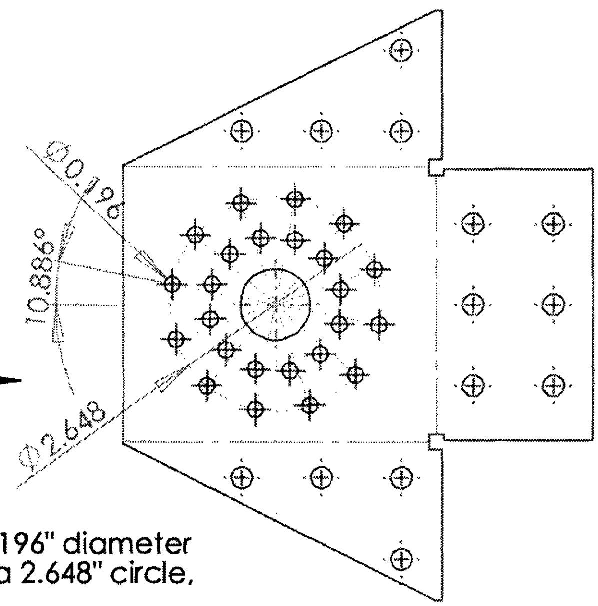
Holes marked "A" are mounts, and their position relative to each other after folding is critical, requiring dimensional tolerances between "A" holes of ± 0.02", while all other lengths require ± 0.03".

Unless otherwise marked, all holes are 0.2656" +0.006/-0.001 diameter.

All seams should be welded together.

These holes on the center panel are 0.196" diameter and are spaced 30 degrees apart on a 1.676" circle, rotated 17.354 degrees clockwise.





These holes on the center panel are 0.196" diameter and are spaced 30 degrees apart on a 2.648" circle, rotated 10.886 degrees clockwise.

Steven Leeb

Motor Kit Project

MATERIAL Al 5052

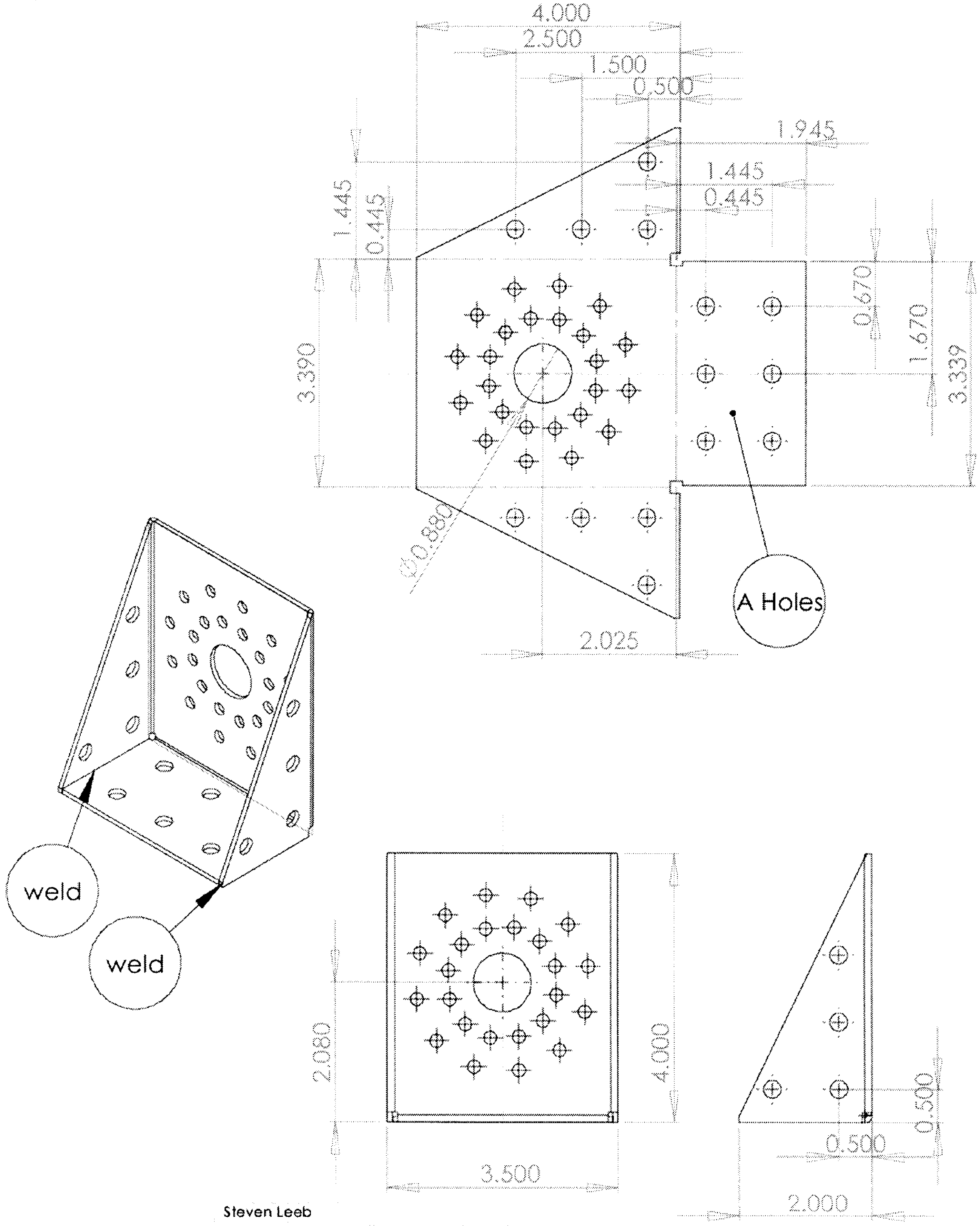
FINISH Brushed

COMMENTS:

SIZE A DWG. NO. pillowblock - (angles)

SCALE: 1:2

The rest of the holes are sized as normal,
symetric about the horizontal center line.



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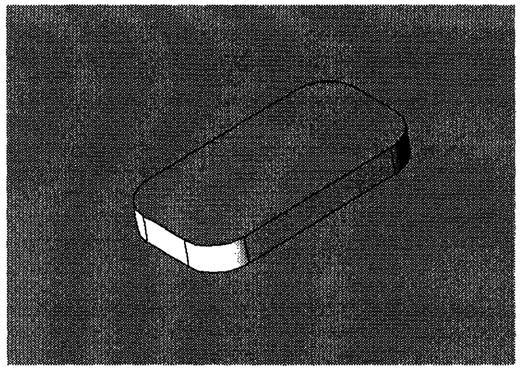
COMMENTS:

SIZE DWG. NO.
A pillowblock - (assembly)
SCALE: 1:2



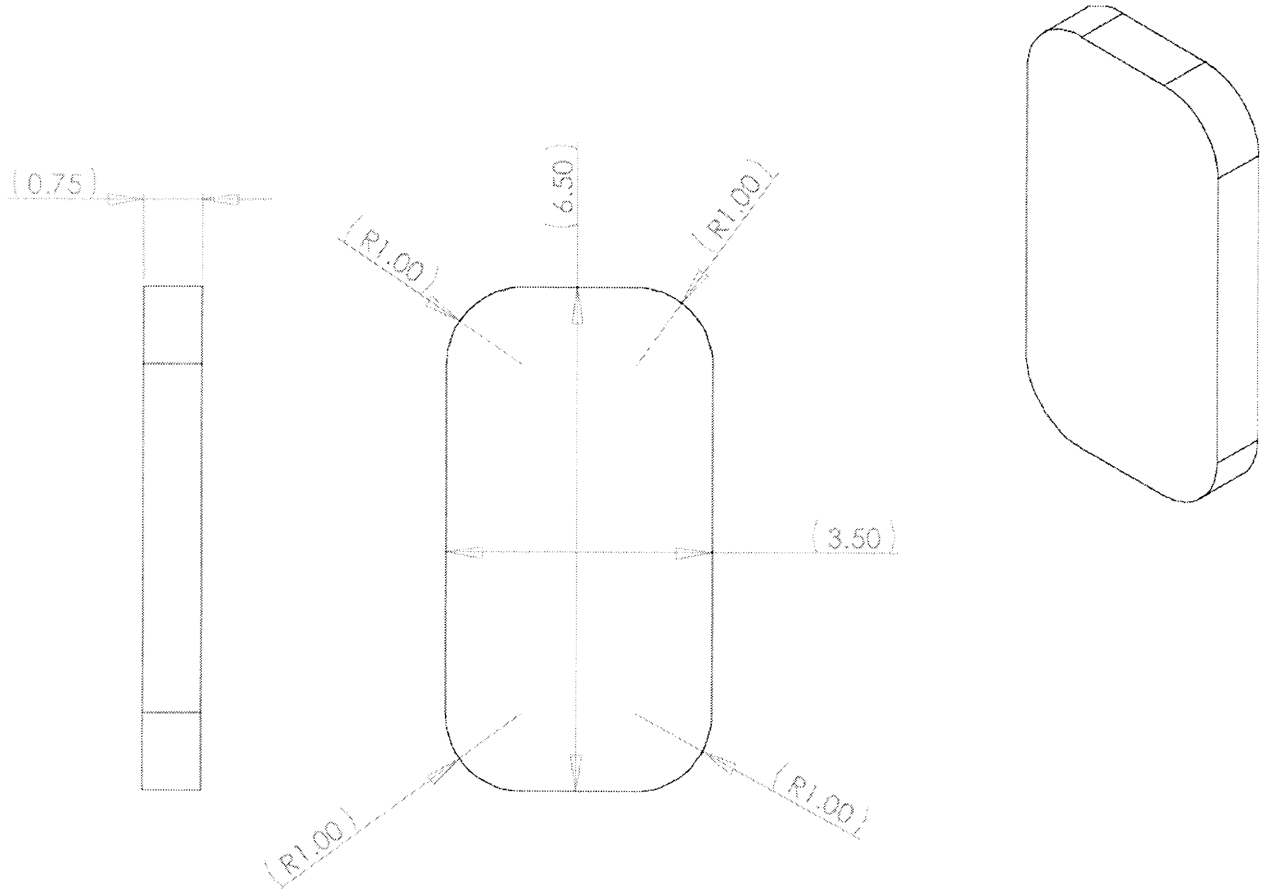
Wood Block for Dipole Motor Base

These blocks are used as the bases for the dipole motor experiment.

Message Sent to supplier:

This is a 3.5 inch by 6.5 inch by 0.75 inch pine #2 wood block, avoiding large knots; small, tight knots and pin knots are acceptable.

Dimensions are +/- 0.01 inch with fine surface finish (probably planed top/bottom and sanded sides).


(0.75)
(6.50)
(R1.00)
(R1.00)
(3.50)
(R1.00)
(R1.00)

Additional Parts List

Description	Part #	Company
DC Motor Kit		
Copper Foil Tape for Motor Rotor Contacts	76555A652	McMaster-Carr
Shrink Wrap For 1" Rotor	7132K794	McMaster-Carr
Shrink Wrap For 2" Rotor	7132K824	McMaster-Carr
Paper Clip Commutator, Contact Black Nylon Hex Nut 10-32 Screw Size	94900A411	McMaster-Carr
Paper Clip Commutator, Contact Binding Head Slotted Machine Screw Black Nylon, 10-32 Thread	94690A827	McMaster-Carr
Paper Clips Commutator, Paper Clips	12765T41	McMaster-Carr
Paper Clip Commutator, Nylon 6/6 Flat Washer #10	90295A120	McMaster-Carr
Power Plant Lab		
Awl For Punching Holes in Combustion Chamber	19195A22	
Sterling Engine Combustion Chamber Paint Cans	4084T42	McMaster-Carr
Rubber Band For Belting to Stirling Engine 3" Long x 1/8" Wide	12205T54	McMaster-Carr
Magnet Car		
Coils For Magnet-Car (.3mH air core)	255-028	PartsExpress