A WIND DRIVEN POWER GENERATING SYSTEM: INITIAL DESIGNS AND CONSTRUCTION

By

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A thesis submitted in partial fulfillment of the
requirements for the degree of

Bachelor of Science

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Abstract

The goal of this study is to design and build a low cost, mechanically efficient wind driven power-generating system in the 1 to 5 kilowatt range and to predict and improve its performance based on equations derived from fundamental principles. Construction and assembly have begun for a directly coupled, low "rpm" (angular frequency) generator consisting of a disk of copper coils sandwiched between two rotating disks of neodymium (NdFeB) magnets to which the blades will be directly coupled.

Thesis Supervisor: Dr. Ronald Rohe.
Title: Associate Professor of Physics

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INTRODUCTION

1.1 Introduction

Whether in the form of manual labor, the use of animals, water, or wind, people have long sought power to do work. They have been building machines to use mechanical motion to do work for centuries. For example, watermills and windmills were developed as farmers ground grain or irrigated crops. Over the past century (since 1890), windmills have been designed to transform power from the wind into electrical power [1]. Today, the largest windmills, or, as they are more commonly known, wind turbines, have a rated capacity of up to 5 MW [2].

In the past, windmills were often located not only in areas where there was a continuous strong wind, but also where there was a need for grinding of grain. Most often, windmills were built on hills close to fields of corn. These machines tended to be inefficient however. Today, the electrical output expected must be worth the cost of constructing a wind turbine. It is important to build wind turbines at a site where wind is continuous and strong, much like watermills needed to be near rivers.

During the last couple of decades, there has been a revival in interest in renewable energy sources, including wind power. This is due in part to increasing demand for electrical energy coupled with the inadequacy of traditional fuel supplies [3]. The result has been an increase in research into large and small wind turbine systems. This research, coupled with the development of better electrical components, has improved the power output of both wind turbine systems and generators. Utilizing these developments for the purpose of providing power to isolated or rural communities and individuals, the goal of this project is to design and build a small wind turbine. By observing its output under various conditions, improvements will be made to lower the cost of construction and maximize efficiency.

1.2 Previous Wind Turbines and Generators

Wind turbine system designs vary greatly from the common multi-blade horizontal axis turbines found on farms to the experimental vertical axis φ-Darrieus primary lift-type turbines [4]. Several features affect wind turbine systems design and output. As seen in Figures 2 and 3, most wind turbines have some kind of rotor, drive/power train, bearings, generator, and support stand/foundation. These features can also be found in different forms on the more common upwind horizontal axis large wind turbine system seen in Figures 1 and 3 [5]. In the following sections, the different features of a wind turbine that pertain specifically to the current generator design will be explained, namely, generators and drive trains.

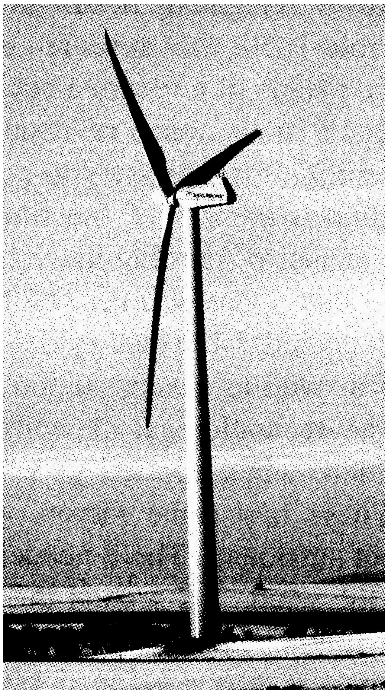


Figure 1. Example of a Modern Wind Turbine. Common three blade upwind turbines have a housing which contains a gearbox, generator, and turbine control systems all mounted on a 100 – 150 ft. tower. Figure taken from Ref [6].

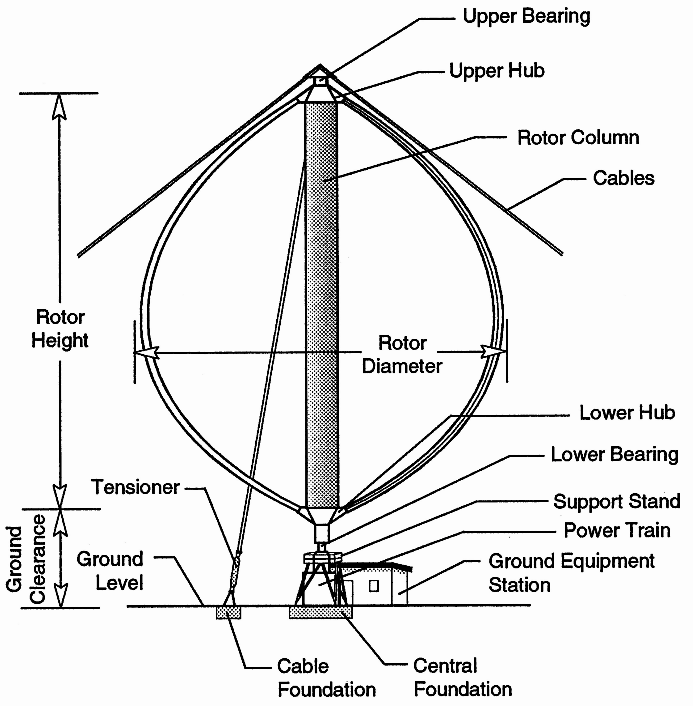


Figure 2. φ-Darrieus Primary Lift Wind Turbine. Many of the components needed to produce power with the φ-Darrieus wind turbine are also needed for other wind turbine systems, like a rotor column (or shaft) and a power train. Figure taken from Ref [7].

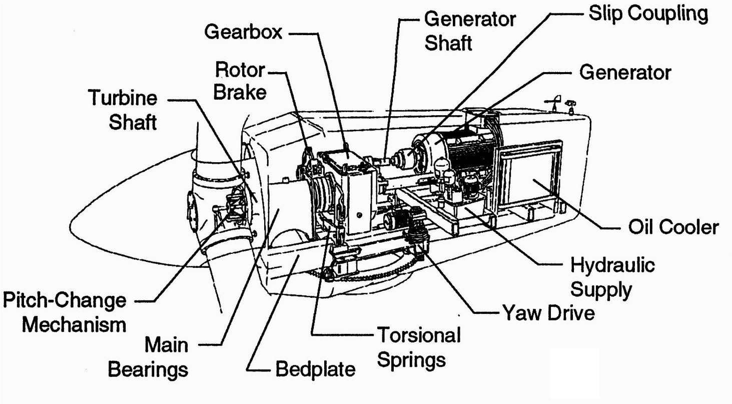


Figure 3. Common Medium Scale (kilowatt output) Wind Turbine System. A variety of components are needed to produce power. The slow rotation of the turbine shaft is increased by the gearbox so that the generator shaft rotates faster, producing electricity. Figure taken from Ref [8].

1.2.1 Basics of Generators

A detailed explanation of the theory of generators is beyond the scope of this paper. The basic principles will be explained, however, as they pertain to the generator being constructed for this project. First several types of generators will be briefly described, then a comparison of each to the design for this project will be given in order to clarify the features of the current generator design.

First, it must be understood how a generator converts mechanical power into electrical power. This is done using magnetic induction. A changing magnetic flux induces a current in a conductor by creating an electromotive force (emf), which then drives a load current.

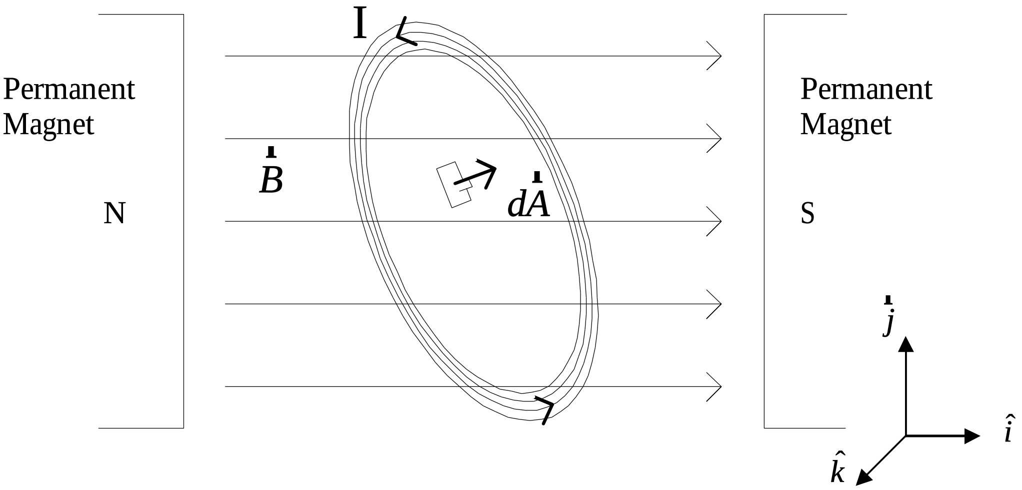


Figure 4. Current Induction. When a changing magnetic flux, φ, passes through a coil of wire, an electromotive force (emf) is induced. If a load is connected to the coil, a current, I, will pass through the coil. The magnitude of the current depends on the direction of the magnetic field through the coil.

Mathematically, the magnetic flux is:

$$\varphi = \int_{Surface} \vec{B} \cdot d\vec{A} \tag{1-1}$$

where φ is the magnetic flux, $d\vec{A}$ is the vector of magnitude dA that is normal to a differential area dA, and $\vec{B}$ is the magnetic field passing through the surface area element $d\vec{A}$. The unit for magnetic flux is the weber (Wb) or a Tesla·meter.

From Faraday's Law, if the magnetic flux is changing, an emf is induced in the loop,

$$\xi = N\frac{d\varphi}{dt} \qquad (1\text{-}2)$$

where ξ is the emf induced, φ is the magnetic flux, and N is the number of turns of the coil.

With the correct setup, it is possible to induce an alternating emf and corresponding alternating current in a coil. One way to induce this alternating current is done by rotating the coil in a constant magnetic field or rotating the magnetic field around a coil. Another possibility is moving adjacent magnets of opposite polarity past a conducting coil. Still another way to induce an alternating current is by using an alternating current in a coil to induce an alternating magnetic field in the same coil, since a current through a coil of wire creates a magnetic field. If the current is alternating sinusoidally, then the magnetic field will change sinusoidally as well, without having to rotate the coil or magnetic field. If another coil of wire is placed in this alternating magnetic field, then an alternating emf will be induced.

In generators, permanent magnets or windings of wire can be used to create a magnetic field. These magnets or windings can be placed on the stator, which is stationary, or the rotor, which is rotated by an external mechanical force. The armature of a generator contains windings of wire as well. If a changing magnetic field passes through the windings on the armature, then an emf is induced. Different arrangements for generators can be seen in Figure 5.

In Figure 5a, two permanent magnets on the stator are used to induce a current in the armature coils on the rotor. In Figure 5b, the permanent magnets are on the rotor instead of the stator. In Figure 5c and 5d, field coils are used to create the same magnetic field as permanent magnets. Most generators used for wind turbines use field coils on the rotor and armature coils on the stator, similar to Figure 5d.

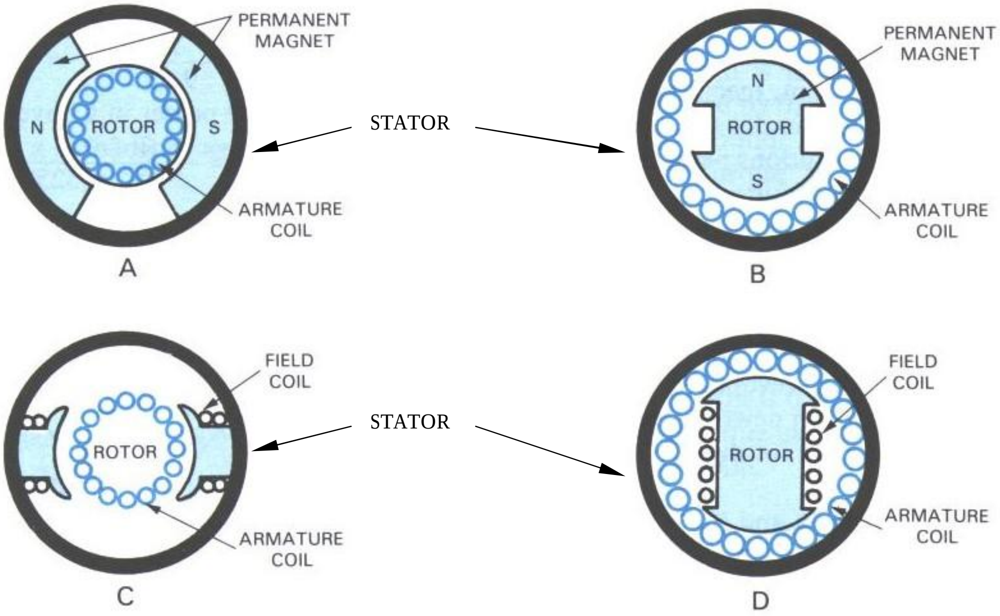


Figure 5. Rotor and Stator Parts. The rotor and stator can be made so that a magnetic field is produced from either pairs of permanent magnets (A, B) or windings, or coils (C,D). The generator's electrical output comes from the current induced in the windings of the armature. Figure taken from Ref [9].

1.2.1.1 Alternators or ac Generators

There are two types of alternating current generators, or alternators, that are used for wind turbine systems: synchronous and induction (also known as asynchronous) generators. Both contain a stationary armature, shown in Figure 5, through which alternating current is sent. The result is a rotating magnetic field in the armature coils, where the magnetic field changes direction with time.

In synchronous generators, the rotating magnetic field in the armature coils interacts with an induced magnetic field of the rotor, as seen in Figure 6. This magnetic field results from current passing through the coil windings on the rotor. The direct current power source needed to induce magnetic field in the rotor comes from an external power source which is either alternating current from an electrical grid converted to direct current or a small dc generator mounted on the shaft of the synchronous generator's rotor [10]. In order to generator power, the magnetic fields of the rotor and stator must rotate synchronously, i.e. they rotate at the same speed and frequency [11]. If torque is applied to the rotor, electricity will be generated. If the wind turbine output is connected directly to an ac network, then active speed controls of the wind turbine may be needed in order to keep the rotor rotating at synchronous speed [12].

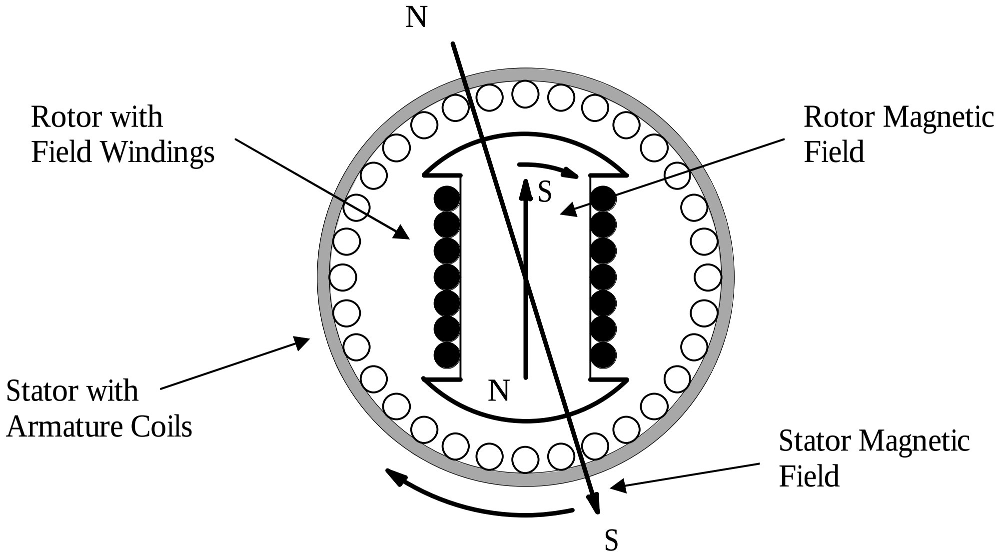


Figure 6. Magnetic Field in a Synchronous Generator. The magnetic fields produced by the rotor and stator rotate at the same speed, resulting in a single field. Figure taken from Ref [13].

In induction generators, the rotating magnetic field in the stator interacts with an induced magnetic field in the rotor (see Figures 7 and 8) that results from an induced current in the conducting bars. These conducting bars form what has been commonly called a "cage", shown in Figure 7a, allow current to pass through them, as seen in Figure 7b. In order for electricity to be produced, the speed of the rotor needs to be slightly different than the synchronous speed of the rotating magnetic field in the stator. This difference is used to induce a current in the rotor conducting bars, which then creates a magnetic field. The interaction of the two fields causes elevated voltage at the terminals of the armature coils as the rotor's magnetic field leads the stator's field.

Not all induction machines use this “cage”. It is possible to have an induction generator that uses windings on the rotor. These generators are known as wound rotor generators and are used in variable speed wind turbines. Wound rotor generators are more expensive and less rugged than generators with “cage” rotors.


(a)

(b)

Figure 7. Cage Rotor. The cage rotor of induction generators contain conducting bars (a) are commonly made of copper or aluminum connected electrically by aluminum end rings so that current (shown with white arrows) can be induced through the bars (b). Figure taken from Ref .[11].

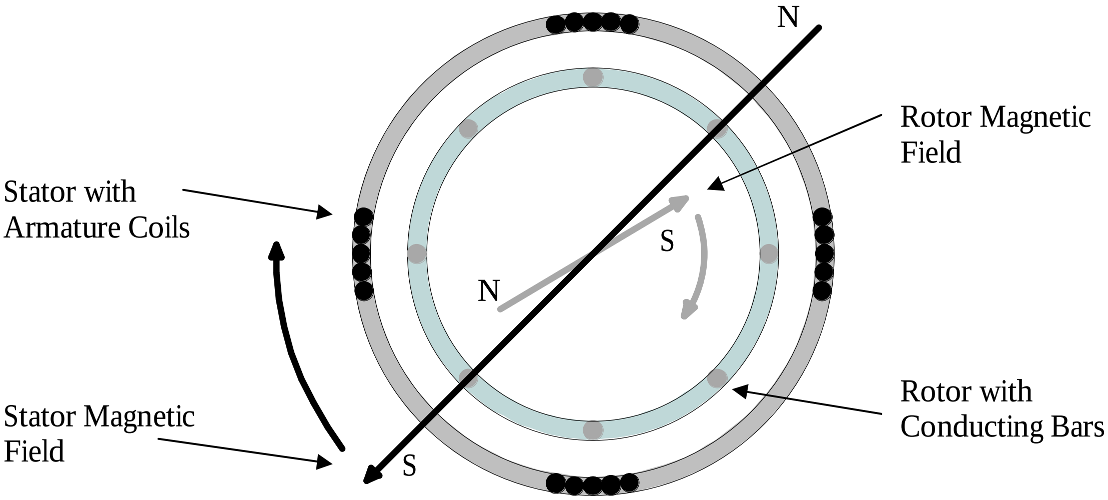


Figure 8. Magnetic Field of the Rotor and Stator in an Induction Generator. The rotor’s magnetic field rotates slightly faster than the stator’s magnetic field. Figure taken from Ref. [14].

The induction generator with the cage rotor is the most commonly used generator for wind turbines because of its simple, but rugged construction. Plus, they can be connected and disconnected from the grid relatively easily. Even though the current is induced in rather than supplied to the rotor, there is still a need for an external source of reactive power for the coil windings in the stator. Like the synchronous generator, active speed control is needed to maintain a constant rotational frequency of the rotor. Unlike the synchronous generator, however, induction generators can be used as motors when connected to an ac network so that the turbines can be brought up to operating speed [13].

1.2.1.2 Dc Generators

Direct-current generators are much like alternating current generators except for their constant current output. They still utilize the theory of induction, but in a slightly different manner. In a dc generator, brushes and commutator, or slip rings, are commonly used to rectify the sinusoidally varying current. As the armature loop in Figure 9 rotates, an emf is induced in the loop. Current is sent to a load only when the slip rings and brushes make contact. These slip rings and brushes are shown in greater detail in Figure 10.

An electronic circuit including a rectifier can also be used to convert alternating current to direct current. These are commonly used with smaller wind turbines to charge batteries, rather than connecting to an ac network (though it is possible to convert a dc output to ac with a specific frequency, see Chapter 5).

In dc generators, the magnetic field used to induce current is commonly on the stator, rather than the rotor as with ac generators, and the rotor contain coils of wire through which current is induced as it rotates. Since the electrical power output comes from the rotor, and not the stator as in the case of ac generators, brushes and a commutator ring are needed in dc generators [15].

The magnetic field in the stator can be produced in two ways, either with a permanent magnet or using an electromagnet. The source of the current for the electromagnet winding is the armature or rotor, output. The output can be connected in three ways: in parallel with the field windings of the stator as in the case of the shunt generator (illustrated in Figure 11b), in series (illustrated in Figure 11a), or a combination of parallel and series (in the case of compound generator illustrated in Figure 11c) [16].

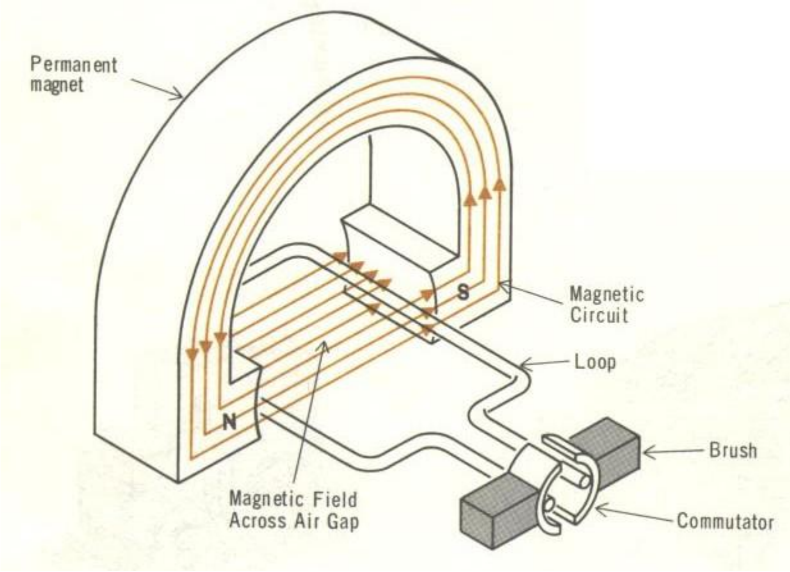


Figure 9. Basic Parts of a Direct-current Generator. These parts include a commutator, brushes, magnetic field, and a conduction loop or winding. Figure taken from Ref. [17].

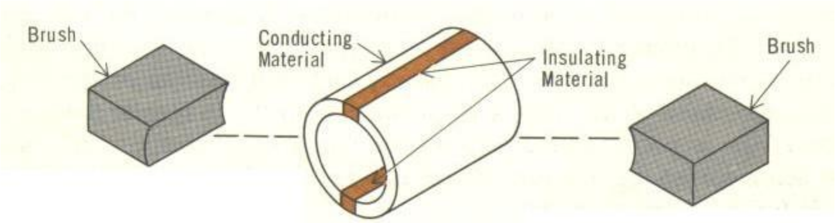


Figure 10. Detailed Illustration of a Commutator Ring and Brushes. The commutator can be several semicylindrical metal pieces separated by insulated material. Brushes are made of soft conduction material, usually carbon. Figure taken from Ref. [18].

One significant difference between dc generators and ac generators is that as the operating speed increases in dc generators, the current through the windings in the stator increases resulting in a greater magnetic field. As the magnetic field strength increases, the electrical power output also increases along with the torque required to rotate the generator shaft.

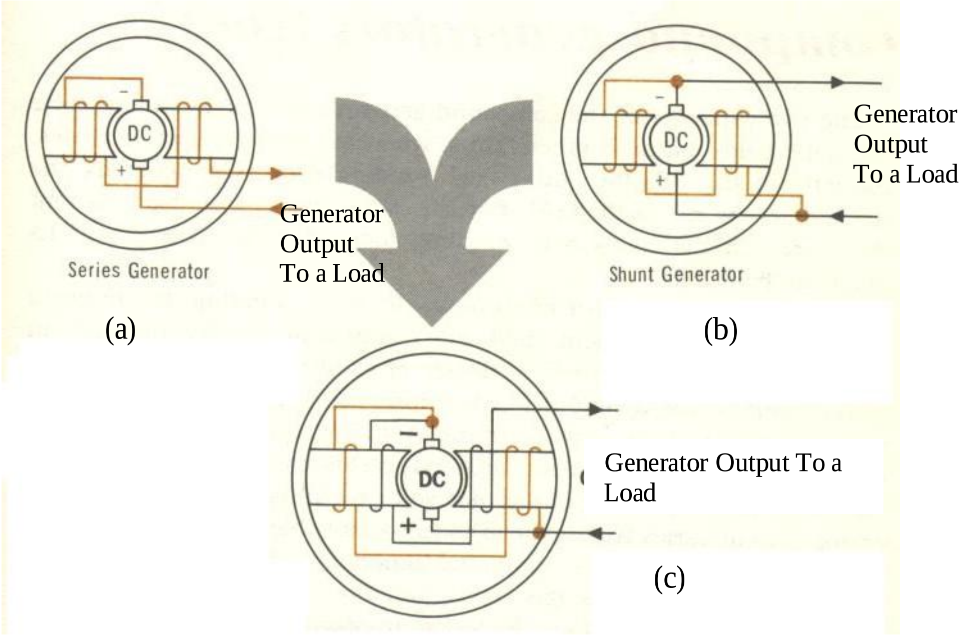


Figure 11. Wiring Configuration of Stator Windings in Direct-current Generators. A series generator's output, the windings on the stator, and the load are connected in series (a) while a shunt generator's output, the stator's windings, and the load are in connected in parallel (b). A compound generator (c) uses a combination of series and parallel electrical connections. Figure taken from Ref. [19].

Another type of dc generator that is being used frequently for small-scale wind turbines with up to a 10 kW output, is the permanent magnet generator (PMG). These use permanent magnets instead of windings with a current supply, illustrated in Figure 7a,b. It is possible to construct this type of generator in such a way as to place the magnets on the rotor so that there are no brushes or commutor rings and the output is then from the armature coils in the stator. Principles surrounding the operation of PMG's are similar to that of the synchronous machines, except that they are run asynchronously [20]. That is, they are not usually connected directly to an ac power grid since the power produced by the generator is initially variable voltage and variable frequency ac. Then it is commonly rectified to dc, as its final output.

1.2.2 Wind Turbine Systems

As was mentioned previously, there are many ways in which a wind turbine rotor may be connected to the rotor of a generator. For medium and large-scale wind turbine systems, a gearbox is used to change the slow rotational speed of the turbine rotor shaft to a fast rotation needed for the generator. Figure 12 shows four examples of this. The rotation of larger turbines is slow compared to turbines used for small-scale systems, but provides much more torque.

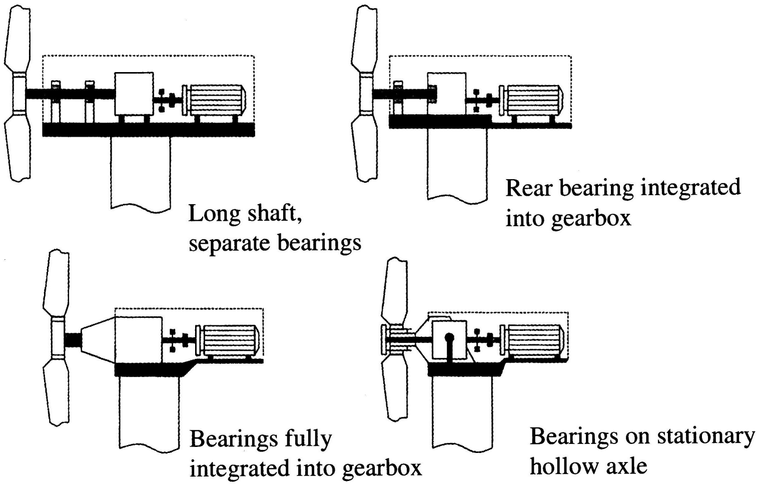


Figure 12. Main Shaft Options. Four possible configurations for coupling the turbine rotor to generator rotor shaft through a gearbox, usually for medium to large scale wind turbines. Figure taken from Ref. [21].

Smaller wind turbine systems commonly use a direct-drive wind system. In this type of design, the turbine rotor is directly connected to the generator, as illustrated in Figure 13. Since the diameter of the wind turbine is generally smaller for smaller wind turbines, resulting in a higher rotational speed, it is not necessary to use a gearbox to increase the speed of rotation of the generator shaft. The result is a smaller loss of mechanical energy due to friction, which can occur in the bearings and gearbox. Also, without the gearbox, the entire system is smaller and generally less expensive. It is, however, still necessary to use bearings to support the main shaft.

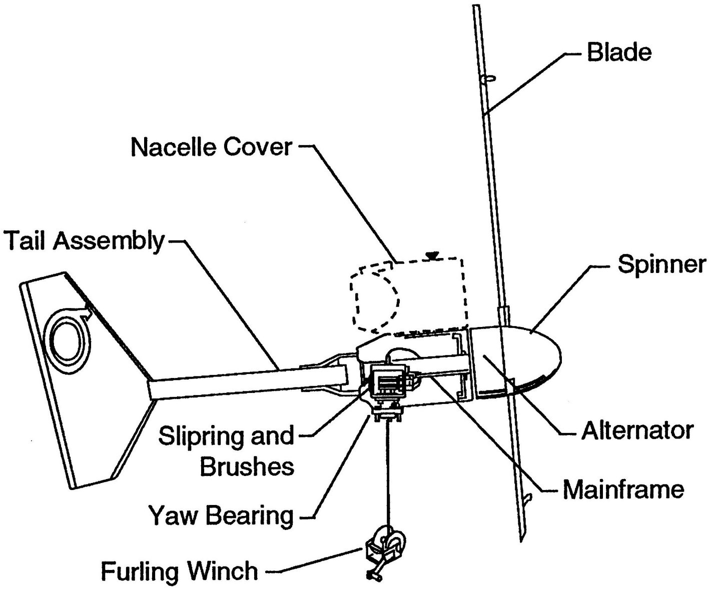
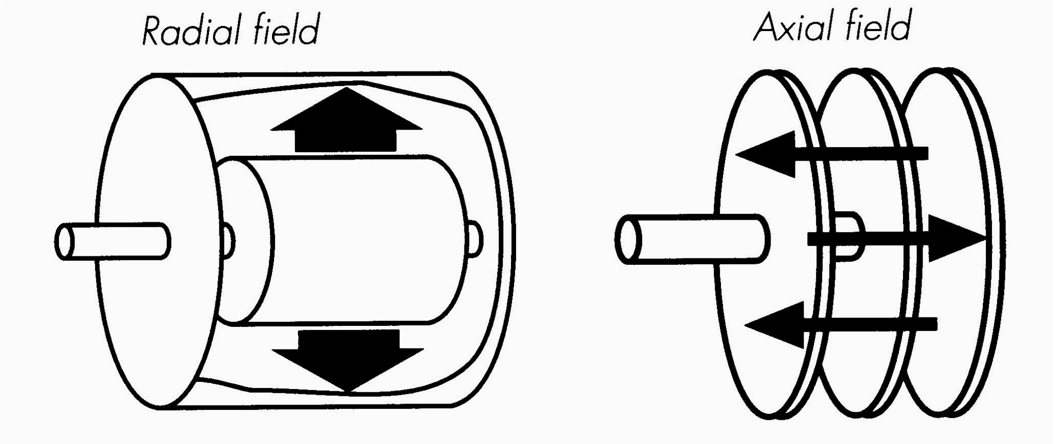


Figure 13. Small Scale Direct-drive Wind Turbine System. Turbine blades are directly coupled to the generator's rotor so that a gearbox is not needed. Figure taken from Ref. [22].

1.3 Other Wind Turbine Generators

Hugh Piggott, who has been involved in designing and building low cost wind turbines using scrap yard parts, has given other designs for wind turbines. Two of these designs include a brake-drum, or radial field, wind turbine and an axial field turbine. The design of the generator being described in this thesis is based on one described in Ref. [23].

Just as most generators and motors use a radial field, it is possible to construct a permanent magnet generator that uses this principle, as shown in Figure 14a. In this model, permanent magnets are placed on the inside of the cover while the core contains the armature coil windings. As a result, the magnetic field is directed radially, inward or outward. The outside cover is commonly the rotor, though it is possible design the PMG so that the core rotates. Similarly, it is possible to use a direct drive system to attach the blades to the inside core or to directly-couple the turbine blades to the outside cover, which is more commonly used. This design is described further in Ref. [24].



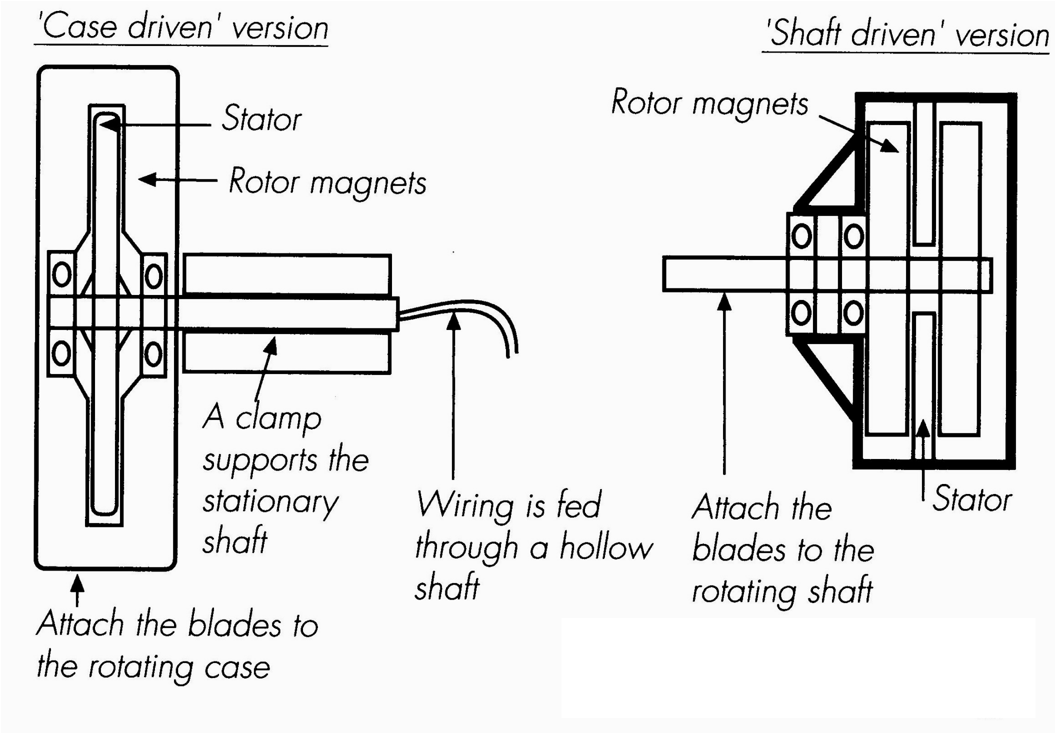
(a) (b)

Figure 14. Permanent Magnet Generator (PMG) for Small Wind Turbine Systems. The magnetic field inside a PMG can be (a) radially directed (inward or outward) or (b) along the axis of rotation. In either the radial field or axial field generator, it is possible for the rotor to be the interior core or the exterior cover. Figure taken from Ref. [25].

In the axial field PMG, shown in Figure 14b, the direction of the magnetic field is parallel to the shaft. As a result, it is possible to have two different designs where the rotor is either directly-coupled to the turbine blades or attached to a shaft which the turbine blades rotate, as can be seen in Figure 15. In both designs of Figure 15, magnets are placed on rotating disks opposite each other with coils of wire in the stator [26].

The design of either the brake drum or axial field generator must take into consideration the radial position of the magnets and coils, the number of poles, the shape of the coils, the number of turns of each coil, the thickness of the wire, and the shape of the magnets. An introduction to these factors will be given here.

A low speed generator using permanent magnets needs to have a large radius. In order to improve the efficiency of a PMG at lower angular velocities, the radial position of the magnets and coils must be large. This can be understood if one realizes that if the diameter of the position of the magnets and coils increases, then the linear speed at which the magnets pass the coils will increase as the angular velocity increases [24].



(a) (b)

Figure 15. Axial Field PMG Designs. The rotor of an axial field generator can be either the (a) exterior or (b) interior part of the generator. Figure taken from Ref. [27].

In theory, the larger the radial position of the magnets and coils, the more magnetic poles that can be placed on the rotor and the more coils that can be placed on the stator. There are additional factors to consider though, when deciding how many poles and how large each of these poles should be. These include the output frequency that is desired, the energy loss due to the copper wire and width of the coils, and the magnetic flux through the coils. The more poles the higher the frequency that can be obtained, but also the more energy loss due to the length of the wire. In the case of the coil width, the smaller the magnetic poles the smaller the coils can be, therefore decreasing the energy loss due to the wire’s resistance. If the poles are smaller, then it is possible to use more of them. If the poles are placed too closely together, however, it is possible that there will be fringing of the magnetic field between opposite poles resulting in some of the magnetic flux passing through adjacent coils.

Many of the factors that influence the design of a generator are interrelated, much like the size of the magnetic pole faces and the size of the coils. The size of the coils determines the number of turns and size of wire that should be used. The number of turns needs to be “chosen so as to give the desired voltage at the desired [angular frequency]” [28]. It is also important to consider the amount of current that will be sent through the coils. Too thin of wire will have a higher resistance which increases the loss to thermal energy. In summary, in order to determine the exact characteristics of the generator, such as the number of turns of the coils, the output desired must first be known and from there, the generator can be designed.

Chapter 2

Generator Project Design

2.1 Design Considerations

The aim of this project is to design and build a home-owner or individual sized wind turbine. Previous permanent magnet generators have met the requirements of low cost, low maintenance, and 1-5 kW output. Some of these generator designs were researched in hopes of improving efficiency and output, and were explained in the previous chapter.

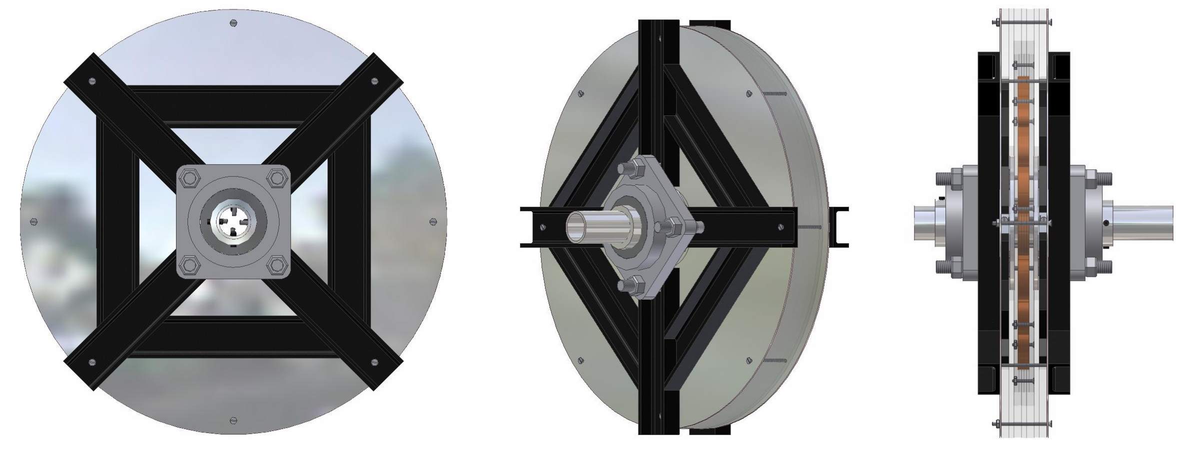
In designing a wind turbine generator, several things were considered. In general, the size of the turbine, the materials to construct the generator, the cost, and the output were all considered. Specifically, the size of the generator in relation to the size of the turbines was considered. Another consideration was whether or not to design a direct-drive system or use a gearbox to increase the speed of rotation of the generator shaft.

It was decided to study a low “rpm” direct-drive permanent magnet generator, since this type of generator is able to produce electrical power even at lower angular velocities (as compared to the larger, more common wind turbines which use induction generators). It is also possible to build a generator large enough to meet the output requirements for the average homeowner and small enough to be built at a low cost. After this had been determined, the type of magnet to use, the amount of time available to machine parts, the availability of materials and even the size and type of bearing to use, were all considered.

It was decided to use sheets of acrylic with metal supports instead of wood and adapt the design given in Ref. [23] so that more magnets and coils could be used. In designing the generator, the general principles for an axial field generator were followed, as were the designs for directly mounting the turbines to the generator.

2.2 Basic Description and Explanation

In Ref. [23], a design is given for an axial field generator with a rotor with eight permanent magnet poles and a stator with six coils. Below, in Chapter 3, it is shown that the output directly relates to both the number of poles and coils. In order to increase the power output, it was decided that more poles and more coils were needed. To accommodate this change, the diameter of the generator was increased and the shape of the magnets and coils altered. The type of permanent magnet was changed as well. As those aspects changed so did the structure of the rotor and stator.



(a) (b) (c)

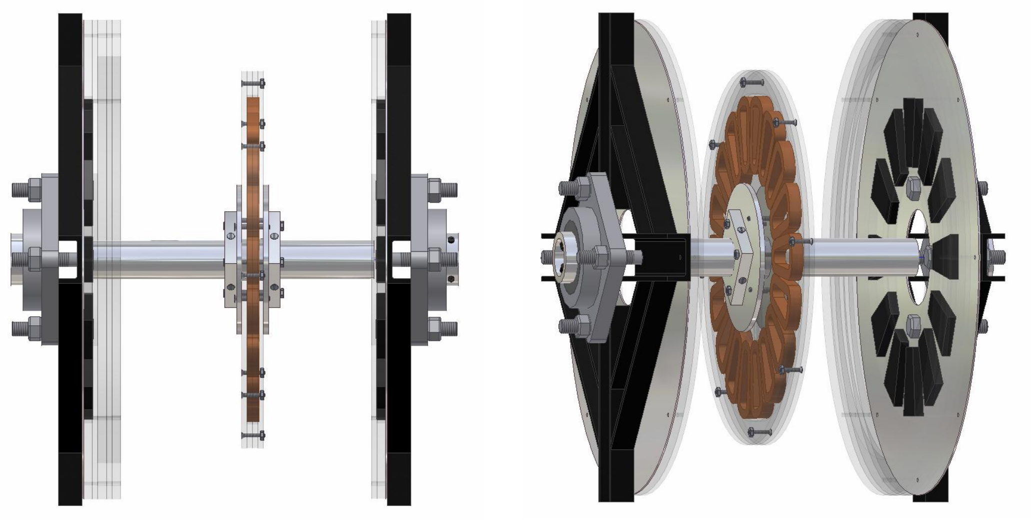
Figure 16. Low "rpm" Permanent Magnet Generator. Welded channel iron provides support for the rotor (a) and screws are used to hold the rotor parts together (b). The stator, housed inside the rotor (c), contains coils through which a current is induced as the rotor turns.

Ref. [24] also explained how the turbine could be directly mounted to the generator. In the current design, this was considered as well. The exact method for mounting the turbines has not been determined although the structure of the rotor makes it possible for additional parts to be added to allow for this. With the rotor supported by channel iron, the blades can be attached to each of the four extending parts, seen in Figure 16 and 18, if four blades are desired. Channel iron can also be attached to these extending parts in order to create an additional structure in case a different number of turbines are desired.

Figures 16-21 show the different parts of the generator. (More detailed designs are shown in the Appendix.) The design of this generator with its parallel disks of magnets follows the design for the "case-driven" axial field generator in Figure 15 described in Ref. [23]. The rotor in the current design completely encases the stator but is free to rotate around it. Two axial ball thrust 4-bolt flange bearings are used at each end of the rotor allow for this motion. These bearings are attached to welded channel iron and sheet metal using 5/8 in. bolts. Twelve magnets are placed on each sheet of steel in a circular pattern shown in Figure 17b and spaced so that they are aligned according to Figure 20. The magnets are supported by circular sheets of acrylic: one on the outside edge, one on the inside edge, and another as a cover. The acrylic sheet used as a cover for the magnets will keep the magnets from being pulled towards the stator. Three other circular rings of acrylic are used in the center to provide space for the stator so that the rotor can rotate without any obstruction from the stator. The ends of the rotor are held together at the outside edge with several screws.

The stator is comprised of aluminum supports and circular sheets of acrylic. The aluminum supports provide a means for attaching the stator to the shaft, which is a steel pipe) so that the stator will not be free to move. Two of the supports (one on either side of the stator) are circular and another two (one on either side) are square in shape, seen in Figure 19. Eighteen coils of wire are in the same circular pattern as the magnets. They are fitted as closely as possible with the wire leads of each coil connected to every third coil in such a way as to produce three phases with six coils in series in each phase, shown in Figure 34. The exact connections are explained further in Chapter 5. These coils are supported on the inside by two thin circular sheets of acrylic and outside by two circular rings of the same thickness. The inside circular sheets are grooved to provide a slot for the wire leads to go out of the stator, through the pipe. The stator is then held together using screws.

In order to allow for future maintenance, several parts are permanently fixed together while others are held together with screws and bolts. The pieces of channel iron are welded together and then welded to each steel sheet while epoxy is used to hold several sheets of acrylic together. Construction and assembly of the generator are made easier by epoxying several sheets of acrylic together (an explanation of which sheets were epoxied together will be given in Chapter 4).



(a) (b)

Figure 17. Low "rpm" Permanent Magnet Generator. The rotor can be easily taken apart so that maintenance and repairs can be done as needed. The magnets on each rotor end allow a changing magnetic flux to pass through the coils as the rotor rotates.

The materials used to build this generator include sheets of acrylic, steel, and aluminum of various thickness, steel channel iron, neodymium (NdFeB) magnets, several sizes of screws and bolts, 19 gauge copper wire, and two bearings. The generator design in Ref [23] uses mostly wood, resin, neodymium magnets, and scrap yard brake drums (which are used because of their strong bearings). The materials used for the different parts in the current generator were chosen after considering the permeability, tolerance to weathering, weight, strength, and cost.

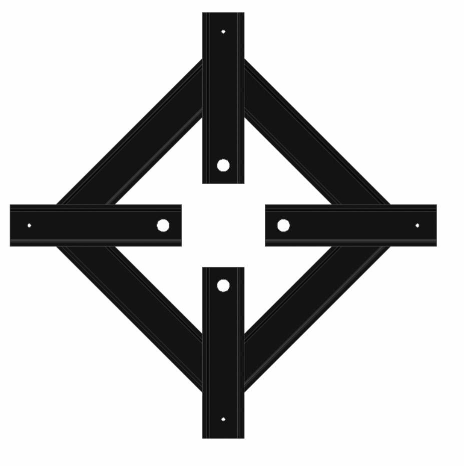


Figure 18. Welded Steel Channel Iron. Angled pieces of channel iron are welded to straight pieces so that the rotor is rigid. This welded channel iron is then welded to the steel sheet that the magnets are attached to.

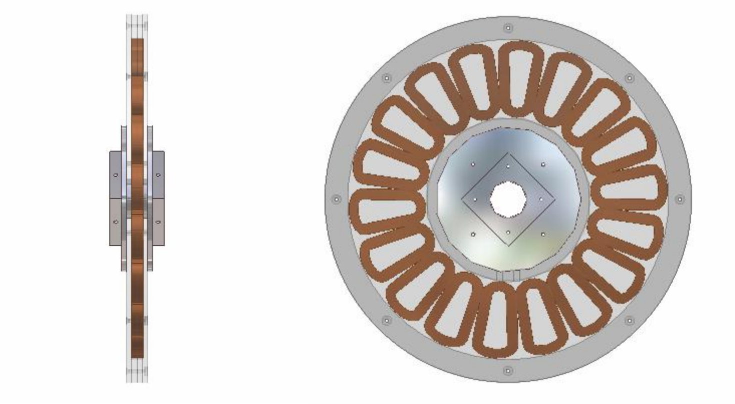


Figure 19. Stator. The coils are contained in an acrylic stator. Support on the shaft comes from the square and circular aluminum parts on each side. The stator is held together using epoxy and screws (not seen in figure).

Acrylic was chosen to encase the coils and magnets. Since acrylic has a low permeability, compared to aluminum, is machinable, and able to withstand weathering, it was chosen over aluminum. Even though aluminum has a low permeability, current can be induced in an aluminum rod, which is commonly done in induction generators. Also, aluminum has a higher specific gravity than acrylic and weighs more for the same volume. The density of aluminum is about 170 lbs./ft^3 (2723 kg/m^3) while the weight of acrylic is 74 lbs./ft^3 (1185 kg/m^3)[29].

Aluminum, because of its tension and shearing strength 45 and 30 lbs/in^2 (31638 and 21092 kg/m^2) respectively, was chosen to support the stator [30]. These supports were designed to fit along the shaft and stator but away from the magnets and coils. Two circular pieces attach directly to the stator while two square pieces attach to the shaft. The square pieces and circular pieces are attached using 4 screws that are inserted into tapped holes in the aluminum, which run parallel to the shaft. These holes also go through the stator and help to hold it together.

In order to hold the magnets in place, a permeable material, steel, was chosen. A steel sheet will also help reinforce the magnetic fields and preserve the strength of the magnets. An outer support would be needed in order to keep the magnets from moving outward as the rotor rotated. The material that was needed to support the magnets and the coils could not be magnetic or have a high permeability. Wood was used in many of Hugh Piggott's designs for this reason and because it is fairly light. It was decided to use acrylic sheets instead because acrylic doesn't absorb moisture, warp, or weather as easily.

With the outer cover being made of acrylic, extra structural support was needed in order to attach the blades. Steel channels provided the support necessary to withstand the high wind speeds and gusts. With the structure shown in Figure 18, with the channels welded together, it is possible to attach blades and still maintain a rigid structure for the rotor.

Neodymium magnets have the strongest magnetic field for a given volume and were chosen for this reason. Shown in Tables 1 and 2 are different grades of neodymium magnets and their characteristics. The grade chosen was N35. The shape of the magnets was also changed from the square design of Ref. [23] to a trapezoidal shape so that more magnets (with a larger surface area) could be placed in a circular pattern. A dimensioned drawing of the magnets is given in the Appendix. The original plan called for two circular magnets, one with a smaller diameter than the other, were to be used to create a magnetic field over a larger area. This would have been accomplished by placing the magnets adjacent to each other, with the smaller magnet closer to the center of the stator and the larger magnet along the outside edge of the stator. Several of these would have been used to create an alternating pattern of North poles and South poles, much like the pattern in Figure 20. Instead of purchasing several circular magnets, fewer magnets in the shape of a trapezoid were custom cut. The area of the trapezoidal magnets is similar to the area of two circular magnets except it is solid in the center, allowing for a more uniform magnetic flux.

The shape of the coils was then determined from the shape of the magnets, but enlarged slightly. Nineteen gauge enameled copper wire was used principally because of its availability. It has a 0.9416 mm (0.03589 in.) diameter which is small enough to allow for several turns per square centimeter but large enough to allow up to approximately 5 A of current, without overheating. The number of turns was then determined by the availability of space in the 322.58 mm^2 (0.5 in.) thickness and the 322.58 mm^2 (0.5 in.) width desired for the coil. The coils were wrapped using the coil former shown in Appendix A. The result was a coil with 110 turns with an average resistance of 0.5 Ohms.

Table 1. Physical and Mechanical Properties of NdFeB Magnets. The table shows the properties of neodymium magnets and possible surface treatments of zinc, copper and nickel, epoxy, gold, silver as well as others. Table taken from Ref. [31]

Thermal Conductivity	7.7 kcal/m-h-°C
Young's Modulus	1.7 x 104 kg/mm^2
Bending Strength	24 kg/mm^2
Compressive Strength	80 kg/mm^2
Electrical Resistivity	160 µ-ohm-cm/cm^2
Density	7.4-7.5 g/cm^3
Vickers Hardness	500 - 600

2.3 Comparison

In Chapter 1, the different types of generators were briefly explained. Now that the new design has been described, the different generators can be compared, which will show the benefits and drawbacks of the current design.

The current generator design uses a sinusoidally varying magnetic field to induce a current in the coils similar to most generators. The result is an alternating voltage and current output. In the case of dc generators, this output is converted from ac to dc using mechanical connections, ie. a commutator and brushes. The current design will output ac but then, if necessary, convert to dc using a rectifier circuit so that these kinds of mechanical connections are not needed. (The circuit for converting ac to dc is explained further in Chapter 5.)

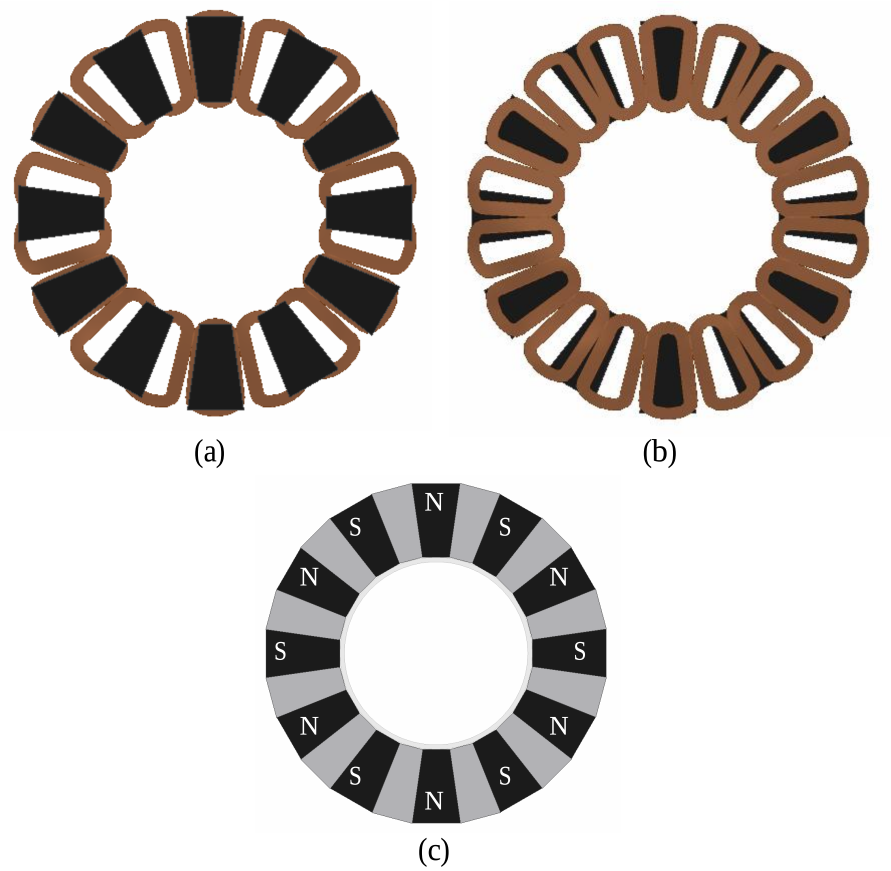


Figure 20. Magnet and Coil Configuration. For every three coils, there are two magnets (a). This allows the coils to be connected so that the electrical output is in three phases. The magnets and coils were designed to fit in a circular pattern with the magnets covering as much area of the coils as possible (b). The magnets are placed on the rotor in the pattern shown in (c) so that a changing magnetic field passes through the coils.

Table 2. Sintered NdFeB Magnet Properties. The grade of neodymium magnets chosen was N35 for its strength and lower cost. Table taken from Ref. [32].

Grade	**Max. Energy Product**		**Remanence**		**Coercive Force**				**Rev. Temp. Coeff.**		**Curie Temp.**	**Working Temp.**
	$(BH)_{max}$		**B_r**		**H_c**		**H_{ci}**		**B_d**	**H_d**	**T_c**	**T_w**
	MGOe	*kJ/m³*	*kG*	*mT*	*kOe*	*kA/m*	*kOe*	*kA/m*	*%/°C*	*%/°C*	*°C*	*°C*
N33	31-33	251-268	11.5	1150	>10.5	>840	>12	>960	-0.12	-0.6	310	80
N35	33-36	268-293	11.9	1190	>10.9	>872	>12	>960	-0.12	-0.6	310	80
N38	36-39	293-317	12.3	1230	>11.3	>904	>12	>960	-0.12	-0.6	310	80
N40	38-41	309-333	12.7	1270	>11.6	>928	>12	>960	-0.12	-0.6	310	80
N42	40-43	325-349	13	1300	>11.6	>928	>12	>960	-0.12	-0.6	310	80
N45	43-46	349-374	13.5	1350	>11.0	>880	>12	>960	-0.12	-0.6	310	80
N48	46-49	374-398	14	1400	>10.5	>840	>12	>880	-0.12	-0.6	310	80
N50	47-51	374-406	14.2	1420	>10.5	>840	>12	>960	-0.12	-0.6	310	80
N33M	31-33	252-268	11.5	1150	>10.5	>840	>14	>1120	-0.12	-0.59	320	100
N35M	33-36	268-293	11.9	1190	>10.9	>872	>14	>1120	-0.12	-0.59	320	100
N38M	36-39	293-317	12.3	1230	>11.3	>904	>14	>1120	-0.12	-0.59	320	100
N40M	38-41	309-333	12.7	1270	>11.6	>928	>14	>1120	-0.12	-0.59	320	100
N42M	40-43	325-349	13	1300	>11.6	>928	>14	>1120	-0.12	-0.59	320	100
N45M	43-46	349-374	13.5	1350	>11.0	>880	>14	>1120	-0.12	-0.59	320	100
N33H	31-34	252-276	11.5	1150	>10.5	>840	>17	>1360	-0.11	-0.58	320-350	120
N35H	33-36	268-293	11.9	1190	>10.9	>872	>17	>1360	-0.11	-0.58	320-350	120
N38H	36-39	293-317	12.3	1230	>11.3	>904	>17	>1360	-0.11	-0.58	320-350	120
N40H	38-41	309-333	12.7	1270	>11.6	>928	>17	>1360	-0.11	-0.58	320-350	120
N42H	40-43	325-349	13	1300	>12.0	>960	>17	>1360	-0.11	-0.58	320-350	120
N44H	42-45	326-358	13.3	1330	>12.6	>1008	>17	>1360	-0.11	-0.58	320-350	120
N33SH	31-34	252-276	11.5	1150	>10.6	>848	>20	>1600	-0.11	-0.55	340-360	150
N35SH	33-36	268-293	11.9	1190	>11.0	>880	>20	>1600	-0.11	-0.55	340-360	150
N38SH	36-39	293-317	12.3	1230	>11.4	>912	>20	>1600	-0.11	-0.55	340-360	150
N40SH	38-41	309-333	12.7	1270	>11.8	>944	>20	>1600	-0.11	-0.55	340-360	150
N42SH	40-43	325-349	13	1300	>12.3	>984	>20	>1600	-0.11	-0.55	340-360	150
N28UH	26-29	211-236	10.6	1060	>9.6	>768	>25	>2000	-0.11	-0.51	350-380	180
N30UH	28-31	228-252	11	1100	>10.2	>816	>25	>2000	-0.11	-0.51	350-380	180
N33UH	31-34	252-276	11.5	1150	>10.7	>856	>25	>2000	-0.11	-0.51	350-380	180
N28EH	26-29	211-236	10.6	1060	>9.8	>784	>30	>2400	-0.11	-0.51	350-380	200
N30EH	28-31	228-252	11	1100	>10.2	>816	>30	>2400	-0.11	-0.51	350-380	200

One difference between the current design and other ac generators is the frequency of the output voltage and current. In many medium and large-scale wind turbines, the output is directly connected to the power grid. These generators need to have an output frequency of 60 Hz. Although it is possible for the current generator to have a 60Hz output frequency (at wind speeds high enough to give the rotor a large angular velocity), it is not necessary. Instead, an inverter circuit, phase-locked to the power “grid” will be used to allow the rectified or stored dc output to be connected to the grid (explained further in Chapter 5).

Other generators, specifically ac induction and synchronous generators, rely on magnetic fields in the stator and/or rotor, which is another major difference. The generator researched here uses magnetic fields, created by permanent magnets on the rotor. This alternating magnetic field (produced by the rotation of the magnets) induces a current in each of the coils in the stator. This avoids the necessity of high angular frequencies for significant power output as compared with other generators, which need the higher angular frequencies to generate strong magnetic fields.

Another difference between the current design and most generators is the rotational speed of the rotor. In other generators, large angular frequencies are needed in order to output a frequency of 60 Hz, due to their fewer numbers of magnetic poles. Table 3 shows the relationship between the number of poles and the angular frequency needed for the output frequency to be 60 Hz. The common number of poles is four, so 1800 rpm is needed to have an output frequency of 60 Hz. while an angular frequency of 600 rpm is needed for the current generator, which has twelve poles. It is important to note that for the current design, 600 rpm is more than expected or needed if an electronic circuit is used to convert the variable frequency current to dc and then back to ac.

Yet another difference is the common use of an additional power source. Generators that do not use permanent magnets need an additional power source in order to create a magnetic field. For most ac generators it is external and commonly the power grid. For dc generators, parallel and serial connections are made from the output terminals to create a magnetic field in the field coils, which is then used to induce current in the armature coils.

Finally, for generators which rely on the emf induced in the armeture to create a magnetic field in the field coils, similar to dc generators, the output emf depends on the angular velocity squared, ω^2. In other words, the fields are excited by an increased angular velocity, resulting in the maximum magnetic field strength being dependent on the angular velocity. In the current design, the maximum magnetic field strength is constant so that the output emf depends on ω, the angular velocity of the rotor, and not on ω^2. This is shown in Eq. 3-4.

In summary then, some of the benefits of the current design include the lack of mechanical connections, smaller required angular frequency, and a constant maximum magnetic field strength. There will be less maintenance required since there is no need for the mechanical connections needed in dc generators. Since the generator's output emf is dependent on ω it is more efficient than generators with an output emf dependent on ω^2 at lower angular frequencies. Also, since it is not necessary for the output frequency to be 60 Hz, it is possible to have either a dc or an ac output.

Table 3. Generator speed for a Given Number of Magnetic Poles. Most generators used for wind turbines have four poles and so require a synchronous speed of 1800 RPM in order to output a frequency of 60 Hz. The generator researched and designed has twelve poles, requiring an angular frequency of 600 RPM in order to have an output frequency of 60 Hz. Table taken from Ref. [32].

No. of Poles	Synchronous Speed (RPM)	No. of Poles	Synchronous Speed (RPM)
2	3600	14	514
4	1800	16	450
6	1200	18	400
8	900	20	360
10	720	22	372
12	600	24	300

2.4 Design Problems and Solutions

In trying to improve the PMG design from Ref [23], there were many problems to solve. One problem was the cost of the permanent neodymium magnets. The magnets also had to be cut specifically to the dimensions desired, adding to their cost. Since the magnets are the most important part of the design, the cost was accepted. Because of the high cost of the magnets, it was important to reduce the cost of the rest of the generator. This was achieved by machining as many parts as possible and even using scrap pieces of steel.

Another problem was the time it took to build the generator. Eighteen coils had to be wound by hand so that each one was the correct size and shape and firmly held together. Also, acrylic sheets needed to be cut and drilled. The aluminum supports also had to be cut into the shapes desired, but these parts also needed to be drilled and tapped. Each of the channel iron pieces needed to be cut and drilled. Some of these parts were easy to construct, like the channel iron and coils. Others, mostly those that needed to be cut in a circular shape, required extra time. The main reason these parts took so long, (over 150 hrs.), is the operators inexperience with machine shop tools and equipment. The pipe for the main shaft was bought after the bearings were bought, but was not the correct size. Only 32.26 mm (0.05 in.) needed to be taken off, so it was thought that this could be done with a lathe. This process took longer than expected, mostly because of inexperience. Also, when parts needed to be welded, extra time was needed to learn this process.

In order to increase the number of magnetic poles and the number of coils in the generator, the radius of the rotor and stator had to be larger than the designs given in Ref [23]. As a result, more material was needed, which increased the weight of the generator. The weight was reduced by using channel iron instead of solid steel. The pieces of channel iron were welded together and then welded to the steel sheet. Channel iron was used instead of wood or aluminum because the steel sheet needed to be permanently fixed to the rotor since the magnets are attached to it. Welding the channel iron and steel sheets provide more strength than using other materials and screws or bolts.

Some other problems include supporting the stator, attaching the bearings to the channel iron, the size and shape of the magnets, the space taken up by an acrylic cover for the magnets, the wire leads from the coils, and the need to check and maintain the various parts. The stator needed to be supported by something besides thin sheets of acrylic. It was decided to use aluminum, but the problem was the lack of space between the stator and the rotor. To accommodate this, two pieces of aluminum were used for each side, one circular and another square in shape. The circular piece was thin enough to fit between the acrylic on the stator and the bolts used to attach the bearings to the rotor. The square pieces were then designed to fit in the space under the bolts and support most of the torque that the stator will experience (due to a back emf). The steel sheets then needed to have the center hole enlarged in order to make room for the square aluminum pieces.

At first, it was thought that the channel iron should be welded together and then sections of the channels cut out so that the bearing could lie flat on the surface of the channel iron. This would have required more time and also would have weakened the channel iron. Several options were then considered for attaching the bearings to the channel iron and then channel iron to the steel sheets. One was to weld the outer edges of the channel iron, instead of the flat side, to the steel sheets. This might have worked for a more experienced welder. Instead, the flat side of the channel iron was welded to the steel sheets. The bearings were then attached using nuts and bolts so that each one lies on the outer edges of the channel iron.

The possible sizes and shapes of the magnets were described previously in this chapter. The problem was simply using the right shape in order to create a strong magnetic field through the entire area of the coils. This would have been difficult if two circular magnets were used. The problem was solved using a trapezoid shaped magnet.

In the present design, acrylic is used to cover the magnets to prevent weathering and to keep the magnets attached to the steel sheets. In the design in Ref. [23], resin was used to hold the magnets in place. The problem with the current design is the space between the rotor and stator along this cover. As it is, the rotor will not be able to rotate. To solve this problem, a metal adhesive called *loctite* will be used to fasten the magnets to the steel sheets so that the acrylic cover is not needed. Since the magnets are coated with epoxy, there will be less weathering. The acrylic cover can then be cut so that the inner diameter is 346.71 mm (13.65 in.) instead of 182.88 mm (7.2 in.).

The most important parts of this generator are the coils of wire in the stator. In order to produce power, the ends of the wire must go from the stator to a load. It was assumed that it would be possible to send the wires through the pipe. To allow the wires to pass through the pipe, channels are milled out of the inner center acrylic supports and a hole is drilled in the pipe. It was thought that drilling a hole might weaken the pipe so a collar was designed to support the area around where the wires pass through the side of the pipe. This steel collar (basically a slightly larger pipe) is then fastened to the main shaft using *loctite*. A better solution might have been drilling several smaller holes.

In order to allow for maintenance, the stator and rotor are held together using screws and nuts. The stator uses several screws to fasten it to the pipe and to hold it together on the outer edge. Along the edges of the stator, the acrylic is drilled and then counter sunk on one side and bored on the other so that the heads of the screws and nuts will be flush with the surface of the acrylic. The bearings are attached to the channel iron using bolts while the outer edges are drilled for screws. Besides using bolts and screws which can be undone easily, pieces of acrylic need to be epoxied together so that when the screws are undone, the coils don’t fall apart. An explanation of which pieces are epoxied is given in Chapter 4.

Chapter 3

Estimated Output

3.1 Theory

In Chapter 1, an introduction was given describing how magnetic induction is used to convert mechanical power into electrical power. In this chapter, that theoretical description will be further developed as it pertains to the generator's current design.

It was shown previously that the expected emf induced in a coil of wire from a changing magnetic flux, φ is:

$$\xi = N\frac{d\varphi}{dt} \tag{3-1}$$

where ξ is the emf induced as φ changes over time, t, as the flux passes through N turns of the coil of wire.

In the current design, as the rotor rotates, the magnets pass by a single coil such that a sinusoidally varying magnetic field:

$$\vec{B} = B_{\max}\cos(2\pi ft)\hat{i} \tag{3-2}$$

passes through the coil. The magnetic field is directed along the axis of rotation, in this equation designated by the unit vector $\hat{i}$, and is of a magnitude $B_{\max}$ and frequency f. This can be seen in Figure 6, only in the design of this generator, $d\vec{A}$ is directed along the same unit vector as $\vec{B}$.

The frequency (in Hz) at which the magnets pass by the coil is:

$$f = \frac{m\omega}{120} \tag{3-3}$$

where m is the number of magnetic poles (or the number of magnet pairs) and ω is the angular frequency (in rpm) of the rotor.

Combining Eq. 3-3 , 3-2 and 1-1 yields, after differentiation, the open circuit emf:

$$\xi = \frac{\pi}{60} NAm\omega B_{\max} \sin(\frac{m\omega\pi}{60} t)\,. \tag{3-4}$$

3.2 Determining Equation Variables

In order to calculate the unloaded emf, it is necessary to determine the number of turns in the coil, the angular velocity in rpm of the rotor, the magnetic field strength between two magnets, and the area of the coils that the magnetic field passes through. As was explained earlier, each coil has 110 turns +/- 5 turns. For now, it is estimated that the average rpm of the wind turbine will be 120 rpm. The magnetic field strength was measured using a F.W. Bell Gauss/Tesla Meter (model 5070) for a series of positions with two magnets with opposite poles facing each other at a separation distance of 2.16 cm (0.85 in.). The average field strength was measured to be 0.365 Tesla at the center of the magnets.

In order to measure the area of the coil that most of the magnetic flux passes through, the dimensions, given in Figure 19, were used. The area of the shaded region was calculated to be 0.0023 cm^2 (3.6 in^2), using Autodesk Inventor software.

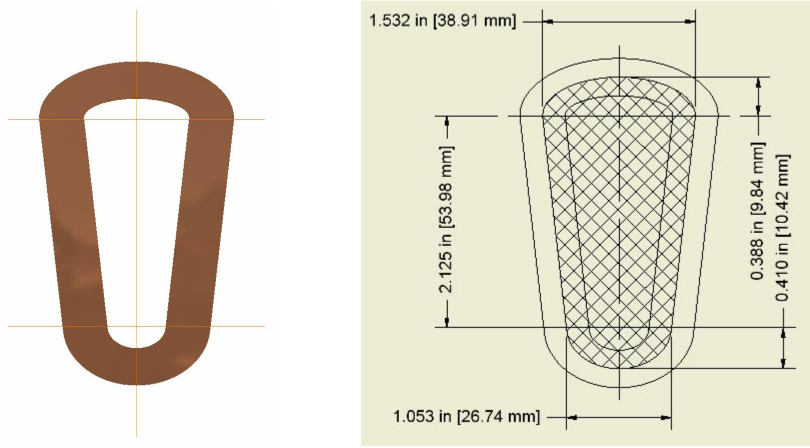


Figure 21. Coil Area. The figure on the left is a drawing of the coil and the draft on the right shows the average area. The area of this region was calculated in order to determine the output emf. The dimensions of the central trapezoid and the two ellipses on the top and bottom are given. These were used to calculate the area, which is 0.0023 cm^2.

3.3 Estimated Output

After substituting into Eq. 3-4 the values for the number of turns, area of the coils, etc., the expected emf output for a single coil is:

$$\xi = 0.580\omega\sin(60\pi t)\ \text{volts.} \tag{3-5}$$

The current design uses 18 coils divided into 3 phases. The output emf is going to depend on how each coil is connected to the other coils. If the current design is used, then there will be six coils in series in each phase. This will increase the amplitude of the output emf for a single phase by six. In Figure 19, three phases are shown for the estimated emf output for 6 coils in each phase. Each phase is 120 deg. out of phase from the other 2 phases.

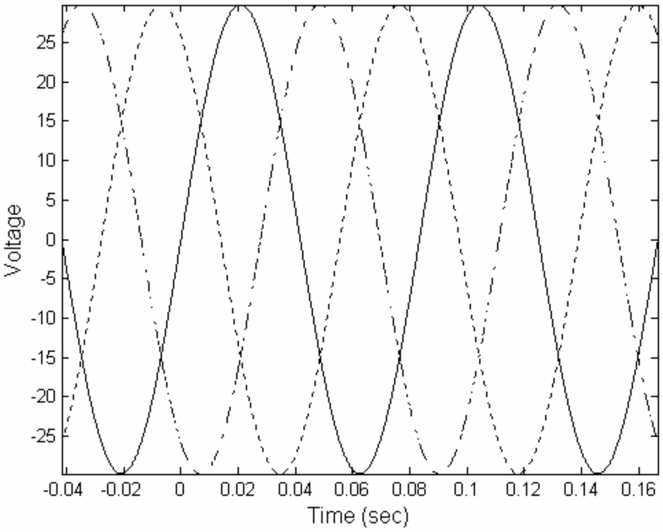


Figure 22. Expected AC Output of the Generator. The output of the generator, showing phase one (solid), phase two (dashed), and phase three (dashed-dotted), was calculated for 6 coils in series for each phase at an angular velocity of 120 rpm.

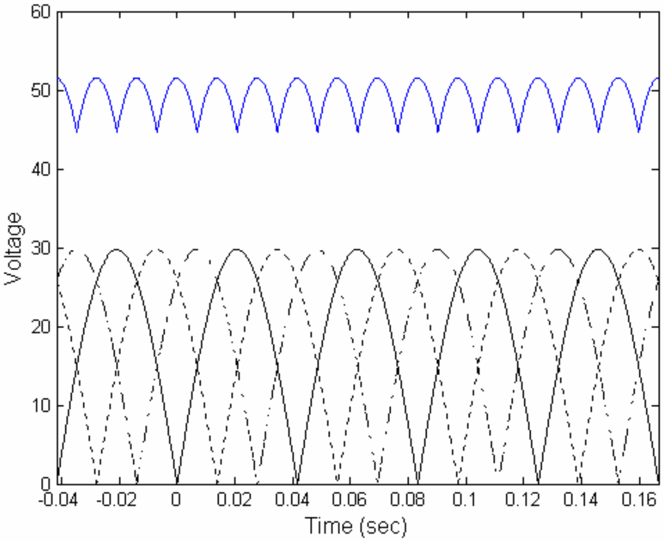


Figure 23. Expected Rectified AC Output of the Generator. The output emf for 6 coils in series for each phase(dark solid, dashed, and dashed-dotted) at an angular velocity of 120 rpm is rectified (blue) and then added to give the total DC output emf voltage.

Chapter 4

CONSTRUCTION AND ASSEMBLY

4.1 Overview

In Chapter 2, the design of the generator was explained. In this chapter, a detailed explanation will be given for the process of machining and assembly of the parts of the generator. A table of the parts to be constructed and the materials needed to construct them will be given as well.

4.2 Materials and Cost

Tables 4 and 5 list the materials needed for the different parts of the generator, e.g. the rotor and stator. In each table, the estimated amount is given. The cost shown is given for the amount of material and it should be noted that these prices are valid as of April 2004. These prices were taken from Ref. [33] and Ref. [34].

4.3 Construction

In the Appendix, mechanical drawings are given for the different parts needed to construct the generator. An explanation of the construction of each part will be given first. Then, the mistakes made and how they were corrected will be described. Finally, the process used for drilling and tapping is given. The parts needed for the rotor will be described first, then the parts for the coil former, and finally, the parts for the stator.

4.3.1 Machining

The process for machining the parts of the generator may be changed according to the machines available and the skill of the machinist. In the construction of this generator, there were several attempts to create parts because of mistakes made while constructing the parts. As a result several techniques for machining the parts were developed. The process that resulted is given in the following explanation with brief descriptions of the mistakes that were made.

Table 4. Rotor Parts and Material List. The materials needed for the construction of the different parts of the rotor are listed. The estimated cost for the amount of material needed is also given.

Quantity	Item Description	Notes	Size Needed	Cost
1	Acrylic Sheets: 48 in. x 48 in. x 0.375 in.	Cost per sheet: $120.24	48 in. x 48 in. x 0.36 in.	$ 120.00
2	Acrylic Sheets: 48 in. x 48 in. x 0.25 in.	Cost per sheet: $88.83	60 in. x 48 in. x 0.225 in.	$ 111.00
1	Channel Iron	2 in. x 1 in. with 0.2 in. thickness	13 ft. length	$ 14.00
1	Sheet Iron: 48 in. x 96 in. x 0.1 in.	Cost per sheet: $72.00	40 in. x 20 in. x 0.07 in.	$ 18.00
4	10 - 24 Screws	with nuts	2.75 in. length	$ 10.00
4	10 - 24 Screws	with nuts	3.0 in. length	
8	5/8 in. bolt	with nuts	3.0 in. length	
2	Axial Ball-Thrust Four-Bolt Flange Bearing	4 - 0.62 in. holes for attachment	1.61 in. center-hole diameter	$ 50.00
24	Permanent Magnets	Custom made neodymium (NdFeB) magnets	See Appendix	$ 500.00
3	Loctite - High Strength Adhesive	Metal Adhesive	Tube - 50 mL	$ 85.00

4.3.1.1 Machine Shop Equipment and Tools

The machines used to construct the parts of the generator include an 11 in. Logan lathe (model 920), a vertical turret Enco milling machine (model 100-1599), 14 in. vertical Wilton band saw, a Sprunger drill press (model 8201), a non-gas dual purpose Clarkeweld MIG welding machine (model WE 6524 180 EN), an 8 in. Phase II rotary table, and a drill press vice. The bits used for the milling machine include ¼ in. and ½ in. roughing bits and a ¼ in. finishing bit. The bits used for the drill press include a 5/8 in. bit, as well as metric bits: No. 29, No. 25, and No. 17. Tapping was done using No. 10-24 and No. 12-24 taps. A hybrid blade with a width of 3/4 in. was used for the band saw. For cutting aluminum, the milling machine spindle speed was 1100 rpm while the band saw speed was 3000 SFM. The same speeds were used for cutting acrylic and plywood. When steel or iron was milled or cut, the milling machine spindle speed was 850 rpm and the band saw speed was 125 SFM. The welding machine current was set to “high” with a medium feed rate when the channel iron and iron sheets were welded.

Table 5. Stator Parts and Material List. The materials needed for the construction of the different parts of the stator are listed. The estimated cost for the amount of material needed is also given. The cost of the acrylic is included in the cost of the same acrylic in Table 4.

Quantity	Item Description	Notes	Size Needed	Cost
	Acrylic Sheets: 48 in. x 48 in. x 0.25 in.	Cost per sheet: $120.24	60 in. x 48 in. x 0.225 in.	$ -
1	Aluminum: 18 in. x 18 in. x .25 in.	Cost per sheet: $52.29	13 in. x 6.5 in. x 0.211 in.	$ 35.00
1	Aluminum: 3 in. x 72 in. x 0.5 in.	Cost per sheet: $45.32	6 in. x 3 in. x 0.5 in.	$ 14.00
1	Steel Pipe	1.37 exterior diameter	12 in. length	$ 12.00
1	Pipe Collar (Steel Pipe)	1.62 in. interior diameter; 0.063 in. thick	.9 in. length	$ 5.00
8	8 - 32 Screws	Including nuts	1 in. length	$ 15.00
4	10 - 24 Screws	Including nuts	2.5 in. length	
4	12 - 24 Screws	Including nuts	1.5 in. length	
8	12 - 24 Screws	Including nuts	1.25 in. length	
1	Copper Wire	19 gauge	84 ft. length	$ 20.00
1	Electrical Tape		Roll	$ 5.00
2	Epoxy	40-minute curing time	1 oz. - 2 Tubes	$ 10.00
3	Epoxy	5-minute curing time	1 oz. - 2 Tubes	$ 10.00

4.3.1.2 Rotor Parts

The eight squared channel iron parts were cut using the band saw. The length of each was measured from the end of the channel iron, after the previous piece had been cut. The same process was used in cutting the angled channel iron. The length of the longest side of the angled channel iron was used to measure and cut these parts. The 45° edge was drawn with pencil on the flat side at each end and cut using the band saw.

The two steel sheets and the circular acrylic parts were all milled out of 508 mm x 508 mm (20 in. x 20 in.) pieces using a rotary table clamped to the horizontal table of a milling machine. In order to fasten these parts to the rotary table, four 15.875 mm (0.625 in.) holes were first drilled through each part near the center. The edge of the rotary table's spindle rotated higher than the surface of the table so that it was necessary to use several thin pieces of plywood to raise each steel sheet and each piece of acrylic up at least an inch. The pieces of plywood were cut to be circular and have the same diameter as the rotary table and the same four holes were drilled through each piece of plywood. For the steel sheets, these holes were centered at a radial distance of 73.55 mm (2.9 in.) from the center, as shown in the mechanical drawing for this part in the Appendix. For the acrylic sheets, it was not important where these holes are drilled since these parts are rings. For efficiency, though, holes were drilled at the same radial distance as the steel sheets.

To mill out a steel sheet, it was centered on the rotary table and secured. To center the sheet, first the center of the steel sheet was marked and then placed on the rotary table using four 5/8 in. nuts and bolts. The nuts were partially tightened so that it was possible to nudge the steel sheet using a hammer. After attaching a ¼ in. milling bit, the milling machine's vertical head was lowered close to the surface of the steel sheet. The table was rotated slowly to determine the center of the steel sheet remained under the bit. The steel sheet was tapped so that the center mark was in the same position relative to the milling bit as the sheet rotated. Once it was centered, the nuts were tightened completely and then the milling table was moved horizontally so that the bit was 254 mm (10 in.) from the center of the steel sheet. With the milling machine on and the bit spinning, the bit was slowly lowered while the rotary table was rotated. Once the exterior edge was cut, the milling table was moved horizontally so that the bit was 51.32 mm (2.02 in.) from the center. The center hole was milled out with the same bit in the manner just described.

Occasionally, the steel sheet would move horizontally on the rotary table, just after beginning to mill out the sheet. When this happened, the steel sheet was centered again and the bolts were tightened even more. To prevent the bending of the steel sheet around the four holes, washers were used.

To mill a thick acrylic support, the acrylic was centered using the same method described for the steel sheet. Once it was centered and fastened, the milling table was moved horizontally so that the bit was 254 mm (10 in.) from the center of the steel sheet. The bit was slowly lowered while the rotary table was rotated. Once the exterior edge was cut, the milling table was moved horizontally so that the bit was 173.36 mm (6.85 in.) from the center, in order to mill the center hole. The same process was followed for milling the thin acrylic cover, thick acrylic ring, thin acrylic ring, and the inner acrylic support. (See Stator Parts drawings in the Appendix for details.) Each of the inner acrylic supports were milled using the interior pieces of acrylic from the thick acrylic supports or the thick acrylic rings.

Magnet spacers have not been constructed. These parts will be constructed from scrap circular pieces of acrylic. Plywood could also be used. The circular scrap pieces of acrylic will be used have an outer arc that fits along the inner edge of the outer acrylic supports and inner arc that fits along the outer edge of the inner acrylic support, with straight edges matching those of the magnet spacer dimensions in the Appendix. The straight edges will be marked and then cut using the band saw.

4.3.1.3 Coil Former Parts

The coil former parts were all cut using a band saw. Since these parts are small, it was necessary to use several smaller pieces of wood to guide the pieces being cut. To cut the coil former end, its dimensions and its edges were marked on plywood that was 70.1 mm x 106.7 mm x 10.9 mm (2.76 in. x 4.2 in. x 0.43 in.) in size. Cuts were then be made along these edges. The edges did not have to be exact, since this part was only used to hold the coils while they were being made. To cut the coil former center, its dimensions were marked on plywood that was 29.2 mm x 66 mm x 10.9 mm (1.15 in. x 2.6 in. x 0.43 in.) in size. The edges were cut to be as rounded (and smooth) as possible. The shape of this part had to be exact since the coil shape depended on the shape of this part.

4.3.1.4 Stator Parts

The dimensions of the square aluminum support were first marked on a 914.4 mm x 101.6 mm x 12.7 mm (36 in. x 4 in. x 0.5 in.) piece of 6061 aluminum. Four holes were drilled so that the part could be fastened to the rotary table. These holes were drilled at a radius of 35.92 mm (1.41 in.) from the center and had a hole diameter less than 5.49 mm (0.216 in.) so that they could be tapped later. Washers were needed since the heads of the screws are small enough to slide through the clamping slots on the rotary table. The center of the aluminum was marked and centered on the rotary table. Once this was done and the nuts were tightened, the milling table was moved horizontally so that the bit was 20.57 mm (0.81 in.) from the center of the square aluminum so that the center hole could be milled. The edges were then cut using the band saw.

The milling machine could have been used, instead of the band saw, to cut the edges of the square aluminum supports. As a result of operator inexperience, the edges of the square supports were not smooth nor perpendicular to each other. This could have been avoided if the entire piece had been cut using the milling machine.

One circular aluminum support was milled from 165.1 mm x 165.1 mm x 5.36 mm (6.5 in. x 6.5 in. x 0.211 in.) aluminum using a rotary table clamped to the horizontal table of a milling machine. In order to fasten this part to the rotary table, four holes were first drilled through each part near the center. These holes were 57.15 mm (2.25 in.) from the center and 15.875 mm (0.625 in.) in diameter so that 5/8 in. bolts could be used to fasten the aluminum to the rotary table. The center of the aluminum was marked and centered on the rotary table. Once this was done and the nuts were tightened, the milling table was moved horizontally so that the bit was 79.375 mm (3.125 in.) from the center of the aluminum. The bit was slowly lowered while rotating the rotary table. After the outer edge was cut, the milling table was moved horizontally so that the bit was 20.574 mm (0.81 in) from the center mark and the center hole milled.

Instead of drilling four 15.875 mm (0.625 in.) holes at a radius of 57.15 mm (2.25 in.), holes could have been drilled at a radius of 53.87 mm (2.12 in.) from the center with a diameter of less than 4.17 mm (0.164 in.) so that they could have been tapped later.

Originally, the design for the stator required three sheets of 400 mm x 400 mm (15.75 in. x 15.75 in.) acrylic with two sheets 5.72 mm (0.225 in.) thick and one 9.14 mm (0.36 in.) thick. The outer edge and the center of these sheets were milled according to the dimensions of the acrylic covers and rings in the Appendix. To increase the distance from the front cover to the back cover where the coils will be placed, a groove 3.175 mm (0.125 in.) deep from 175 mm (6.89 in.) to 90 mm (3.544 in.) from the center was milled in each of the covers. To provide space for the wires connecting the coils, acrylic was milled from both covers from the center to 90 mm (3.544 in.) from the center 3.175 mm (0.125 in.) deep, except where the four holes were drilled (since these were used to hold the stator together). The third sheet of acrylic was used to construct the center ring and support. The ring was milled according to the dimensions in the Appendix. The support was constructed from the remaining acrylic. The outer edge was milled at 90 mm (3.544 in.) from the center and then the center hole was milled at 20.57 mm (0.81 in.) from the center.

The design of the acrylic stator parts has changed so that the present design for the stator requires four sheets of 400 mm x 400 mm x 5.72 mm (15.75 in. x 15.75 in. x 0.225 in.) acrylic to make the eight acrylic parts of the stator. These parts should be constructed by first drilling four holes in each of these four sheets. These holes should be drilled at a radius of 53.87 mm (2.121 in.) from the center and have a hole diameter of less than 4.17 mm (0.164 in.) so that they could be tapped later. These holes are needed later to hold the stator together. The front acrylic cover should be centered and then the milling table moved horizontally so that the bit is 200 mm (7.875 in.) from the center of the acrylic. Next, the milling table should be moved horizontally so that the bit is 22.17 mm (0.873) in from the center mark. This process should be repeated for the back acrylic cover.

To mill out the center acrylic pieces in the present design, a 400 mm x 400 mm x 5.72 mm (15.75 in. x 15.75 in. x 0.225 in.) sheet of acrylic should be placed on the rotary table (after drilling four holes in the same location as the front and back covers). After centering, the milling table should be moved horizontally so that the bit is 200 mm (7.875 in.) from the center of the acrylic. Next, the bit should be moved to 175 mm (6.89 in.) from the center mark. Once this edge is cut, the outer rings are finished. The bit should then be moved to 90 mm (3.544 in.) from the center mark to cut out the inner supports. The bit should be moved to 22.17 mm (0.873 in.) from the center in order to mill center hole. Once the center is cut out, the bit should be moved to the edge of the center hole and lowered to 1.9 mm (0.075 in.) below the surface. Two channels should be milled from the center hole to the outer edge following the pattern shown on the drawings for the Inner Center Acrylic (sheets 10 and 11 of the Stator Parts drawings in the Appendix). This process should be repeated for the second outer center ring and second inner center support.

The pipe used as the main shaft for the generator was 609.6 mm (2 ft.) in length and had a 42.3 mm (1.665 in.) outer diameter that needed to be lathed so that the rotor bearings could slide onto the pipe. The pipe was lathed down to 41 mm +/- .127 mm (1.615 in. +/- 0.005 in.) for a length of 304.8 mm (12 in.) from one end of the pipe. A 0.3 in. hole was drilled 6 in. from the end of the pipe where it had been lathed.

The original design did not include a pipe collar. To construct the collar shown in the stator drawings in the Appendix, a pipe with an outer diameter of 44.45 mm (1.75 in.) and an inner diameter of 41.15 mm (1.62 in.) is needed. The pipe can then be cut so that it has a length of 22.86 mm (0.9 in.).

The coils were made using the lathe, the coil former, electrical tape, and epoxy. Since epoxy does not adhere to electrical tape, it was wrapped around the edge of the center part of the coil former and on the inside faces of the outer coil former parts. When the coils were finished and the epoxy had hardened, the electrical tape made it possible to take the coils out of the coil former.

To wrap the coils, the coil former was placed on the lathe so that it rotated freely. With a flat edge of the center part facing up, 19 gauge copper wire was placed along the left corner of this flat edge so that there was about 304.8 mm (12 in.) of wire extending from the coil former. This end was wrapped up so that it was out of the way. The coil former was then rotated so that the other end of the wire began to wrap around the coil former, with each turn wrapping towards the right. Each turn of wire was tightly placed next to the previous turn so that there were 11 turns per layer. Once there were eleven turns on the first layer, *5-minute* epoxy was put on the top and bottom curved edges and on each of the flat edges. Next, the second layer was wrapped tightly from right to left. After two or three more layers had been added, epoxy was placed on the flat edges. A total of 10 layers were wound and epoxy was placed on the ninth and tenth layer. The coil was left so that the epoxy could harden. Electrical tape was used to hold the edges together by wrapping the tape around the curved edges and around the straight edges. Once there were 110 turns, the wire was cut so that there was approximately 304.8 mm (12 in.) of wire extending from the coil. This process was repeated for all 18 coils.

4.3.2 Drilling and Tapping

The methods and tools used to drill holes in each of the parts are described in this section. It is important to note that it was possible to incorrectly align holes between the different pieces, so precision and care were needed. To avoid this problem, some parts were epoxied together before drilling. This process of epoxying will be described in Section 4.4.

4.3.2.1 Rotor Parts

The parts on the rotor that were drilled are the straight channel iron pieces, the circular steel sheets, and all of the acrylic sheets except the inner acrylic support. Some of the holes that needed to be drilled were drilled while preparing to mill the circular pieces.

Holes were drilled in the straight channel iron part at each end. These holes were drilled using the drill press after each part had been cut out. The holes were drilled with a 5/8 in. drill bit at one end and a No. 25 drill bit at the other, according to the specifications given in the Appendix for this part.

These holes in the straight channel iron could have been drilled after the channel iron parts had been welded together and welded to the circular steel sheet. Once the welding was done, these welded parts could have been clamped down to the table of the drill press (or milling machine, depending on the size of the drill press), and a 16 mm (0.63 in.) hole should be drilled an 25.4 mm (1 in.) from the sides and 22.1 mm (0.87 in.) from the end closest to the center of the circular steel sheet. These holes should be drilled in the same location on the straight channel iron part as the four holes drilled in the circular steel sheet.

The rotor is held together using eight No. 10-24 screws. The holes for these screws were drilled along the outer edge, 16.5 mm (0.65 in.) from the outside edge of each of the acrylic parts and the steel sheets and 23.4 mm (0.92 in.) from the end of the straight channel iron parts. It was possible to drill these holes in each of the parts one part at a time, but to ensure that the holes were correctly aligned, all of the parts were clamped together and the holes drilled through all of them at the same time. To do this, a No. 25 drill bit of 190 mm (7.5 in.) in length was needed.

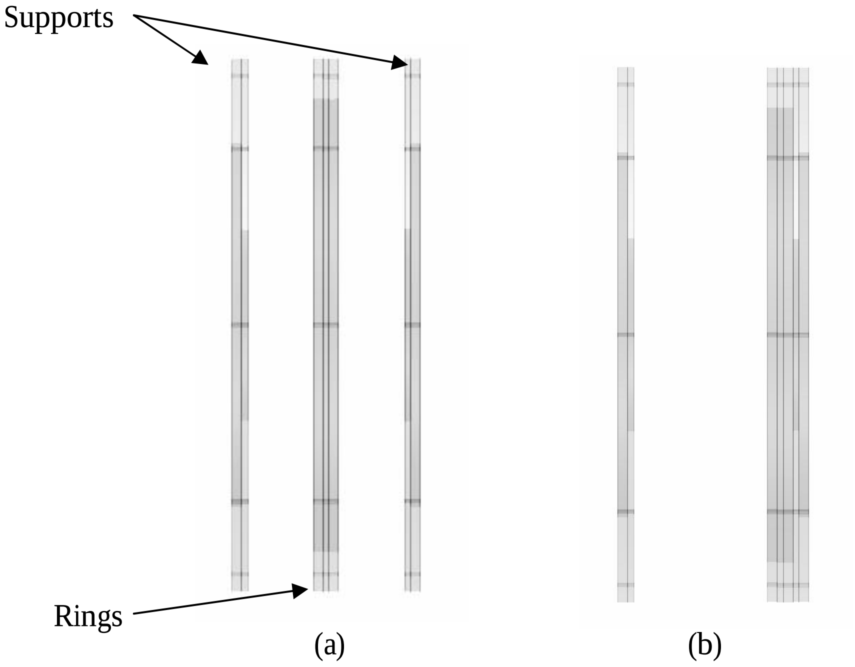


Figure 24. Epoxying Acrylic Parts of the Rotor. First, the thick acrylic support was epoxied to the thin acrylic support, for each end of the rotor. At the same time, one thick acrylic ring was epoxied to the thin acrylic ring. As soon as these set, the second thick acrylic ring was epoxied to the other rings. Finally, these rings were epoxied to one of the epoxied supports (b).

4.3.2.2 Coil Former Parts

The location of the holes for the screws used to hold the coil former together was not important. It was more important that the coil former be held together tightly while providing an easy method for taking it apart. The present design is the result of several attempts at making sure that the outer parts didn’t move. It was also important that the holes for one part match those of the other parts and that the edges of the center part be along the cut-out edges of the out parts. The holes in the center part were drilled first. Two 5.1 mm (0.2 in.) holes and one 10.16 mm (0.4 in.) hole were drilled according to the designs given in the Appendix. Once these holes were drilled, the center part was clamped to one of the outer parts and the holes in the center part were used to guide the drilling of the holes in the outer part. Next, the third part was added so that all three were clamped together, again, using the previous holes to guide the drilling of the holes in the third part.

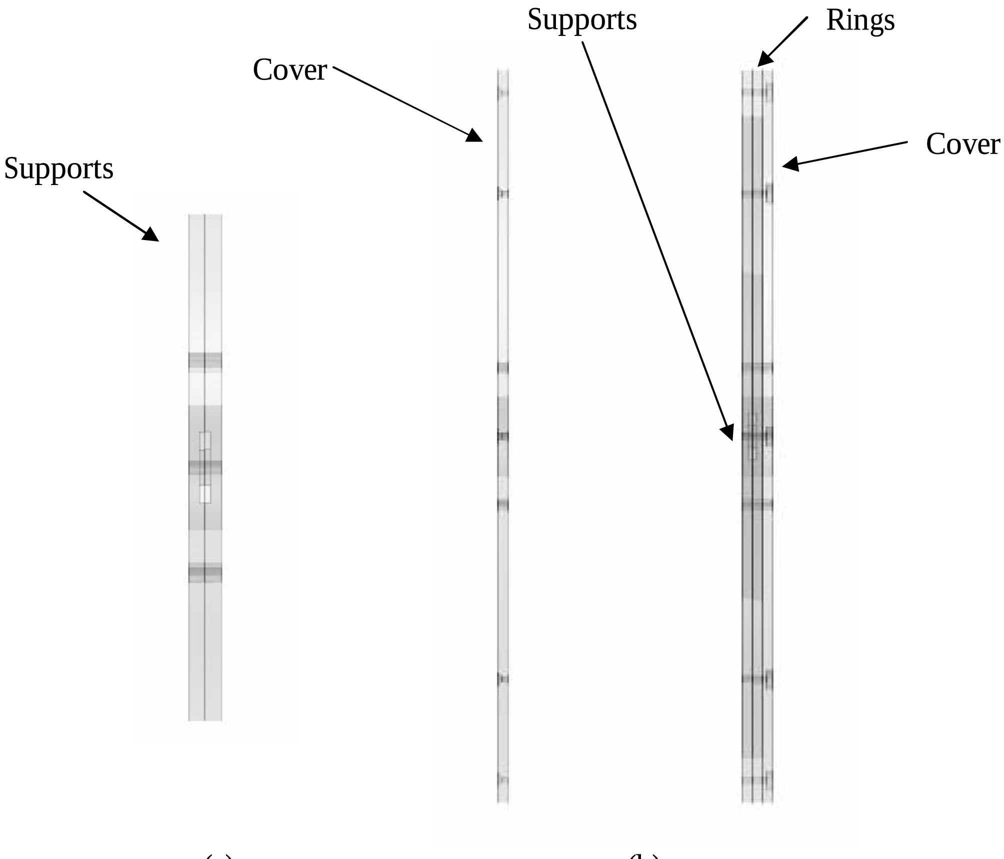
4.3.2.3 Stator Parts

All of the parts of the stator required drilling and the aluminum parts required tapping as well. A hole was drilled on each edge of the square aluminum support, as shown in the drawings for this part, in addition to the four holes drilled when preparing to mill the center hole. All of the holes of the square aluminum support and the circular aluminum support were tapped. The size of the tap was considered when drilling these holes. For holes that needed to be tapped for a No. 10-24 screw, a 3.81 mm (0.15 in.) hole was drilled using a No. 25 bit so that a No. 10-24 tap could be used. For holes that needed to be tapped for a No. 12-24 screw, a 4.38 mm (0.17 in.) hole was drilled using a No. 17 bit so that a No. 12-24 tap could be used.

Before the holes near the center of the front and back acrylic covers were drilled (except for the four needed to fasten the acrylic sheets to the rotary table), the outer holes were drilled. To do this, eight holes were marked and then each was drilled using a No. 29 drill bit. These holes were counter sunk on the front acrylic cover and counter bored on the back cover. One problem that resulted was cracking. Epoxy was used to seal these cracks.

It would have also been possible to clamp the front and back covers together and drill eight holes using a No. 29 drill bit at the locations described in the drawings in the appendix. Using the milling machine, each of these eight holes could have been counter sunk on the front acrylic cover and counter bored the back acrylic cover, according the specifications given on the drawing for this part in the Appendix.

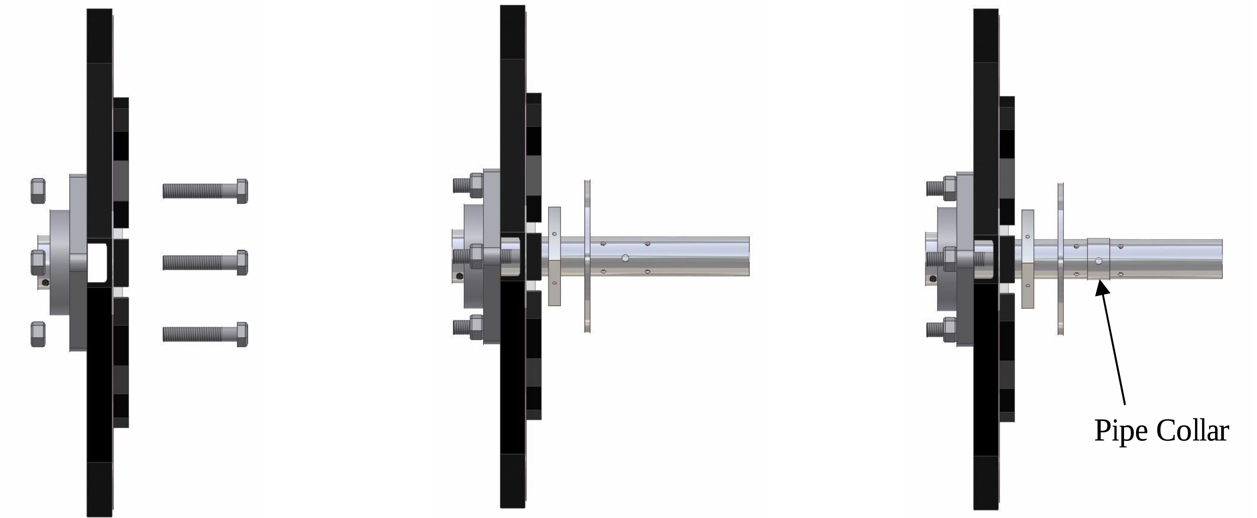
The center acrylic ring was drilled by clamping it to the front acrylic cover. Each of the eight holes drilled in the front acrylic cover were used to guide the drilling of the holes in the acrylic ring. As a result, the holes in the covers and ring must match exactly in order to put the stator together. The front and back acrylic covers and the inner center acrylic support were drilled in the same location as the circular aluminum supports, as shown in the drawings in the appendix. The covers were clamped together and then the front cover was clamped to the center support in order to drill these holes.



(a) (b)

Figure 25. Epoxying Acrylic Parts of the Stator. First, the inner acrylic supports should be epoxied together (a) so that the milled channels make holes for the wire leads of the coils. At the same time, the outer acrylic rings should be epoxied together. Then, both of these, the inner supports and outer rings should be epoxied to the back cover (b).

With the present design, the outer center rings should be epoxied together and then epoxied to the back cover, once the outer holes of the acrylic covers have been drilled, bored, and sunk. Using the holes previously drilled in the back cover, these eight holes should be drilled through the outer center rings.



(a) (b) (c)

Figure 26. Assembled Parts of the Rotor and Stator on the Pipe. One end of the rotor should be assembled (a) and then placed onto the pipe (b). Then the square and circular aluminum supports of the stator should be placed on the pipe (b). Then the pipe collar (c) should be fastened to the pipe using *loctite*.

For the present design given in the Appendix, these interior holes should be drilled by epoxying the two inner center acrylic supports together and then epoxying these parts to the back acrylic cover, as described in Section 4.4. Once this is done, the location of the holes that needed to be drilled should be marked. Also, the location of the holes that needed to be drilled on the front acrylic cover should be marked so that these marks matched the circular aluminum holes and the marks on the epoxied acrylic parts. Then, using eight No. 8-32 screws and nuts, the front cover should be fastened to the epoxied parts. After clamping the circular aluminum onto the acrylic so that the holes in the aluminum matched the marks on the acrylic, the holes in the stator should be drilled using a No. 17 drill bit drill bit by clamping the stator to the table of the drill press or milling machine.

Both the pipe and pipe collar have not been drilled, in order for the wires from the coils to be fed through the pipe. Each of these parts will be clamped to the milling machine table or drill press table using a drill press vise. The hole will be drilled at least 304.8 mm (12 in.) from one end of the pipe and

11.43 mm (0.45 in.) from either side of the pipe collar. It will be 7.62 mm (0.3 in.) in diameter for each of these parts.

4.4 Assembly

Once the parts are machined, the assembly of the generator will be possible. Some of the parts have been assembled together for ease of repair and maintenance, the generator as a whole has not been completely assembled. Diagrams will be given to show exactly which parts will be bolted together and, in the case where several smaller parts were permanently fixed together, an explanation will be given for the process used. Also, any other machining that needs to be done once these parts were together will be described. The final assembly that has not been done will also be explained.

4.4.1 Welding

The channel iron parts were welded together in a pattern shown in Figure 18. Two straight channel iron parts and an angled channel iron part were first welded by clamping two straight channel iron parts to a thick metal plate. They were placed at right angles by clamping one and then using a square to place the second straight part. These straight channel iron parts need to be 57.15 mm (2.25 in.) from the center of the rotor shaft (which was 57.15 mm (2.25 in.) from the corner of the square used to align the parts). The angled channel iron was then clamped 81.79 mm (3.22 in.) from the inside corner of each straight channel iron part. Then, the edges along the inside of the channels were welded. Once the inside edges had been welded, the three parts were turned over and the outer edges of the channel iron parts were welded. This process was done for the other two straight channel iron parts and an angled channel iron part. To weld the other angled parts to these two parts, the two welded parts were aligned using a square so that the edges of each of the straight channel iron parts were at 90° and 57.15 mm (2.25 in.) from the end of the square. After clamping these two parts, each angled channel iron was clamped in the same position as before and welded along the inside edges and then the outside edges. This same process was followed for the second side of the rotor.

These welded channel iron ends were then welded to the iron sheets. This was done by bolting the iron sheet to the welded channel iron using the four holes drilled near the center of the iron sheet.

Once these were bolted, the edges of the iron sheet were clamped to the channel iron along the outside edge and the channel iron parts were welded to the steel sheet along the edges. This same process for welding was followed for the second side of the rotor.

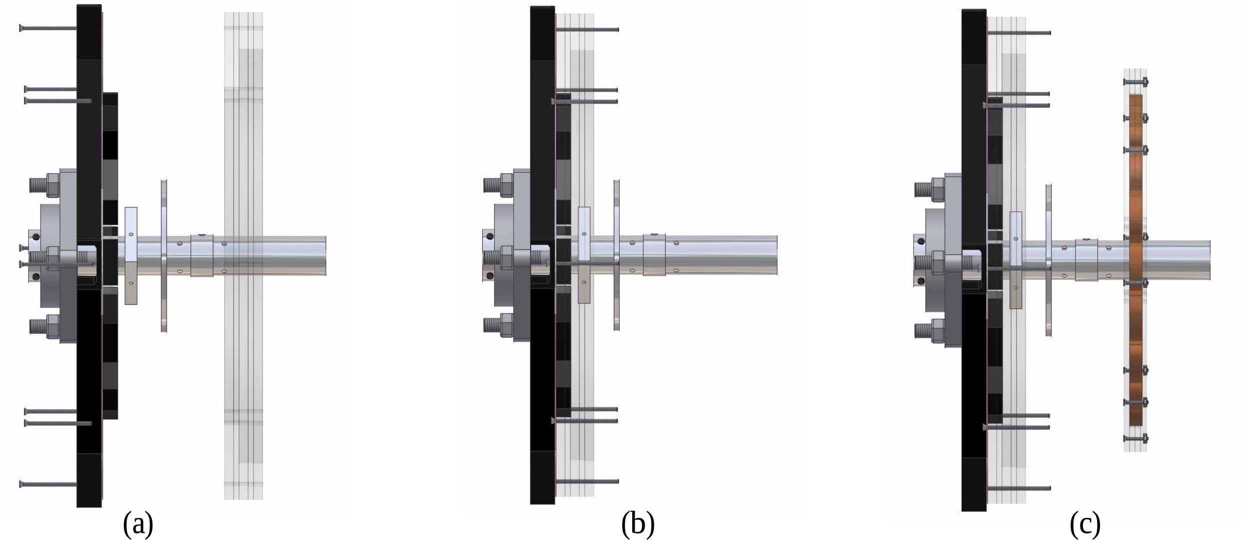

(a) (b) (c)

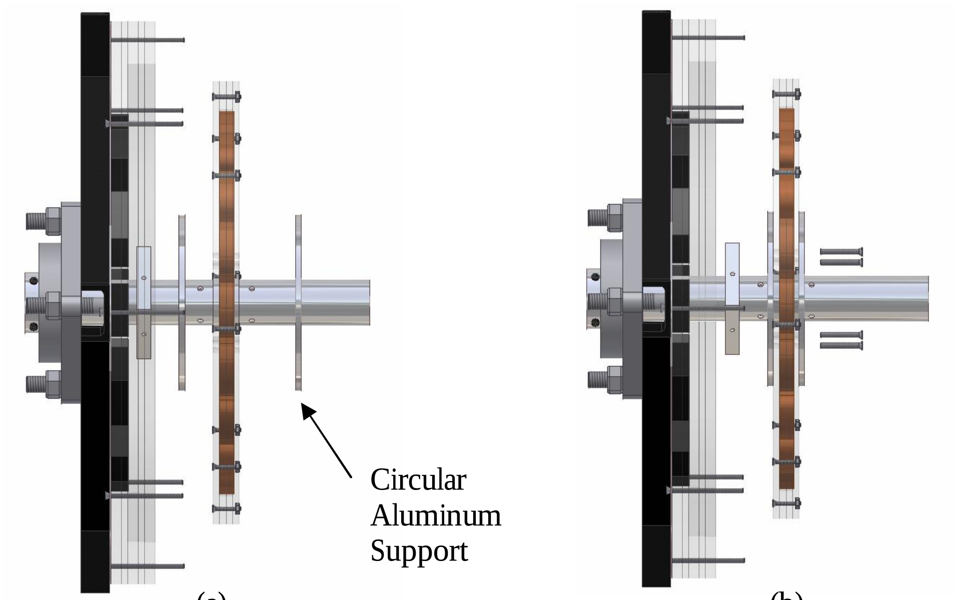
Figure 27. Assembled Rotor and Stator Parts on the Pipe. Using No.10-24 screws, the epoxied acrylic supports and rings should be placed on the rotor end already on the pipe (a,b). Next, the stator, comprised of the acrylic covers, supports, and rings, and coils held together with No. 8-32 screws, should be placed onto the pipe, over the collar (c).

When the steel channel iron was being welded to the steel sheet, the sheet began to warp from the heat. To fix the problem, extra clamps were added and later the sheet was flattened as much as possible using a hammer. Once the steel had cooled, additional welding was done to firmly secure the sheet to the channel iron.

4.4.2 Epoxy

Several parts needed to be epoxied together to make it easier to put parts together and take them apart. The parts of the rotor that were epoxied are the acrylic supports and the acrylic rings. Since time was needed to place the epoxy on one side of the acrylic part and then align and clamp another acrylic part to it, *40-minute* epoxy was used rather than *5-minute* epoxy. For the present design given in the

Appendix, the acrylic center supports and outer rings of the stator should be epoxied to the back acrylic cover.



(a) (b)

Figure 28. Assembled the Circular Stator Supports. Using No. 12-24 screws, the circular aluminum supports should be fastened to the acrylic stator.

The thick and thin acrylic supports for one side of the rotor were epoxied together first using clamps to hold the two parts together. While this was setting, the thin acrylic ring was epoxied to a thick acrylic ring. Then the thick and thin acrylic supports from the second side were epoxied. Once these set, the second thick acrylic ring was epoxied to the second side of the thin acrylic ring. After this had set, the acrylic rings were epoxied to one of the epoxied supports. The parts epoxied together are shown in Figure 24.

The epoxing of the parts of the stator could have been done in conjunction with the drilling of the holes. First, the outer acrylic rings could have been epoxied to each other. The inner acrylic supports could also have been epoxied, but in such a way that the faces with the milled channels are together.

Once the outer eight holes had been drilled and counter bored and sunk in the front and back covers, the epoxied acrylic rings could have been epoxied to the back cover. As was previously mentioned, after the outer acrylic rings were epoxied to the back cover, the outer eight holes could have been drilled. The inner acrylic supports could then have been epoxied to the back cover so that the holes near the center of the stator could be drilled. Each of the interior and exterior edges of each of the parts that are epoxied should be aligned.

4.4.3 Metal Adhesive

In order to fasten the magnets to the iron sheets, *loctite,* a metal adhesive will be used. The magnets have not been placed on the steel sheets. To do this, the epoxied acrylic support will be fastened to one of the iron sheets (which has been welded to the channel iron) using screws. *Loctite* will be placed on the iron sheet directly above one of the boltholes, covering the area of one magnet. A magnet was then placed on the steel sheet were the loctite was. After placing a spacer to the right of this first magnet, loctite will be placed on the iron sheet to the right of the spacer covering the area of a magnet. A second magnet will be then placed to the right of the spacer, with a pole opposite that of the first magnet facing up. This process will be continued around the iron sheet so that the magnets have a pattern shown in figure 20. This process will also be repeated for the second side of the rotor, with the same starting point, but with the pole facing up of the first magnet on the second rotor part opposite the pole of the first magnet on the first part.

The original design does not include a pipe collar, but for the present design given in the Appendix, the pipe collar should be fastened to the pipe using *loctite*. The hole drilled in the pipe collar should be aligned with the hole drilled in the pipe and then *loctite* should be placed along the edges. Before the collar is placed on the pipe, one of the bearings, one of the circular aluminum supports, and one of the square aluminum should be placed on the pipe, since they will not be able to slide over the pipe collar. These parts did not have to be set in place until the generator is ready to be completely assembled.

4.4.4 Screws and Bolts

Screws and bolts will be used to hold the parts of the rotor and stator together. Before anything is put together, the coils will be placed in a circular pattern in the stator and the leads of each of the coils soldered so that every third coil is connected in series. This is described further in Chapter 5. The resulting six leads will be sent through the channels in the inner acrylic supports and then the front cover will be fastened to the back cover using No. 8-32 screws and nuts.

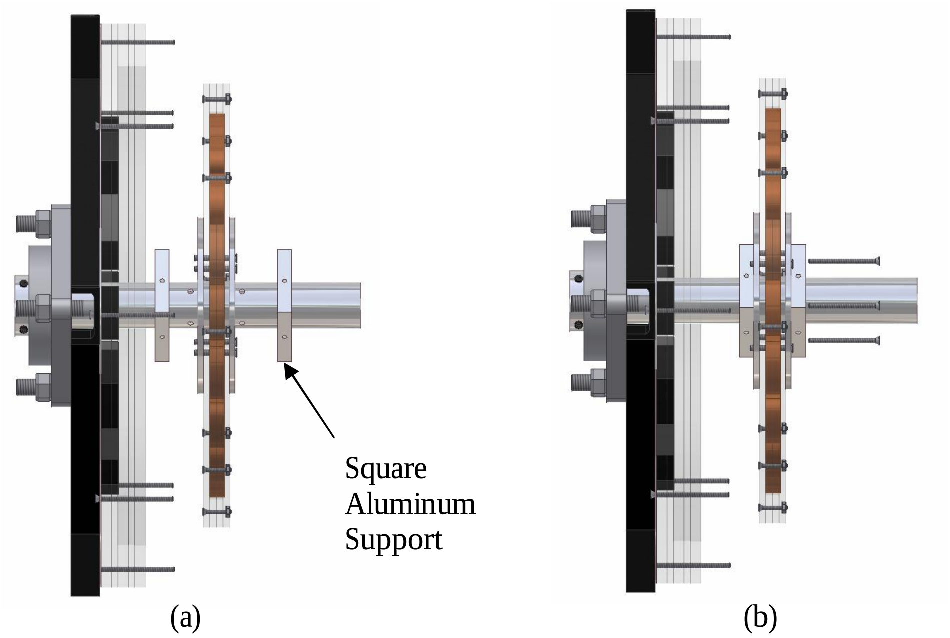
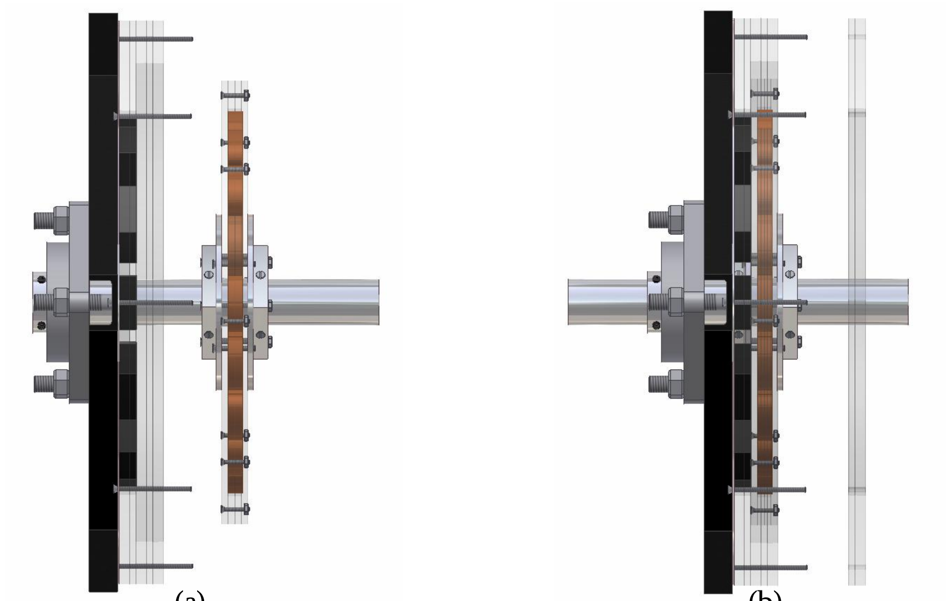


Figure 29. Assembled Square Stator Supports. The square aluminum supports should be fastened to the stator using No. 10-24 screws.

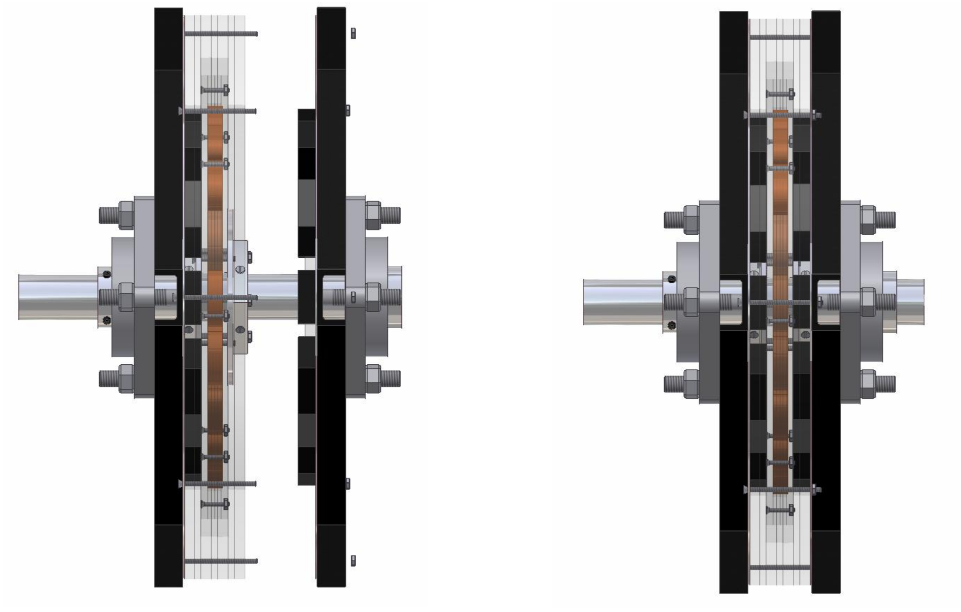
For the original design, one rotor end will be placed on the pipe, followed by the stator. The wire leads will be sent through the hole in the pipe and then No. 12-24 screws will be used to fasten the square aluminum to the pipe. Next, the second rotor end will be placed on the pipe. The rotor ends will be aligned so that the magnetic poles from one rotor end to the other are from North to South, not South to South or North to North. After the ends are aligned, No. 10-24 screws will be used to fasten the two ends together, while leaving room between the stator and rotor. Finally, the rotor will be fastened using set screws on the bearings.



(a) (b)

Figure 30. Fastened Stator and Rotor End. Once the stator is fastened to the pipe using No. 12-24 screws (a), the rotor end should be set in place using setscrews in the bearings. The rotor end should be positioned so that there is less than 2.54 mm (0.1 in.) between the acrylic supports on the rotor and the acrylic cover of the stator. Once this is done, the acrylic supports for the second rotor end should be placed on the rotor (b).

In order to assemble the generator parts given in the Appendix, one welded rotor end (with magnets already in place) should be placed onto the bearing already on the pipe using 5/8 in. bolts, as shown in Figure 26. Next, the epoxied acrylic rings and supports should be placed onto the iron sheet using No. 10-24 screws placed into each of the eight outer holes of the welded rotor end, shown in Figure 27. After sending the six wire leads through the hole in the pipe, four No. 8-32 screws should be used to screw together the other circular aluminum support, the acrylic stator, and the circular aluminum support already on the pipe, shown in Figure 28. Next, the four No. 10-24 screws should be screwed through the other square aluminum support, the other circular aluminum support, the corresponding holes in the acrylic stator, the circular aluminum support already on the pipe, and the square aluminum support already on the pipe, shown in Figure 29. Each of these parts should be fastened so that there are no gaps between any of them. Next, using No. 12-24 screws, the stator should be fastened by screwing the square aluminum to the pipe, as shown in Figure 30a, with the stator oriented so that the wire leads go directly through the hole in the pipe without being bent. (It may be necessary to drill holes in the pipe for these screws before fastening the stator to the pipe).



(a) (b)

Figure 31. Assembled Generator. The second rotor end should then be placed on the pipe and fastened using setscrews in the bearing. Once the magnets are aligned so that the magnetic poles from one rotor end to the other are North to South, the rotor ends should be fastened using No. 8-32 screws and nuts (a). Once the generator is completely assembled (b), the rotor should be rotated in order to check for scraping of rotor parts against stator parts. If there is scraping, then the rotor should be moved along the pipe so that the rotor is free to rotate.

Once the stator is fastened, the rest of the generator should be assembled on the pipe. The bearing already on the pipe should be fastened to the pipe using the setscrew so that the gap between the magnets and the stator is less than 2.54 mm (0.1 in.). Next, the other bearing should be bolted to the second rotor end with 5/8 in. bolts, as shown in Figure 26a. The second epoxied acrylic supports should be placed around the magnets or on the rotor end already on the pipe, shown in Figure 30b. Next, the second rotor end should be placed on the pipe so that the space between the magnets and the stator is less than 2.54 mm (0.1 in.). After aligning the magnets, the No. 10-24 screws should be sent through the welded rotor end and the second bearing should be fastened as shown in Figure 31. The nuts should be tightened onto the 10-24 screws on the rotor. The rotor should be able to rotate so that there are no scraping surfaces. If there are, then the rotor bearings should be moved slightly along the pipe (and then fastened) until none of the surfaces between the rotor and stator scrape.

Chapter 5

POSSIBLE ELECTRONIC CONFIGURATIONS

5.1 Overview

The electrical power produced by a generator can be harnessed in two possible ways: battery storage or immediate use. Batteries allow the electrical power to be stored until it is later needed. On the other hand, if electrical power was needed immediately, it is possible to connect a generator directly to a load or to the power grid. The intention of this project is to provide several methods for utilizing the power output of the generator. First, the output will be converted from variable frequency ac to dc using converter. This dc will then be available for battery storage and later use, or it can be inverted to a 60 Hz ac and then supplied to the power grid or to a load. It has not yet been decided whether battery storage or grid connection will be the method used to exploit the power produced. In this chapter, the possibilities will be introduced and briefly explained.

5.2 Stator Coil Wiring

In Figures 32, 33, and 34, the possible wire connections of one coil to another are shown. It has been explained that in order to achieve a changing magnetic field, adjacent magnet faces must have opposite poles. For this reason, if there were one coil for every magnet, the coils could be wired in a single phase, as shown in Figure 32. If there were two coils for every magnet then it would be possible to have two phases, as shown in Figure 33. In the current design, there are two magnets for every three coils so that the coils can be wired in three phases, as shown in Figure 34, with each phase 120 deg. from the previous. Since the pole faces of adjacent magnets are opposite in polarity, the magnitude and direction of the magnetic field at every third coil is the same. Therefore, it is necessary to wire every third coil in series as shown in Figure 34.

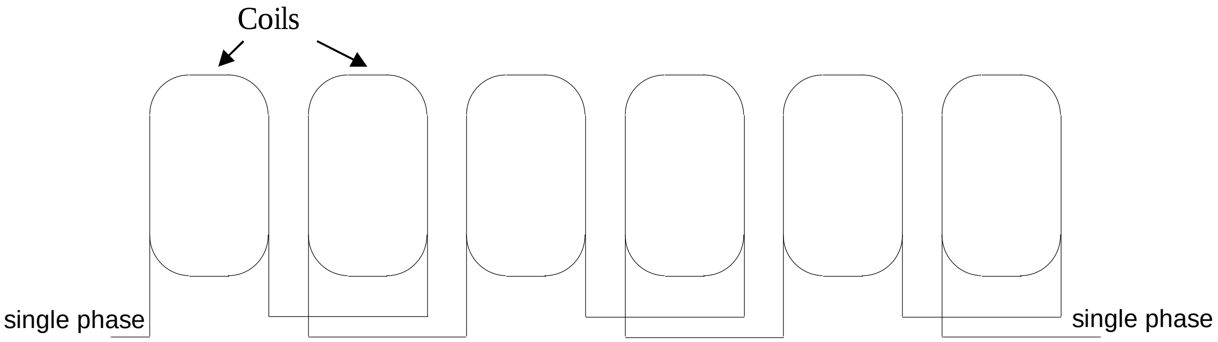


Figure 32. Phase Connection for Coils in Series. If there is a magnet for every coil, then all of the coils could be wired in series. Since the poles of adjacent magnets are opposite, the coils need to be wired so that the end of one lead of a coil is connected the beginning lead of an adjacent coil.

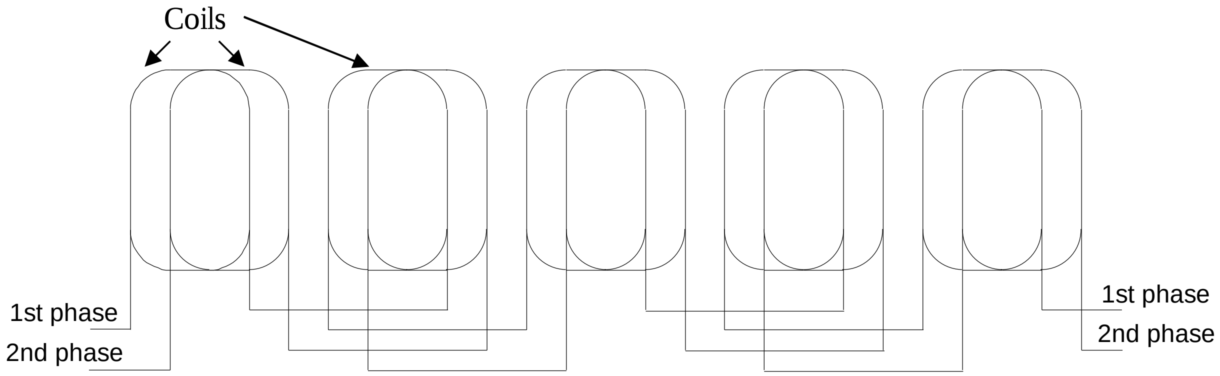


Figure 33. Two Phase Connections for Coils in Series. If there are two coils for every magnet, then every other coil could be wired in series, similar to the single phase wiring in Figure 32.

Once the coils are connected into three phases, it is possible to connect the leads of each of those phases into two configurations: wye or delta. The wye configuration, shown in Figure 34 has only four leads: one is neutral and the difference between neutral and each one of the other three leads is the voltage and current of a single phase. The voltage between any two wire leads is the vector sum of their phase voltages. Since each phase is 120 deg out of phase with another, the voltage between any two leads is 1.73 times the phase voltage, assuming each phase has the same voltage.

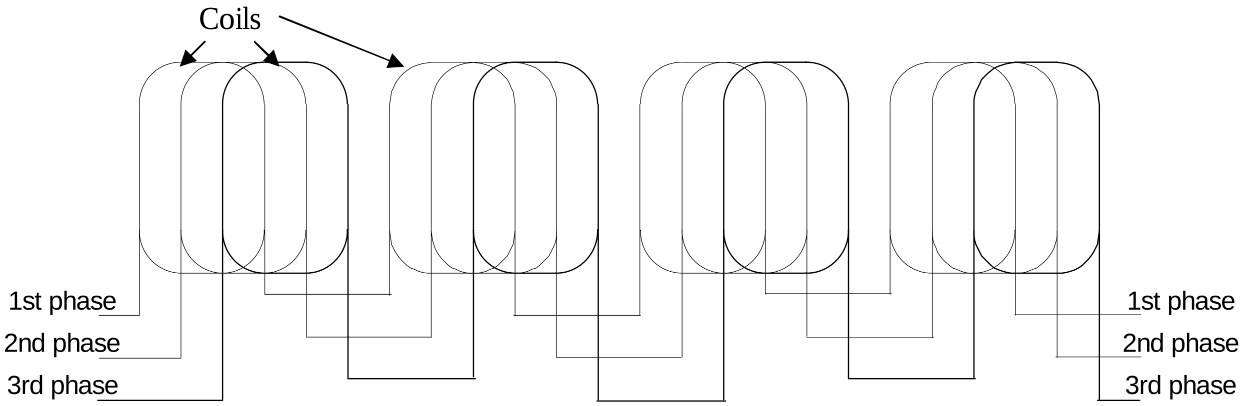


Figure 34. Three Phase Connections for Coils in Series. Six Coils in series comprise each phase of the generator. Each phase is 120° out of phase from the other phases. This is possible because of the 3 coils to two magnets.

The delta configuration, shown in Figure 36 has each lead of each phase connected to the lead of another phase resulting in three wire leads for the output voltage and current. The voltage of a single phase is the difference between two leads while the current through one lead is the vector sum of two-phase currents. Again, since each phase is 120 deg out of phase with another, the current through a single lead is 1.73 times the phase current, assuming each phase has the same current.

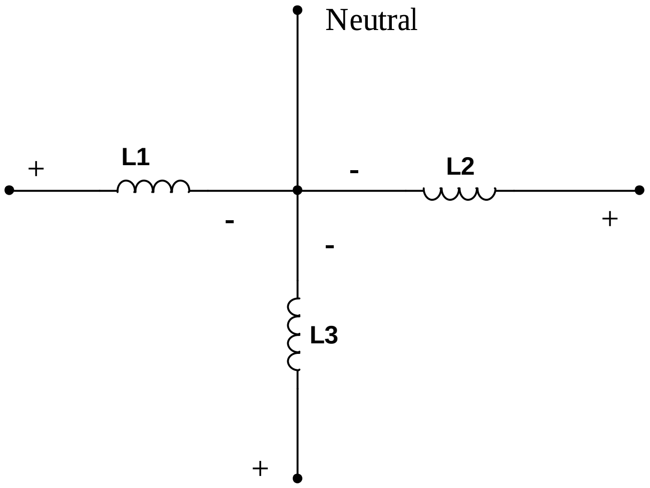


Figure 35. Wye Configuration. One possible wiring configuration of the coils after they have been connected into three phases (L1, L2, L3).

5.3 Power Storage Circuits and Devices

In order to store the electrical power produced by the generator, an electric circuit must be used to convert the alternating current and voltage with its variable frequency to direct current, then batteries can be used as storage devices.

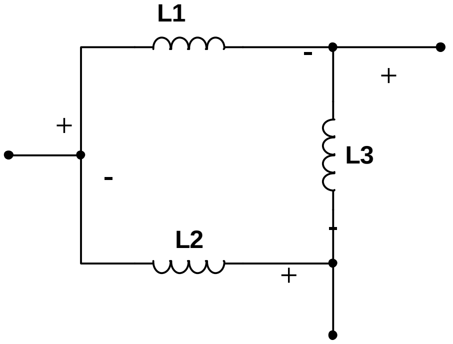


Figure 36. Delta Configuration. Another possible wiring configuration after the coils have been connected in series into three phases (L1, L2, L3).

5.3.1 *Converting Ac - Dc*

Recitifiers are devices used to convert ac into dc. A diode bridge circuit is utilized in the simplest type of rectifiers [35]. This circuit can be seen in Figure 37. The input is three-phase ac and the output is dc. The output of the recitifier circuit is shown in Figure 23 of Chapter 3. The voltage difference between the positive lead and negative lead is fairly constant although it may be necessary to use inductors and capacitors to remove some of the fluctuations. Notice that if the frequency of the output voltage increases, the more constant the dc voltage will be.

5.3.2 *Storage Devices*

Once the ac voltage has been converted to dc, it is possible to store the energy in a battery. Storing energy in batteries has proven to be useful because of their convenience and cost [36]. There are several different types of batteries used for power storage including lead acid, nickel cadmium, and alkaline batteries. Batteries are designed and constructed for different uses, typically for automotive, marine, or deep cycle use. They are constructed in three major ways: flooded (wet), gelled, or AGM (Absorbed Glass Mat).

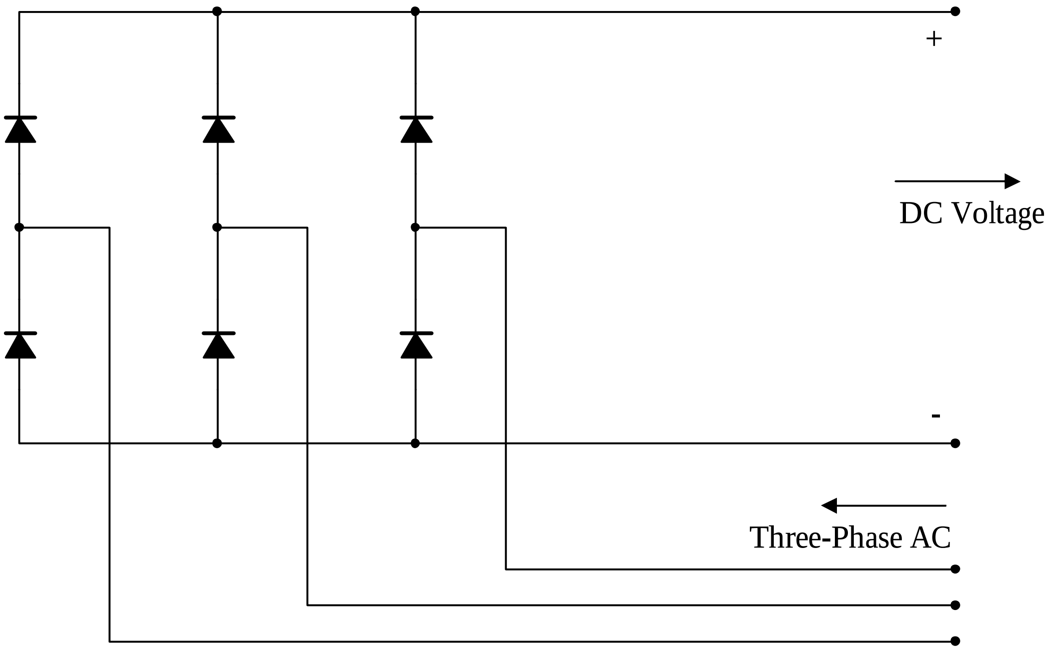


Figure 37. Diode Bridge Rectifier. A three-phase alternating current power supply is rectified to direct current using diodes.

For this project, a battery is needed that can withstand several deep discharges and charges and a wide range of temperatures. The battery needs to have a low self-discharge rate, require a minimal amount of maintenance, and have a long lifespan (can continue to be fully recharged after several charges and discharges). According to Ref [37], deep cycle AGM batteries have these characteristics as well as an amp-hour capacity of 225 AH (the measured amount of current a battery holds while it is discharged down to 10.5 volts for 20 hours, assuming a 12 volt battery is used). The cost of this type of battery, however, is usually two to three times that of flooded batteries of the same capacity.

When charging batteries it is important that they are not overcharged. Overcharging can cause a battery to loose its ability to hold a charge sooner than if they were correctly charged. Circuits can be used to control the charging of batteries to avoid this problem.

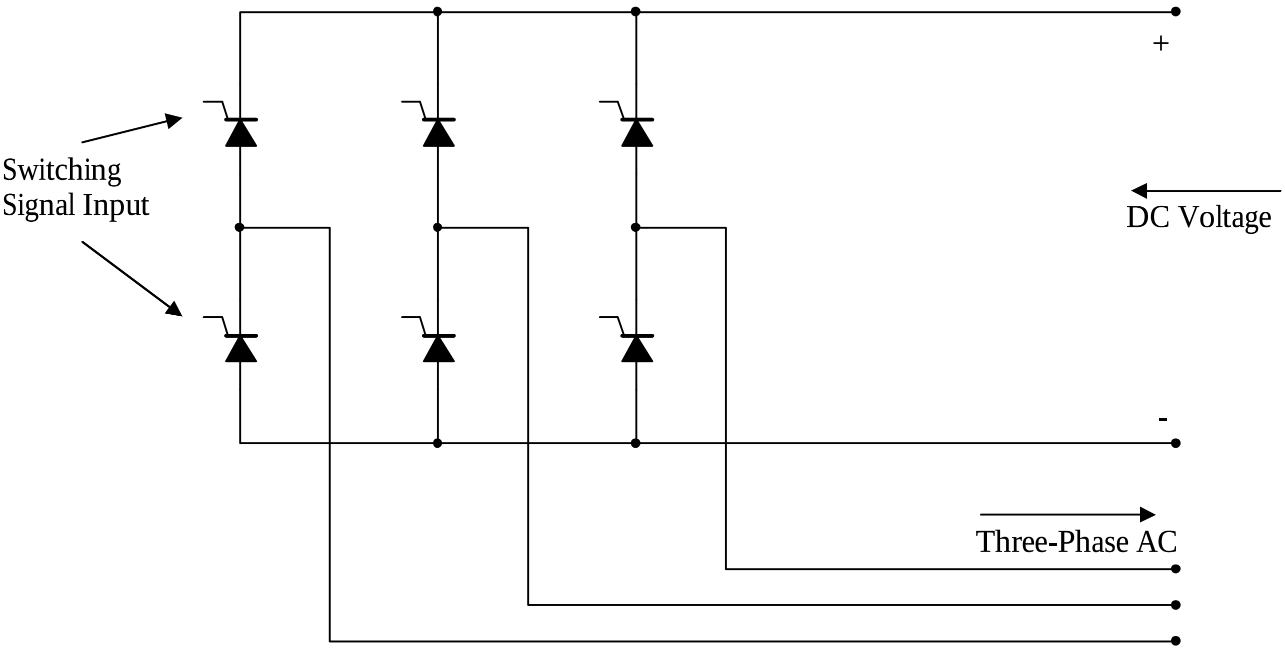


Figure 38. Line Commutated Silicon-Controlled Rectifier (SCR) Inverter. Inverters can be used to change dc voltage to ac with a frequency and phase equivalent to a source connected through the switching signal inputs.

5.4 Connecting to a Grid

In order to connect to the power grid, the electrical output of the generator must have the same frequency as that of the power grid. It can be assumed that the output frequency of the current generator will not be consistent or even match the frequency or phase of the power grid, unless control circuits are used (which are described in the next section). Inverters are, therefore, needed to change the dc, which has been converted from variable frequency ac, back to ac at a specific frequency. To connect to the power grid in the United States, the frequency needs to be 60 Hz. Besides having the same frequency, the phases of the ac from the generator and the ac of the power grid must correspond exactly and the voltage levels must be the same. In order to accomplish this, transformers and line-commutated inverters should be used. In Figure 38, the line commutated silicon-controlled rectifiers can be connected to the power grid to receive a switching signal with the frequency and phase of the power grid.

5.5 Power Output Control

As previously mentioned, the power output can be controlled using electronic circuits, which have not been designed. These electronic circuits can be designed to control the electromotive force, which can control the blade rotation. A back emf is created whenever a voltage is induced on a coil of wire. This back emf is the result of current induced in the coils, which induces a magnetic field that opposes the primary magnetic field. When the ac output is rectified to dc for battery storage, it isn’t necessary to have a constant frequency. However, to increase efficiency and reduce sudden changes in frequency, the torque on the rotor should be controlled to keep the turbines from changing the speed of rotation suddenly. Control can be achieved by controlling the load which then controls the back emf and opposing magnetic field.

Power electronic converters connected to the grid can also be used to control a generator’s output. When a generator is connected to the grid through a power electronic converter, the converter determines the frequency, phase and voltage of the current flowing from the generator [38]. In the current design, since the output current and voltage are rectified and then inverted using a grid connection, the influence of the grid on the generator is not the same as directly connecting the grid and generator through a power electronic converter.

Chapter 6

Conclusions

6.1 Future Construction

Currently, the parts for the first prototype generator are being built. The tapping of the aluminum supports and drilling of outer holes of the rotor parts are currently being finished so that all that is left is the assembly of the rotor and stator with bolts and screws. The coils have been connected into three phases with 6 coils in series in each phase. The magnets still need to be placed on the steel sheets and fastened using *loctite*.

In the near future, an apparatus will need to be designed and constructed so that the generator can be bench-tested to determine its operating characteristics, such as the electrical power output for different mechanical power inputs, i.e. various torques and angular velocities. In future research, wind turbines will be designed and constructed. The method for mounting these turbines to the generator has not yet been designed.

6.2 Future Testing

Once the generator is completed, a series of tests will be performed in order to determine the best way to wire the coils, in a wye or delta configuration, as well as determine the generator's optimal output characteristics, ie. when it is most efficient and a maximum voltage and current for specific loads. One method for testing the generator that has been proposed is to use a variable speed motor and measure the current and voltage output of the generator as the motor turns the rotor.

Future research should be done to perform tests to determine the synchronous impedance of the generator as well as the generator's actual power output for different angular velocities, the 'cut-in' speed, and the rated wind speed at which the generator has reached its full output [39]. The synchronous impedance is the combined effect of the resistance and inductive reactance of the coils. The synchronous impedance can be used to calculate the change in voltage from no-load to full-load and the generator's efficiency [40]. The data from these can then be used to design wind turbines that will allow the rotor to rotate at a desired angular velocity for different wind speeds.

6.3 Conclusions

The design for the present generator has been changed frequently, and with more research, it will continue to be changed and improved. One change that was made was the designing of the pipe collar to support the pipe where the stator coil wires enter through the pipe. It might not be necessary since several small holes will work as well. Another change was made in the design of the acrylic used for the stator. Two thin sheets of acrylic rings and supports replace the single, thick acrylic ring and support. This change was made in order to strengthen the stator. The original plan involved milling away an area for the coils in both covers. With the present design, this is not needed since the two thin sheets provide enough area for the coils in the stator. The drawback, however, is that the coils are not as close to the magnets as in the original design. This was overcome by using *loctite* to fasten the magnets to the steel sheet so that the magnets don't need to be covered, as originally planned. In conclusion, the testing of the generator will determine if these solutions and others previously mentioned were needed. It is expected that more changes will be made.

Appendix

MECHANICAL DRAWINGS

The following pages show the mechanical drawings for each part needed to construct the generator. Besides drawings for the parts of the rotor and stator are drawings for the coil former and the assembly of the generator. Also, the materials needed for each part are given in tables in the generator drawings. Drawings for assembling the generator are given first, followed by the Rotor Parts drawings, Stator Parts drawings, and finally, the Coil Former Parts drawings.

Permanent Magnet Generator
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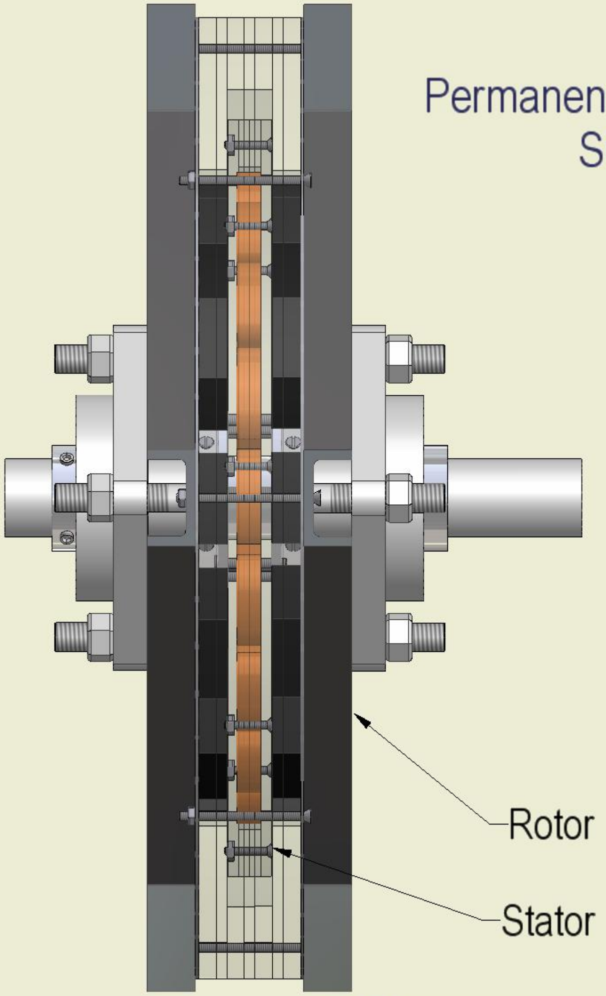

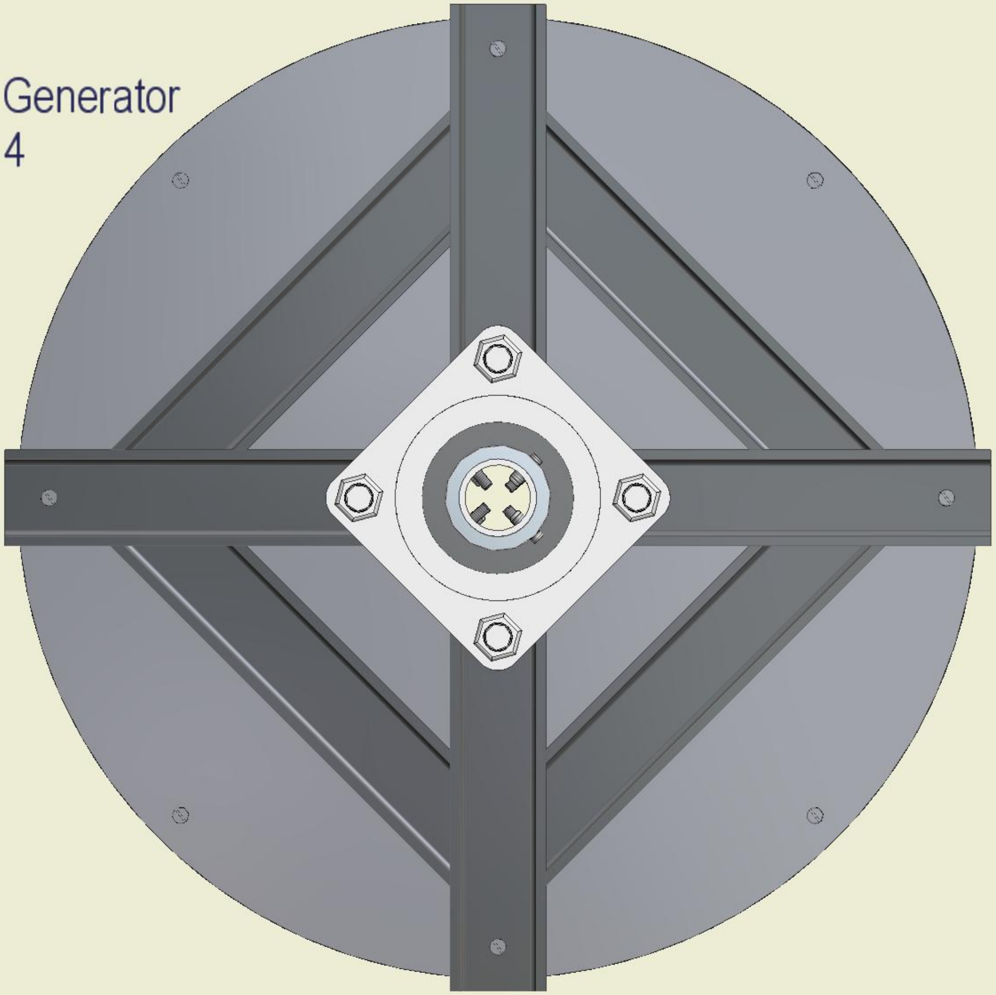

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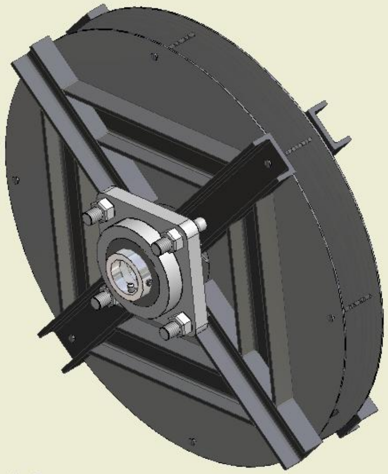

Rotor
SCALE 1 / 8

Parts List			
ITEM	QTY	PART NUMBER	SHEET NUMBER
1	4	No.10-24x_in	
2	4	No.10-24x_in	
3	8	No.10-24_Nut	
4	8	5-8 in.bolt	
5	8	5/8 in. Nut	
6	2	Bearing Component 1	Rotor Parts: 2,3
7	2	Bearing Component 2	Rotor Parts: 2,3
8	2	Bearing Component 3	Rotor Parts: 2,3
9	2	DIN 711 - 514 07 Bearing	Rotor Parts: 2,3
10	4	Set Screw	Rotor Parts: 2,3
11	8	Straight Channel Iron	Rotor Parts: 4
12	8	Angled Channel Iron	Rotor Parts: 5
13	2	Steel Sheet	Rotor Parts: 6
14	2	Thick Acryllic Support	Rotor Parts: 7
15	2	Thin Acryllic Support	Rotor Parts: 8
16	2	Thick Acryllic Ring	Rotor Parts: 9
17	1	Thin Acryllic Ring	Rotor Parts: 10
18	24	Permanent Magnet	Rotor Parts: 11
19	2	Inner Acryllic Support	Rotor Parts: 12

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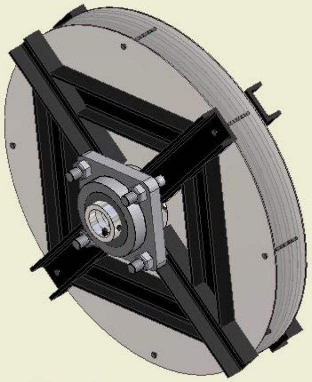
Parts List			
ITEM	PART NUMBER	DESCRIPTION	MATERIAL
1	No.10-24x_in	No. 10-24 screw with 2.75 in. length	Stainless Steel, 440C
2	No.10-24x_in	No. 10-24 screw with 3.0 in. length	Stainless Steel, 440C
3	No.10-24_Nut	No. 10 nut	Stainless Steel, 440C
4	5-8 in.bolt	3.0 in. length	Stainless Steel, 440C
5	5/8 in. Nut	5/8 in. bolt nut	Stainless Steel, 440C
6	Bearing Component 1	Bearing component	Steel, Mild
7	Bearing Component 2	Bearing component	Steel, Mild
8	Bearing Component 3	Bearing Component	Stainless Steel, 440C
9	DIN 711 - 514 07 Bearing	Axial ball-thrust 4-bolt flange bearing	Default
10	Set Screw	Bearing set screw	Stainless Steel, 440C
11	Straight Channel Iron	Main support; rotor component	Steel, High Strength Low Alloy
12	Angled Channel Iron	Angle-cut cross support; rotor component	Steel, High Strength Low Alloy
13	Steel Sheet	Rotor component; magnets attached to	Steel, Mild
14	Thick Acryllic Support	Rotor component; outer magnet holder	ABS Plastic
15	Thin Acryllic Support	Rotor component; possible magnet cover	ABS Plastic
16	Thick Acryllic Ring	Rotor component	ABS Plastic
17	Thin Acryllic Ring	Rotor component	ABS Plastic
18	Permanent Magnet	Neodymium (NdFeB) magnet	Default
19	Inner Acryllic Support	Thick 7.56 in. diameter acryllic	ABS Plastic



Rotor
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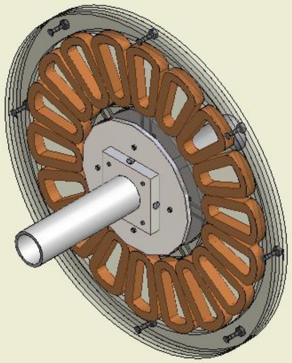

Stator
SCALE 1 / 8

Parts List			
ITEM	QTY	PART NUMBER	SHEET NUMBER
1	8	No.8-32x_in	
2	8	No.8-32_Nut	
3	4	No.10-24x_in	
4	8	No.12-24x_in	
5	4	No.12-24x_in	
6	1	Pipe	
7	2	Square Aluminum Support	Stator Parts: 2
8	2	Circular Aluminum Support	Stator Parts: 3
9	1	Front Acrylic Cover	Stator Parts: 4,5
10	2	Center Acrylic Ring	Stator Parts: 6
11	2	Center Acrylic Support	Stator Parts: 7,8
12	1	Back Acrylic Cover	Stator Parts: 9,10
13	1	Pipe Collar	Stator Parts: 11
14	18	Coil	Coil Former Parts: 6

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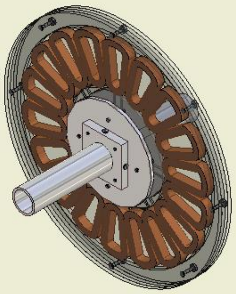
Parts List

ITEM	PART NUMBER	DESCRIPTION	MATERIAL
1	No.8-32x_in	No. 8-32 screw with 1 in. length	Stainless Steel, 440C
2	No.8-32_Nut	No. 8 nut	Stainless Steel, 440C
3	No.10-24x_in	No. 10-24 screw with 2.5 in. length	Stainless Steel, 440C
4	No.12-24x_in	No. 12-24 screw with 1.25 in. length	Stainless Steel, 440C
5	No.12-24x_in	No. 12-24 screw with 1.5 in. length	Stainless Steel, 440C
6	Pipe	Outer Diameter of 1.62 in. with holes for stator supports	Stainless Steel, 440C
7	Square Aluminum Support	Stator support piece	Aluminum-6061
8	Circular Aluminum Support	Stator support piece	Aluminum-6061
9	Front Acrylic Cover	Acryllic stator component	ABS Plastic
10	Center Acrylic Ring	Acryllic stator component	ABS Plastic
11	Center Acrylic Support	Acryllic stator component	ABS Plastic
12	Back Acrylic Cover	Acryllic stator component	ABS Plastic
13	Pipe Collar	Stator component for sending wires through pipe	Steel, Mild
14	Coil	110 turns of 19 - gauge copper wire	Copper



Stator
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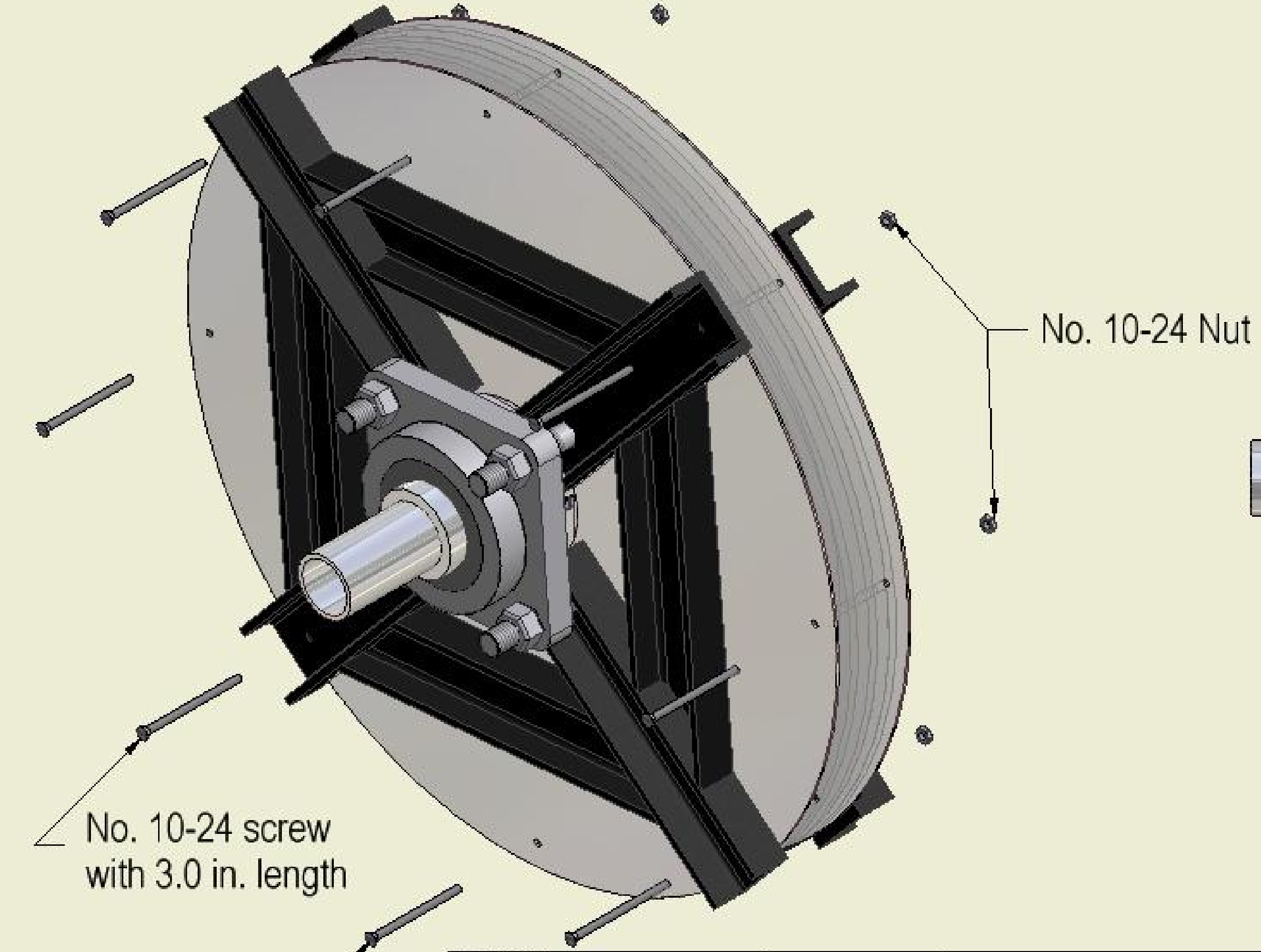

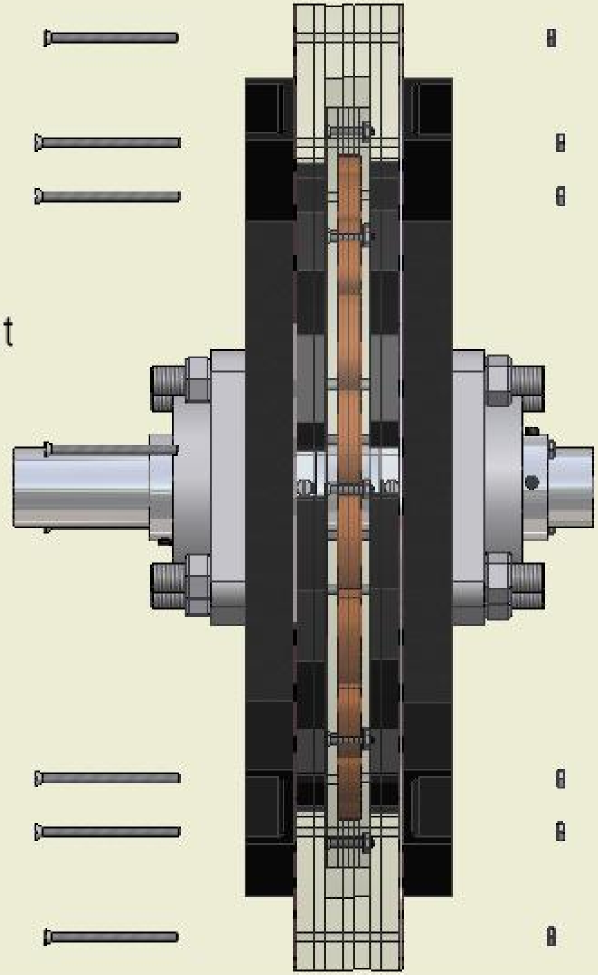

Generator Assembly

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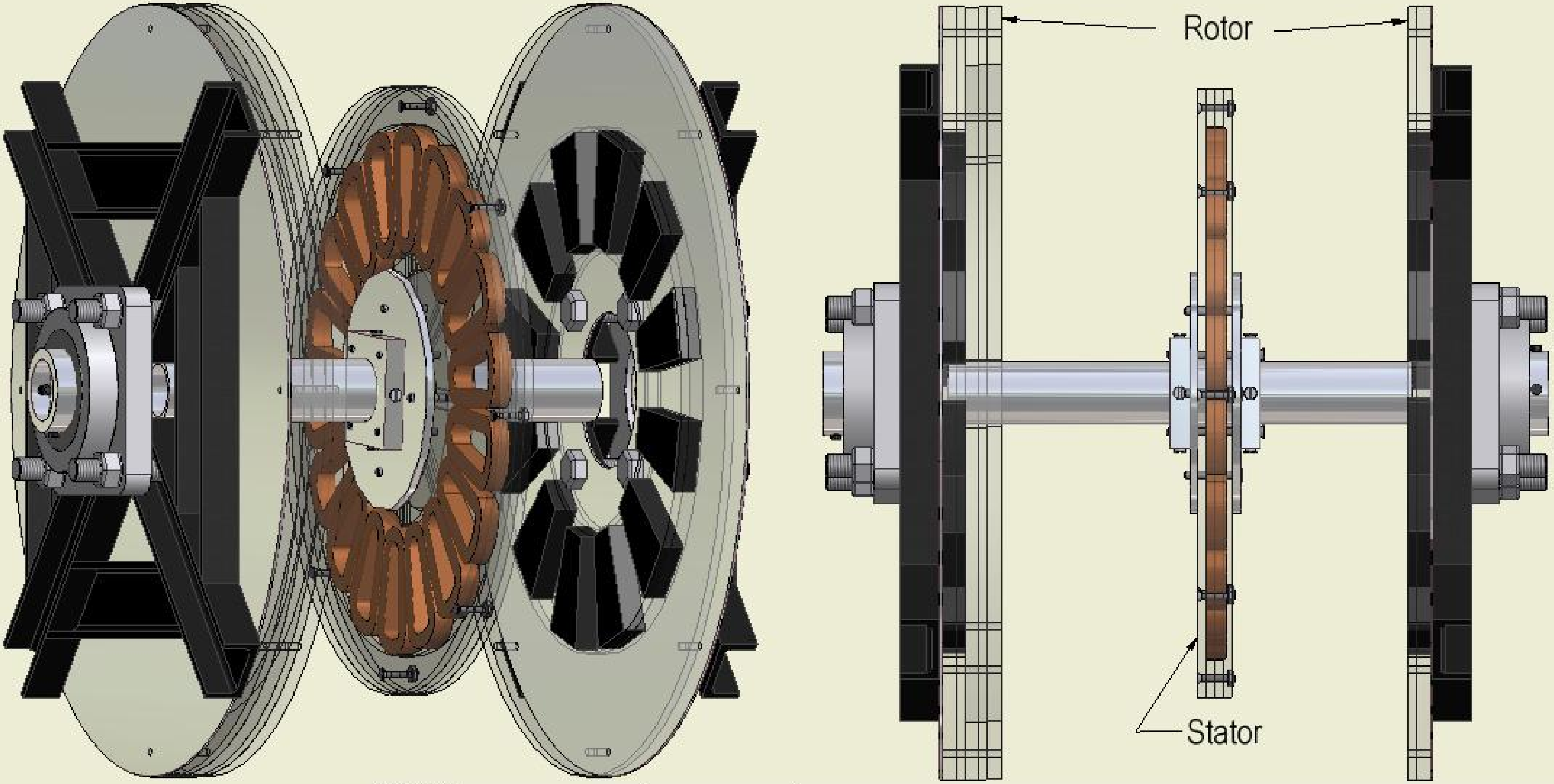

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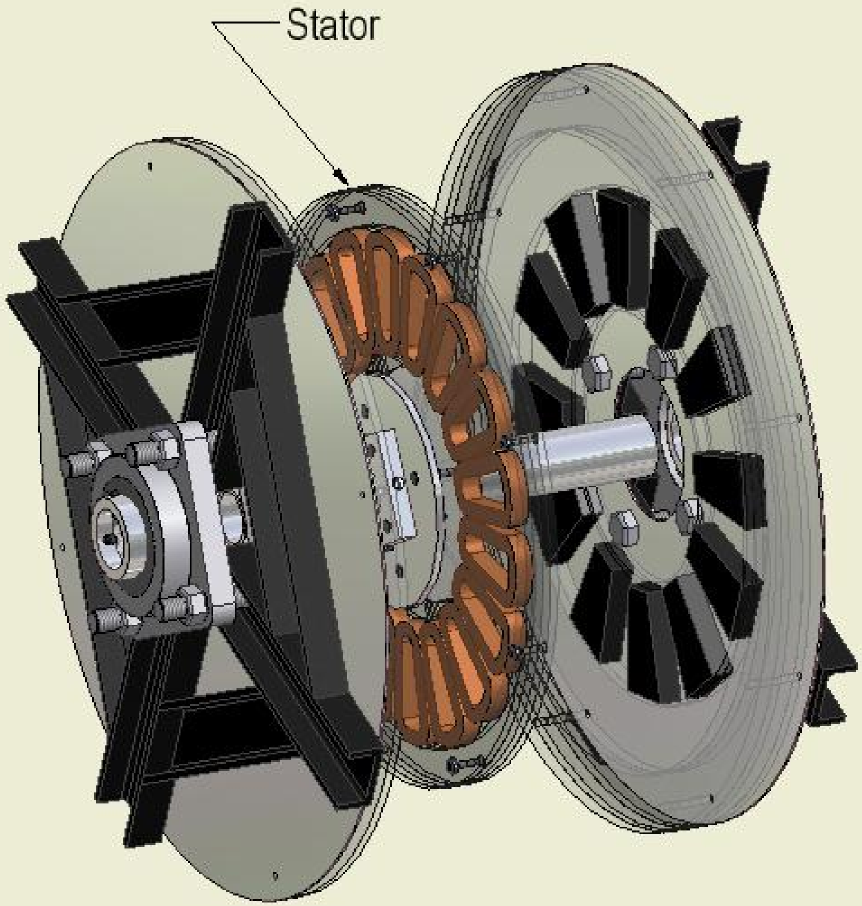

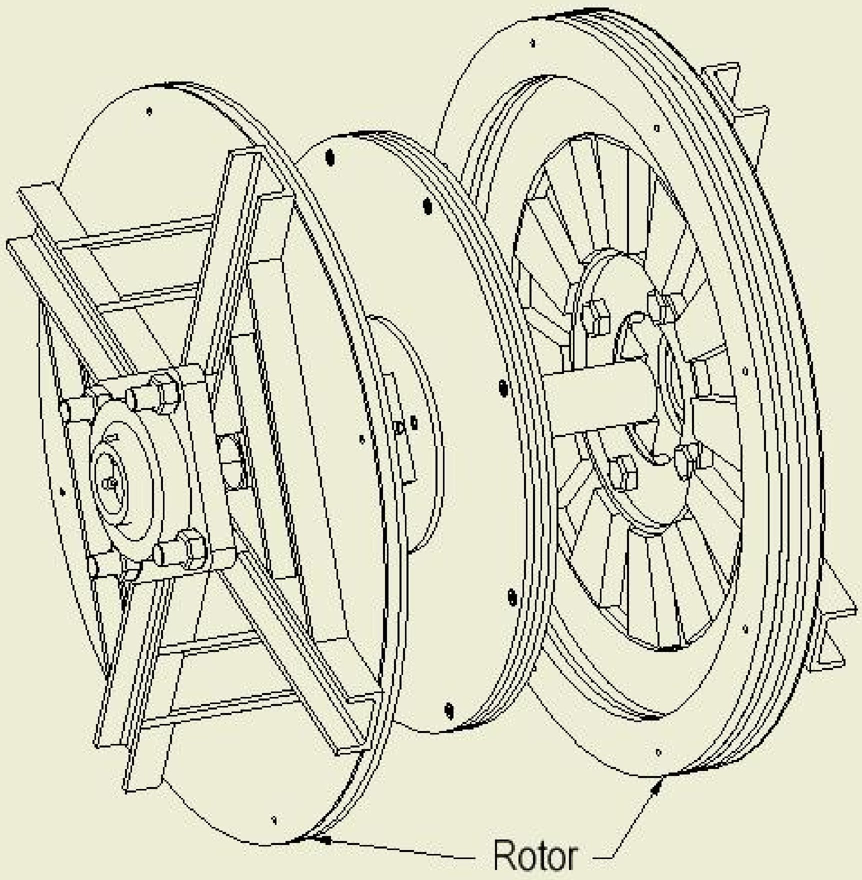

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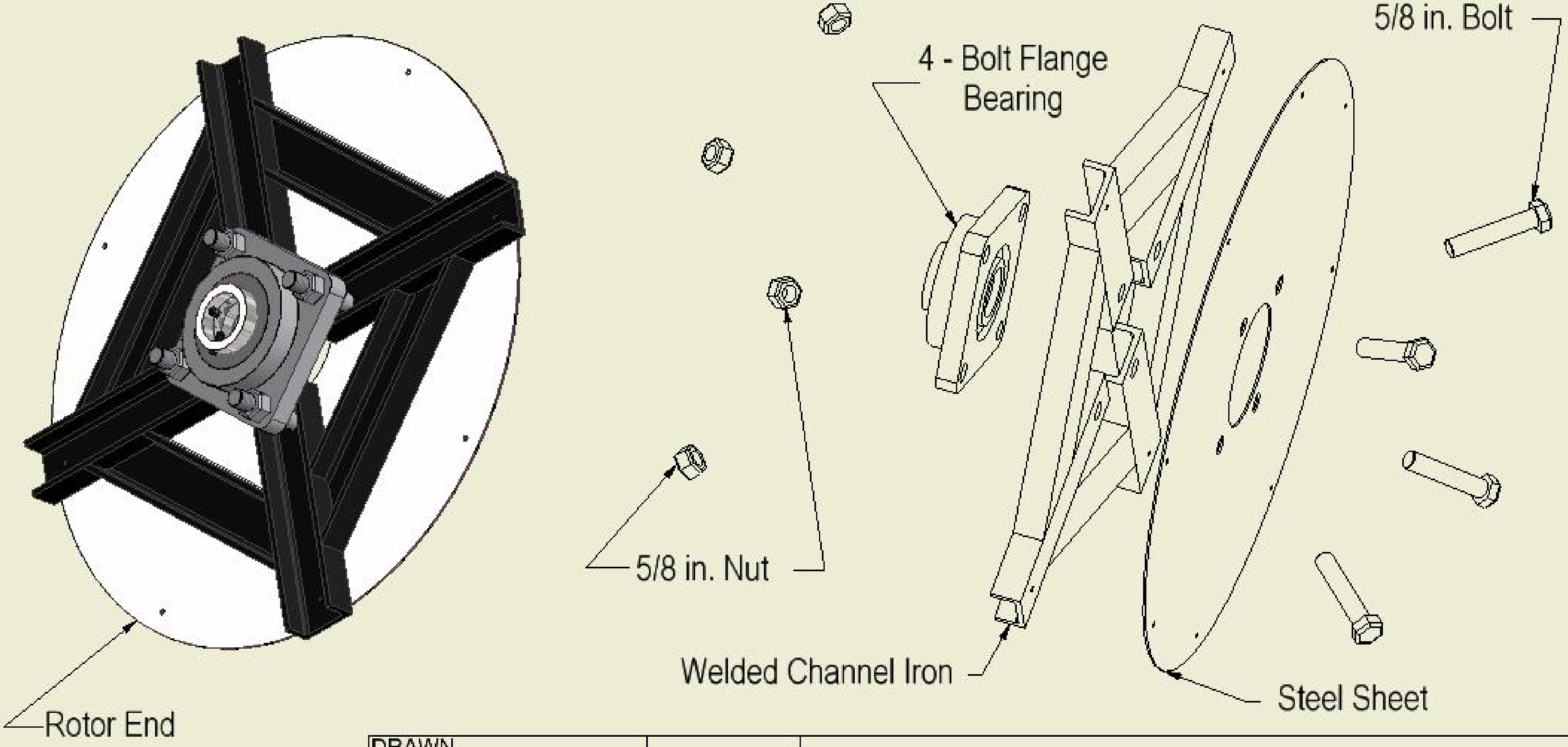

Rotor Assembly

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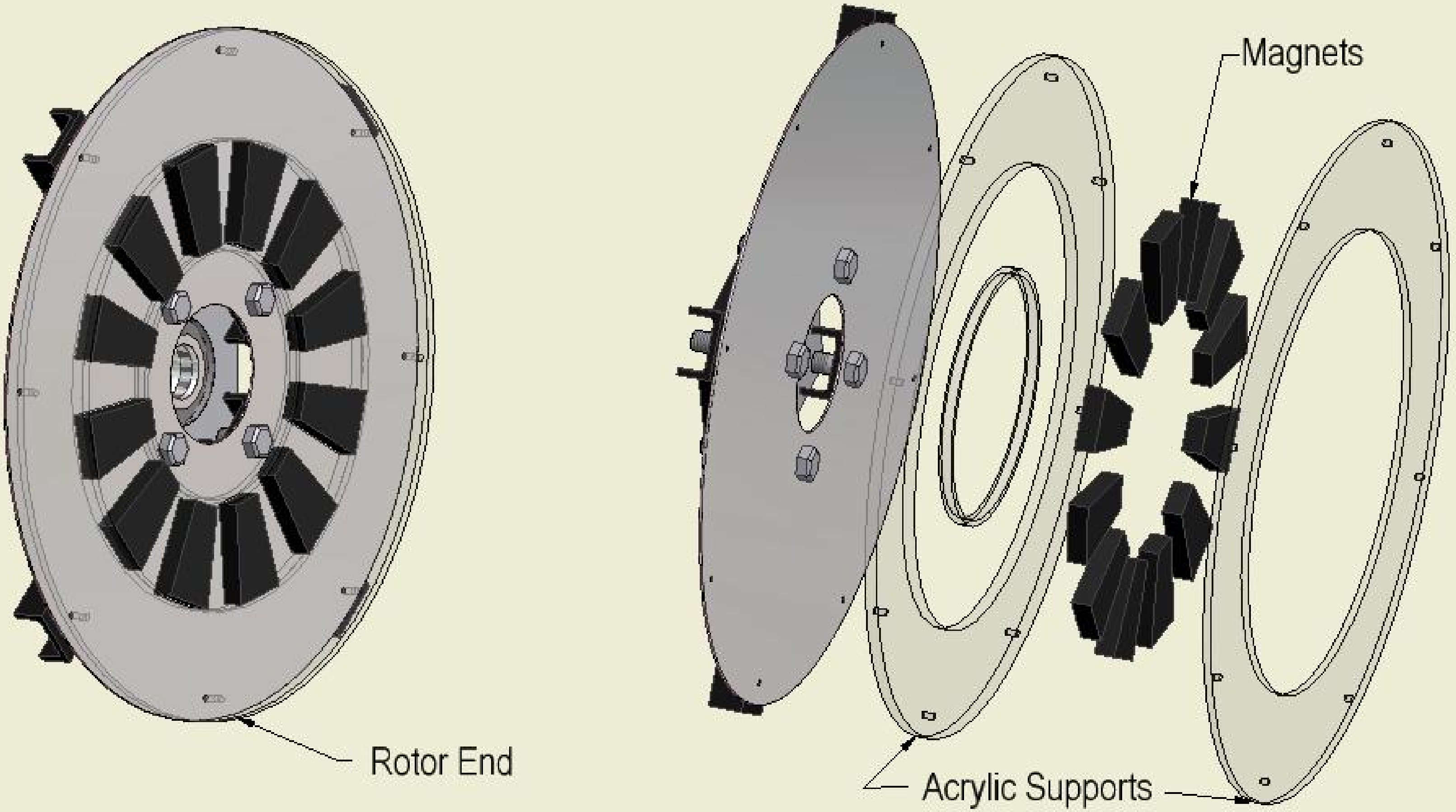

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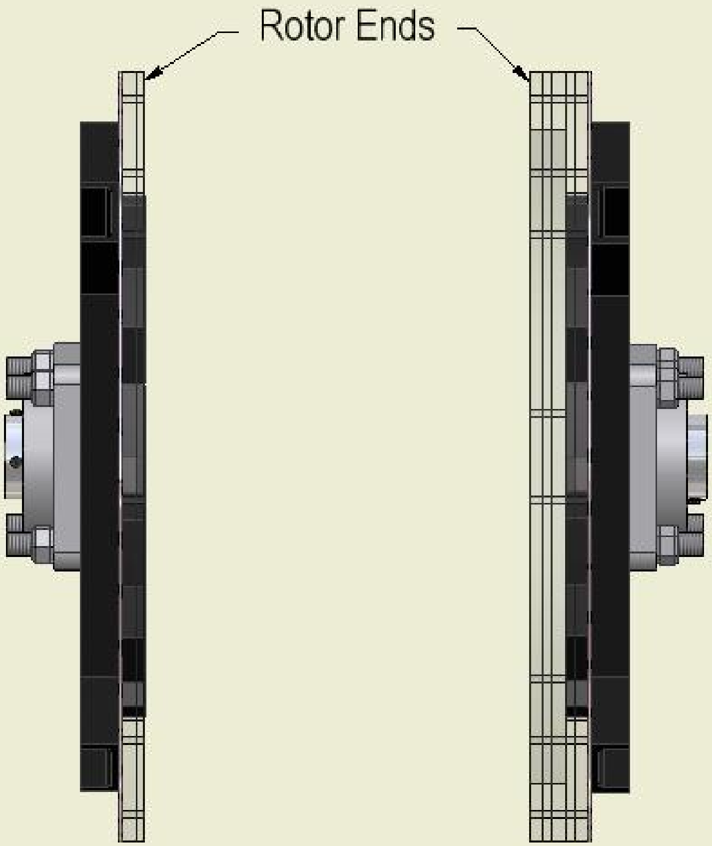
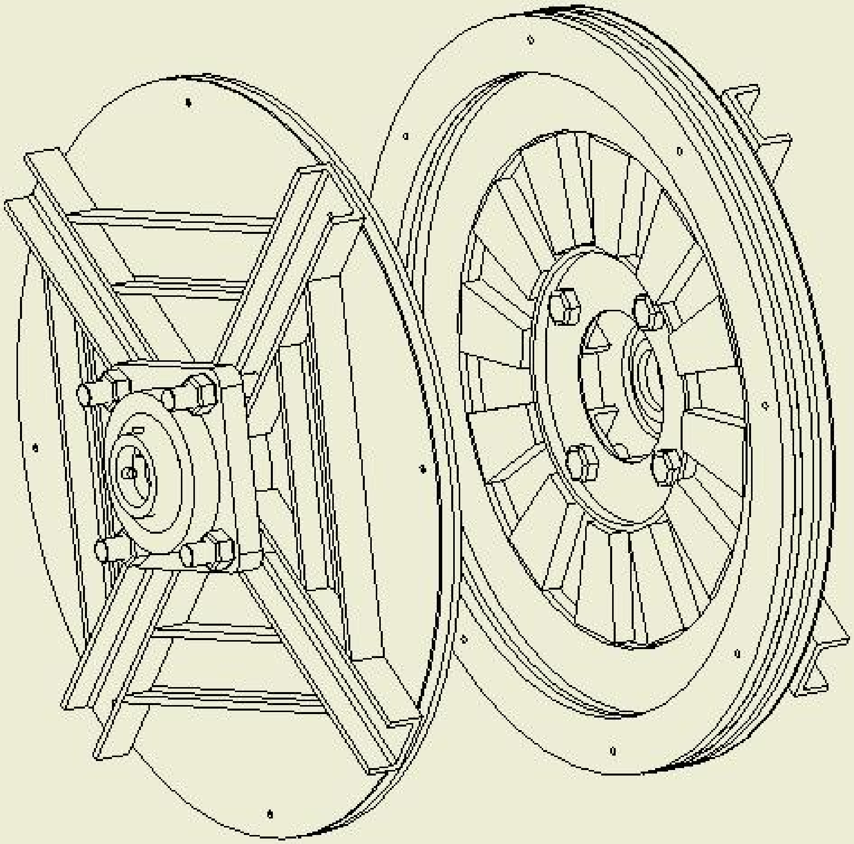
SCALE
SHEET 10 OF 16





Rotor Assembly

DRAWN Donald Merriam Jr.	01/20/2004
CHECKED	
QA	
MFG	
APPROVED	

Houghton College

TITLE

Low-rpm Permanent (NdFeB) Magnet Generator

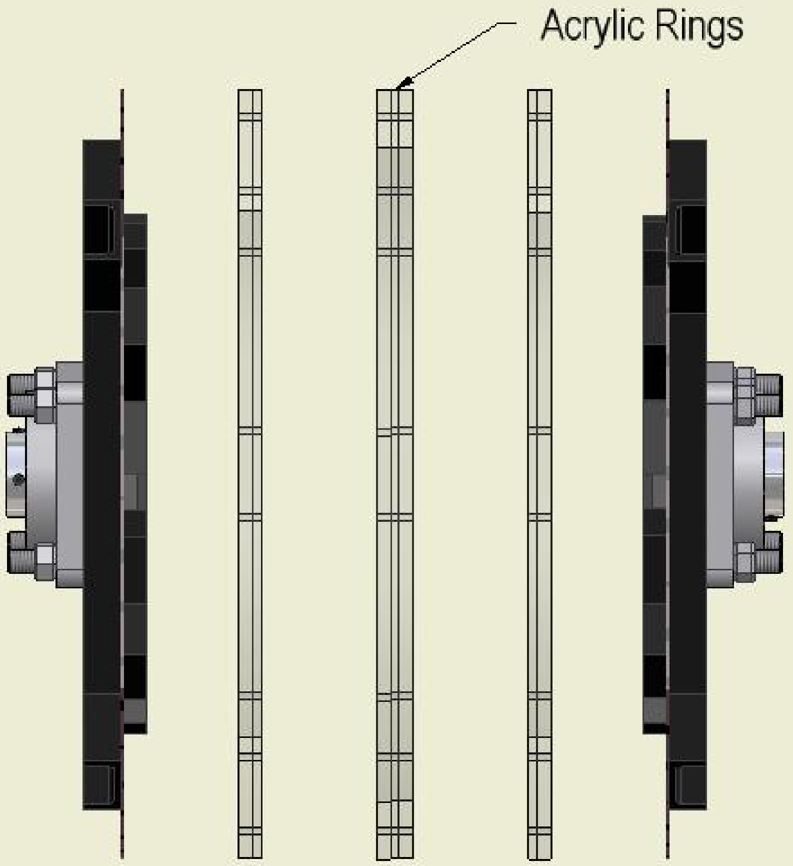
SIZE A

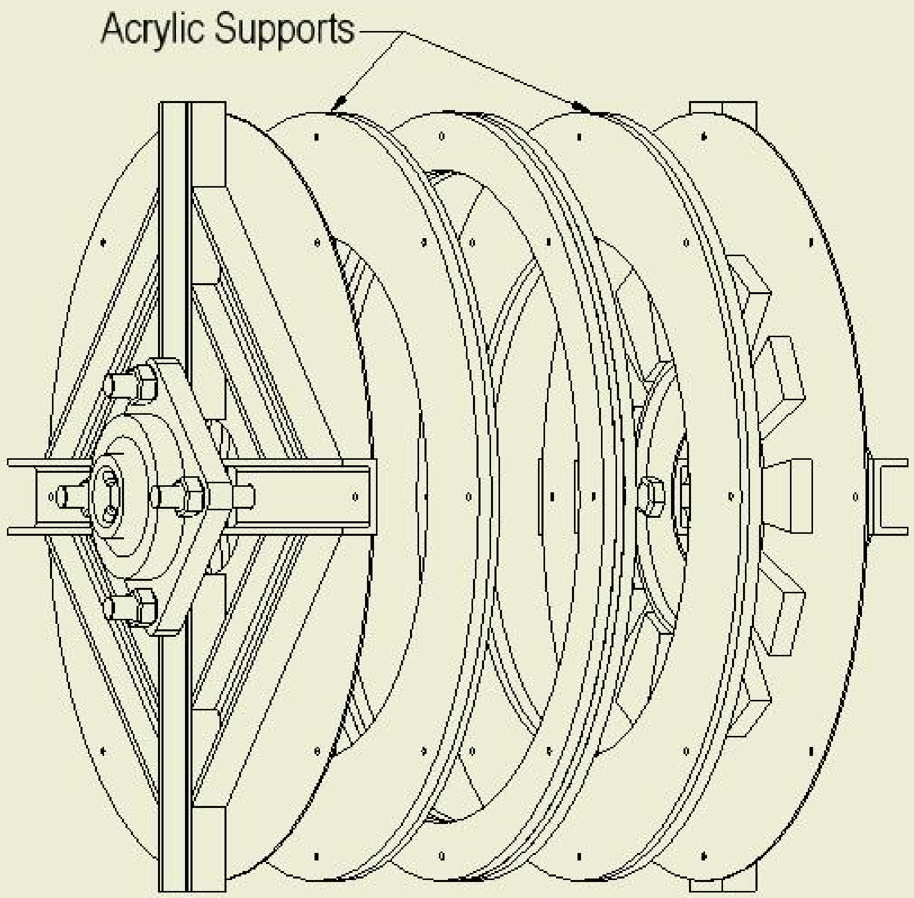
DWG NO Generator Drawings

REV

SCALE

SHEET 11 OF 16

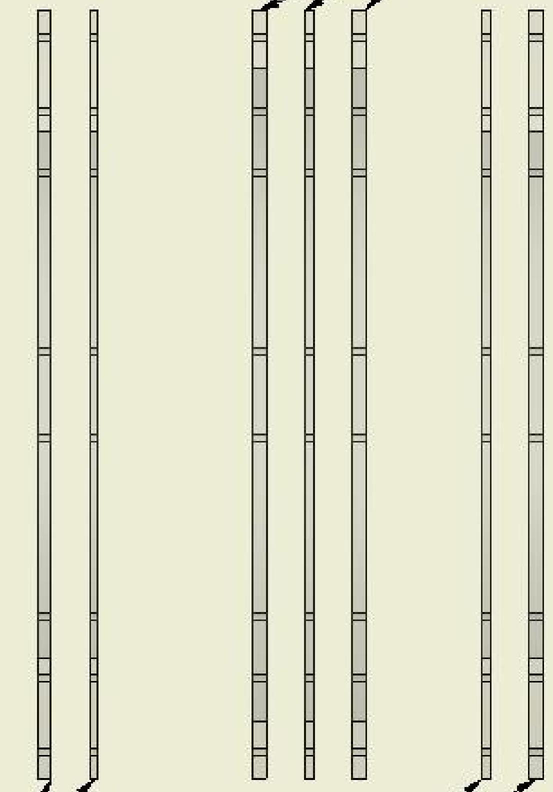


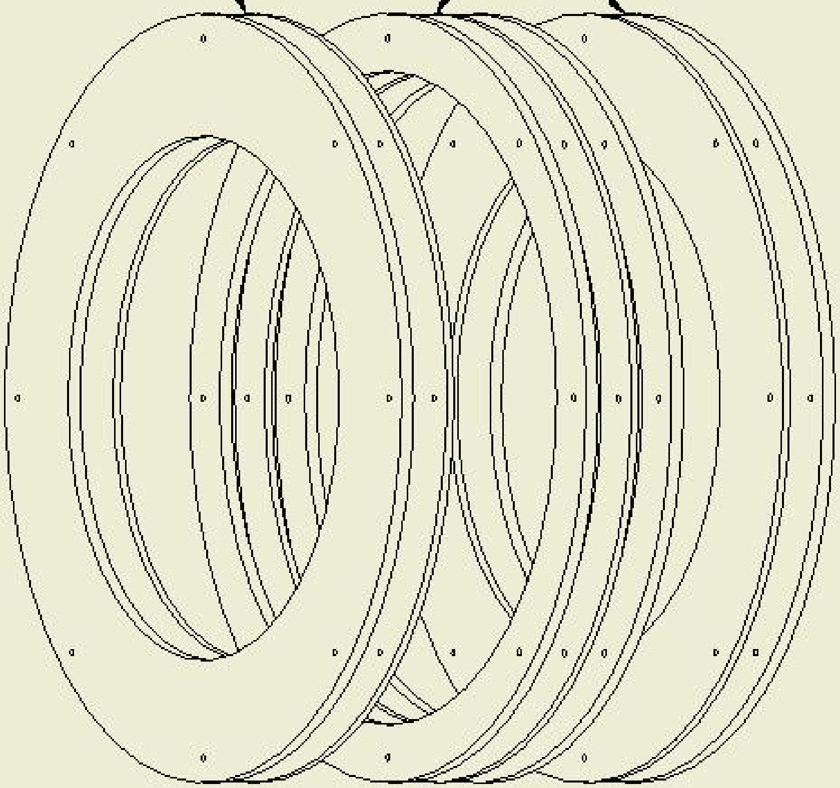


Note position and
thicknesses of acrylic
rings and supports.

Rotor Assembly

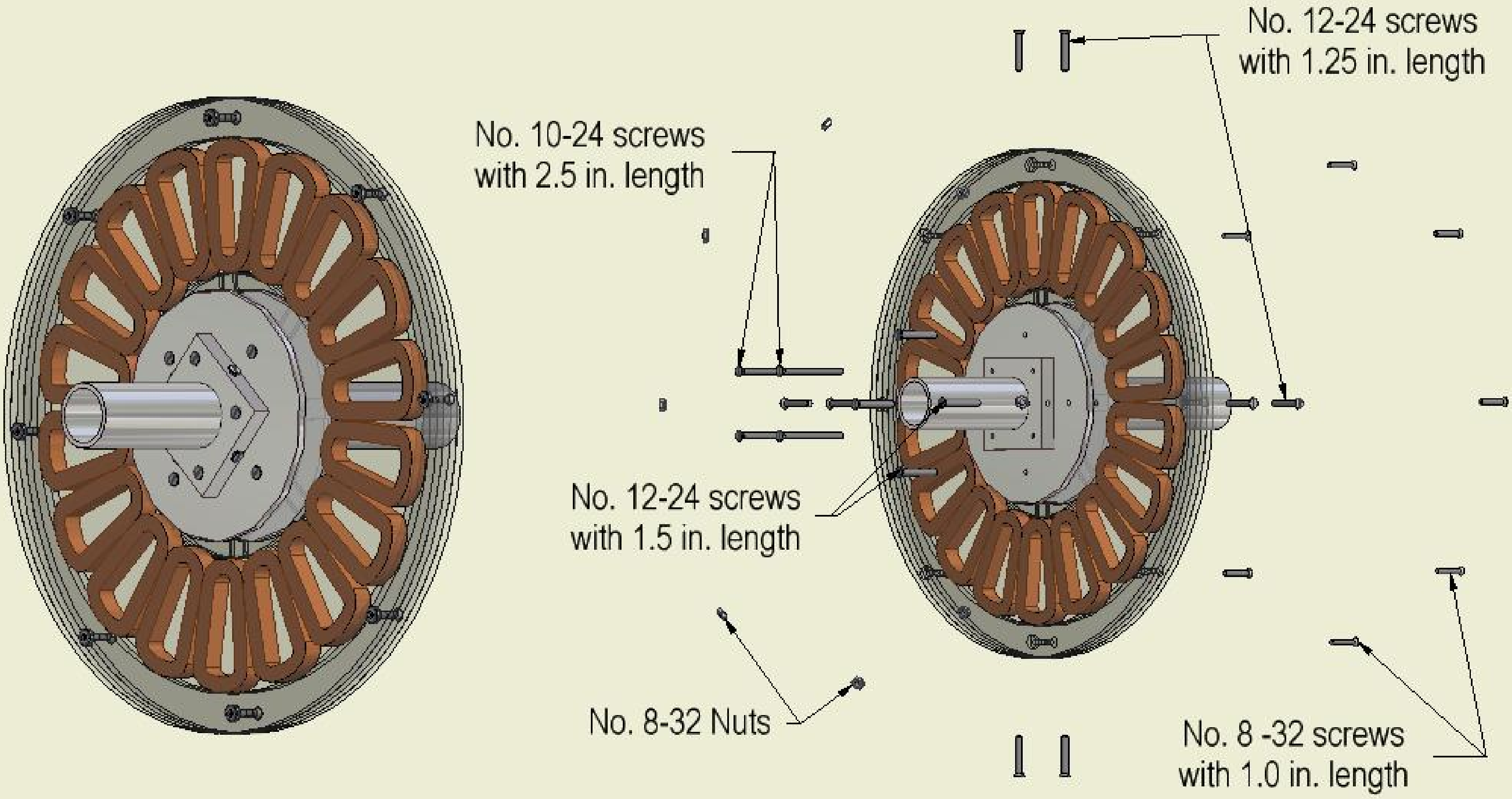
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A · DWG NO Generator Drawings · REV
		SCALE · SHEET 12 OF 16





Rotor Assembly

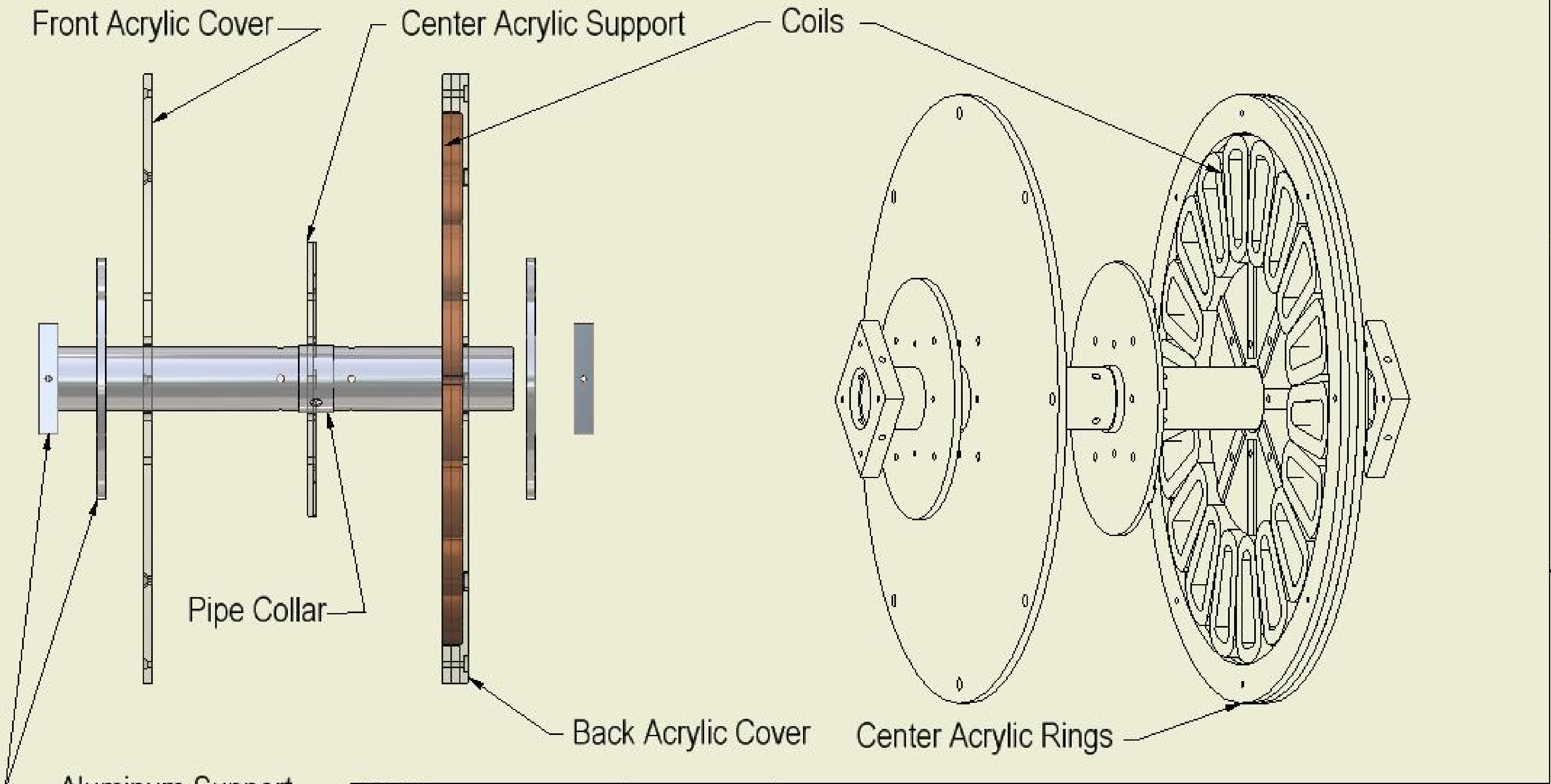
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE **Low-rpm Permanent (NdFeB) Magnet Generator**
QA		
MFG		
APPROVED		
		SIZE A — DWG NO **Generator Drawings** — REV
		SCALE — SHEET 13 OF 16



Stator Assembly

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College	
CHECKED		TITLE **Low-rpm Permanent (NdFeB) Magnet Generator**	
QA			
MFG			
APPROVED		SIZE A	DWG NO **Generator Drawings**
		SCALE	SHEET 14 OF 16

REV



Stator Assembly

DRAWN Donald Merriam Jr.	01/20/2004
CHECKED	
QA	
MFG	
APPROVED	

Houghton College

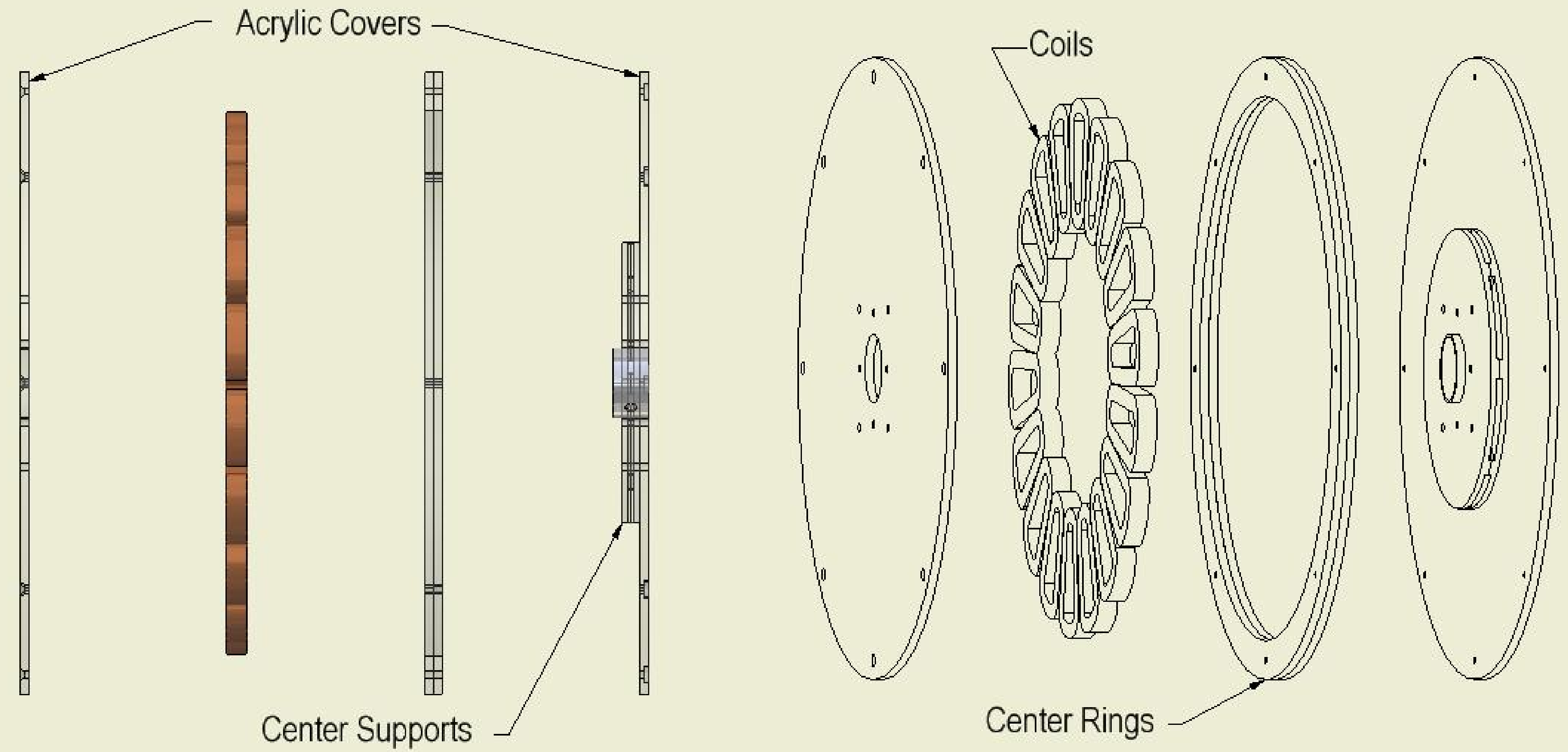
TITLE

Low-rpm Permanent (NdFeB) Magnet Generator

SIZE	DWG NO	REV
A	Generator Drawings	

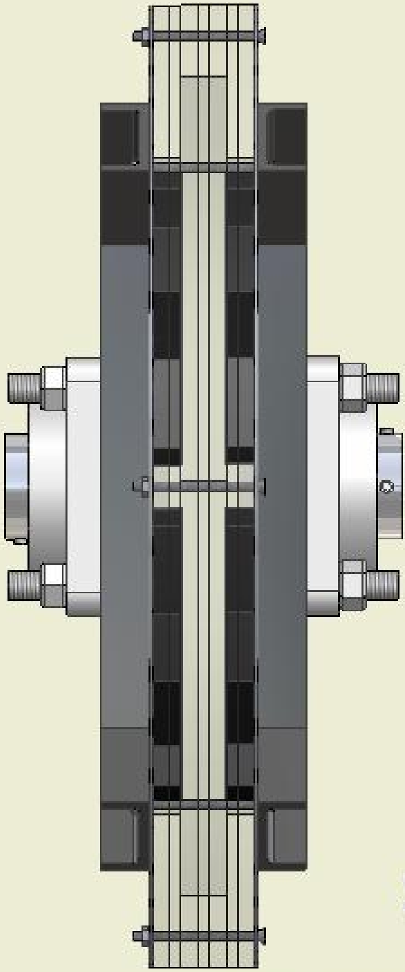
SCALE

SHEET 15 OF 16

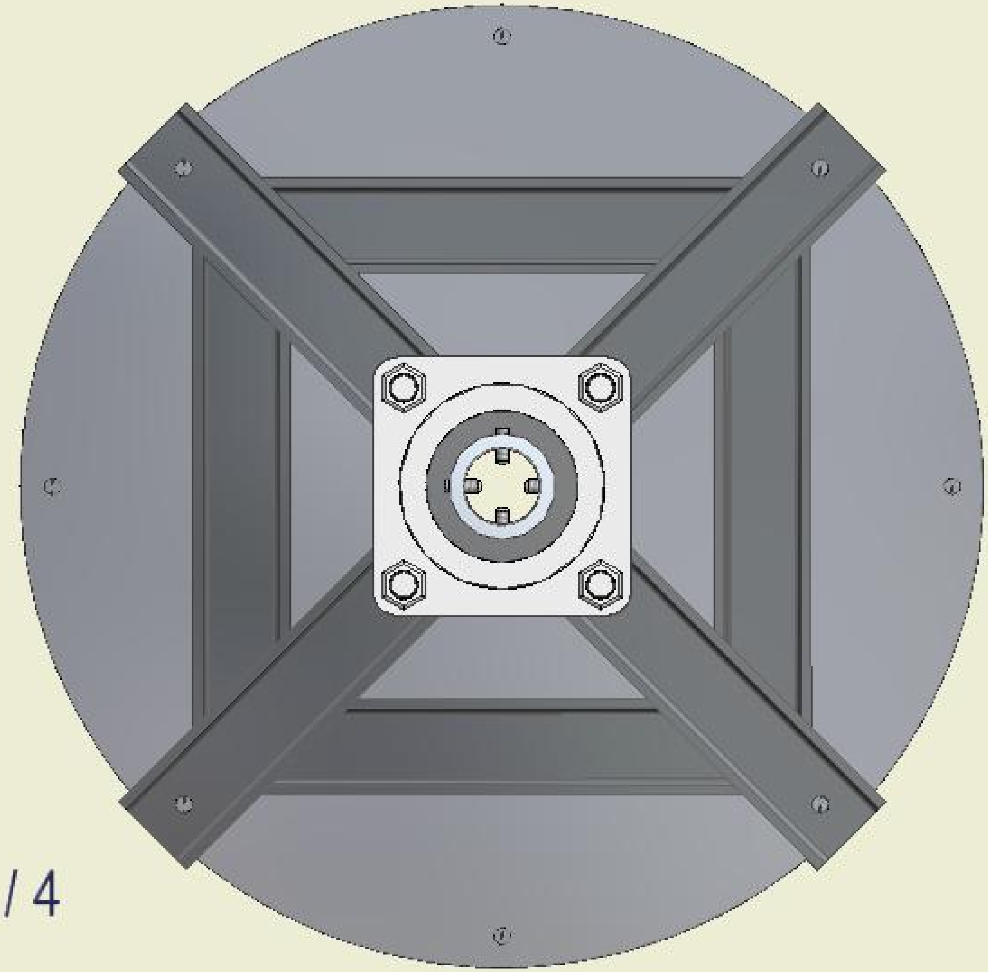


Stator Assembly

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College			
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator			
QA					
MFG					
APPROVED					
		SIZE A	DWG NO Generator Drawings		REV
		SCALE		SHEET 16 OF 16	

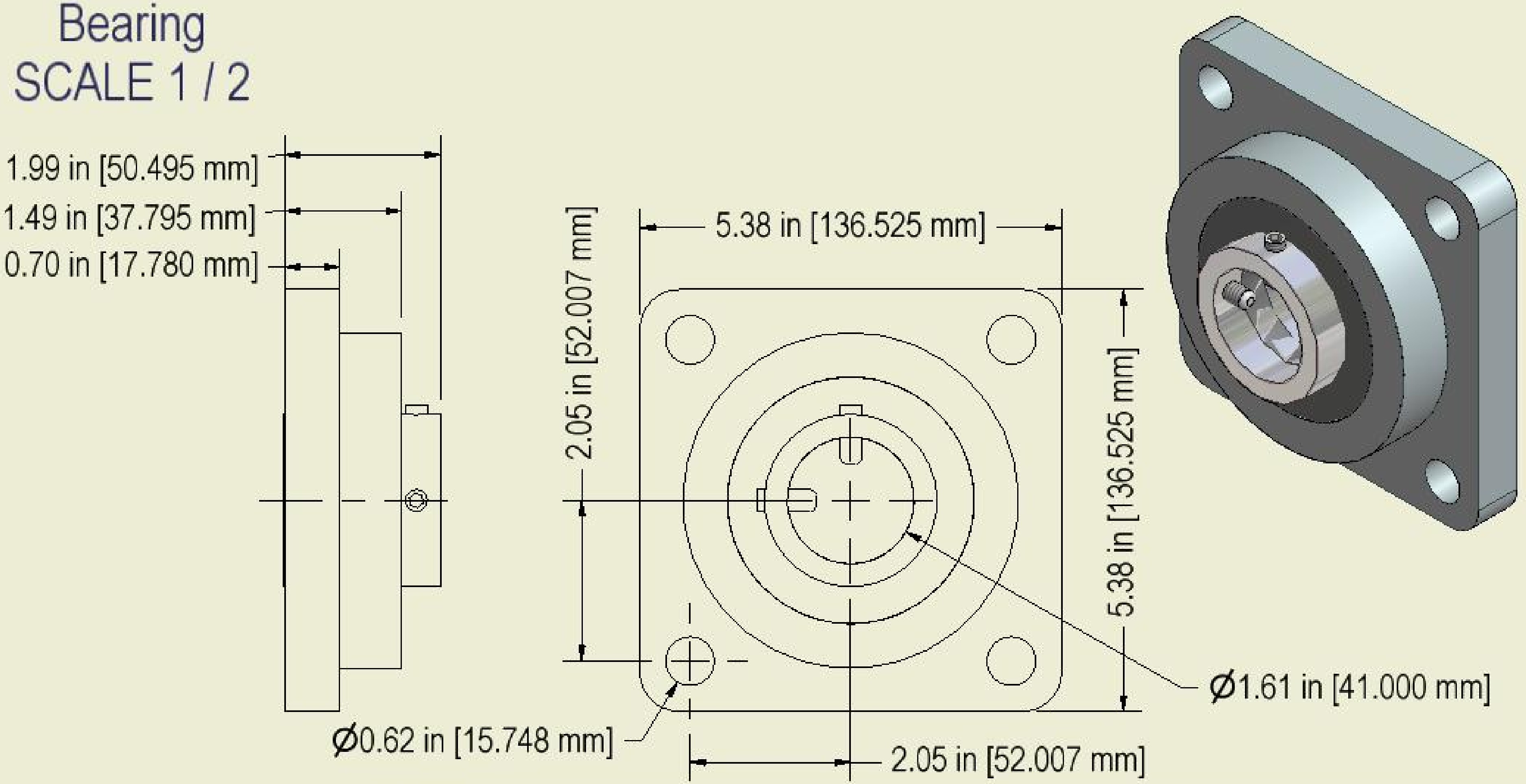


Rotor
SCALE 1 / 4



DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		
		SIZE A
		DWG NO Rotor Parts
		REV
		SCALE
		SHEET 1 OF 14

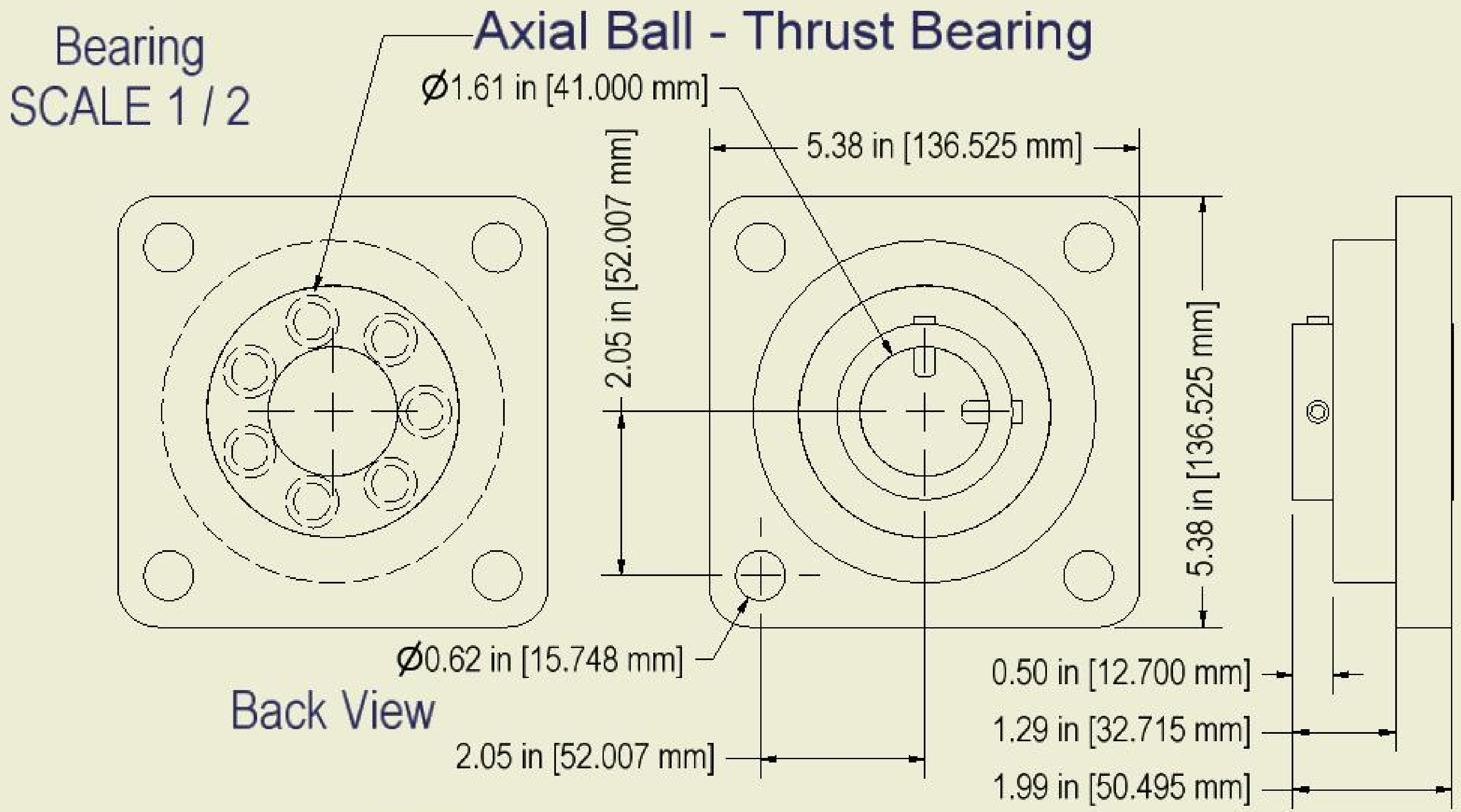
Bearing
SCALE 1 / 2



DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		

SIZE A | DWG NO Rotor Parts | REV

SCALE | SHEET 2 OF 14



DRAWN Donald Merriam Jr.	01/20/2004
CHECKED	02/06/2004
QA	
MFG	
APPROVED	

Houghton College

TITLE

Low-rpm Permanent (NdFeB) Magnet Generator

SIZE A

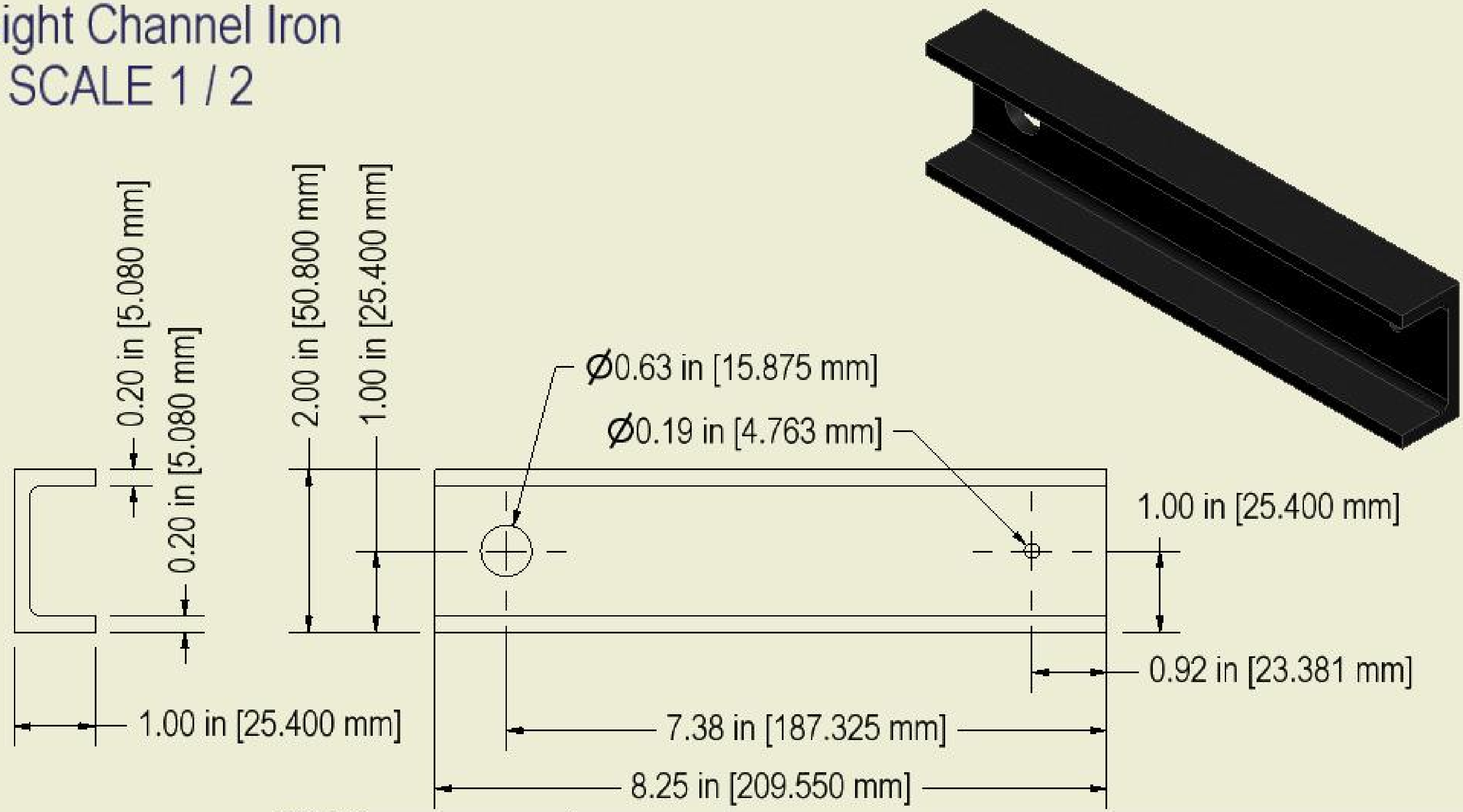
DWG NO Rotor Parts

REV

SCALE

SHEET 3 OF 14

Straight Channel Iron
SCALE 1 / 2

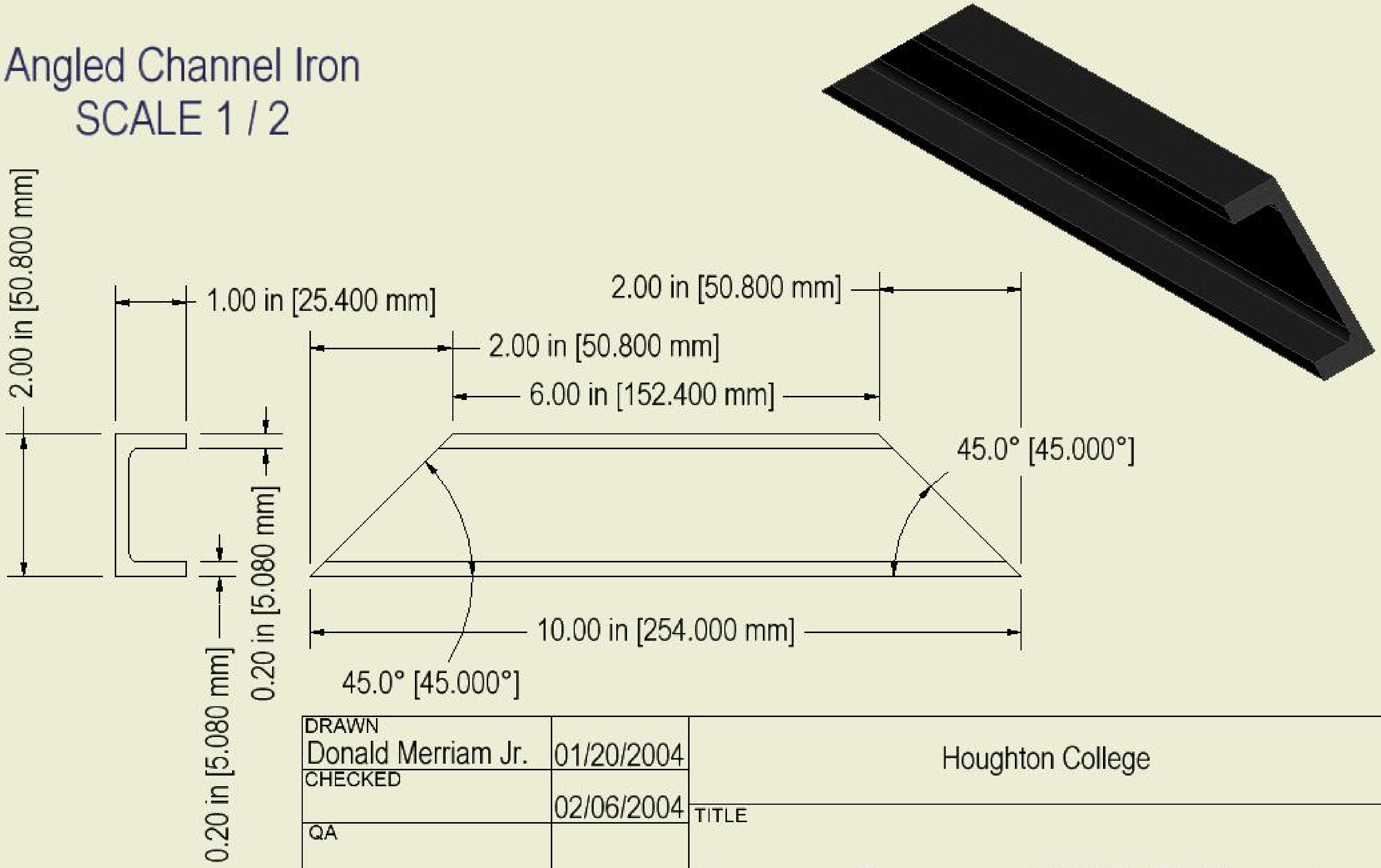


DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		

SIZE A | DWG NO Rotor Parts | REV

SCALE | SHEET 4 OF 14

Angled Channel Iron
SCALE 1 / 2



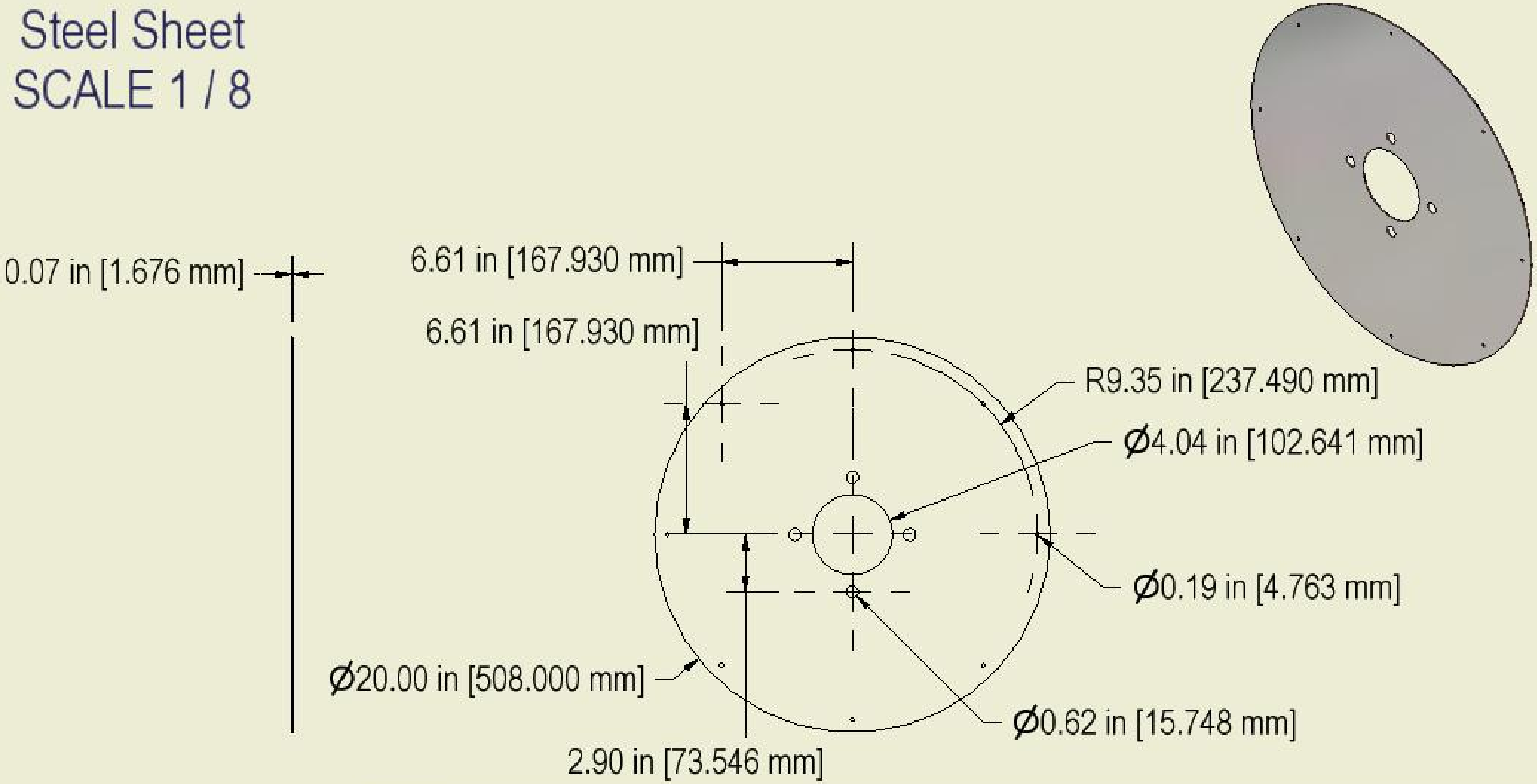
DRAWN
Donald Merriam Jr. 01/20/2004
CHECKED
02/06/2004
QA
MFG
APPROVED

Houghton College

TITLE
Low-rpm Permanent (NdFeB) Magnet Generator

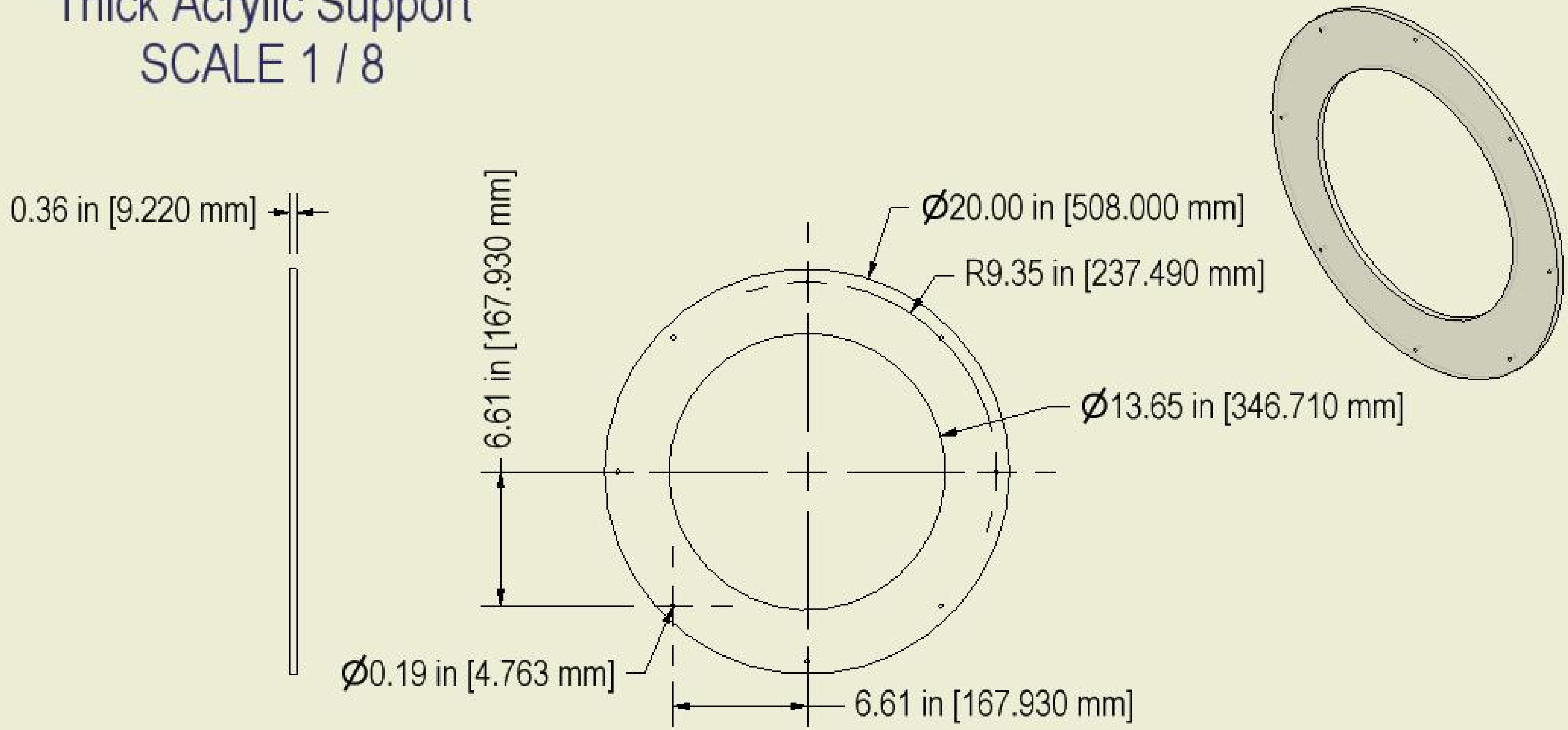
SIZE A
DWG NO Rotor Parts
REV
SCALE
SHEET 5 OF 14

Steel Sheet
SCALE 1 / 8



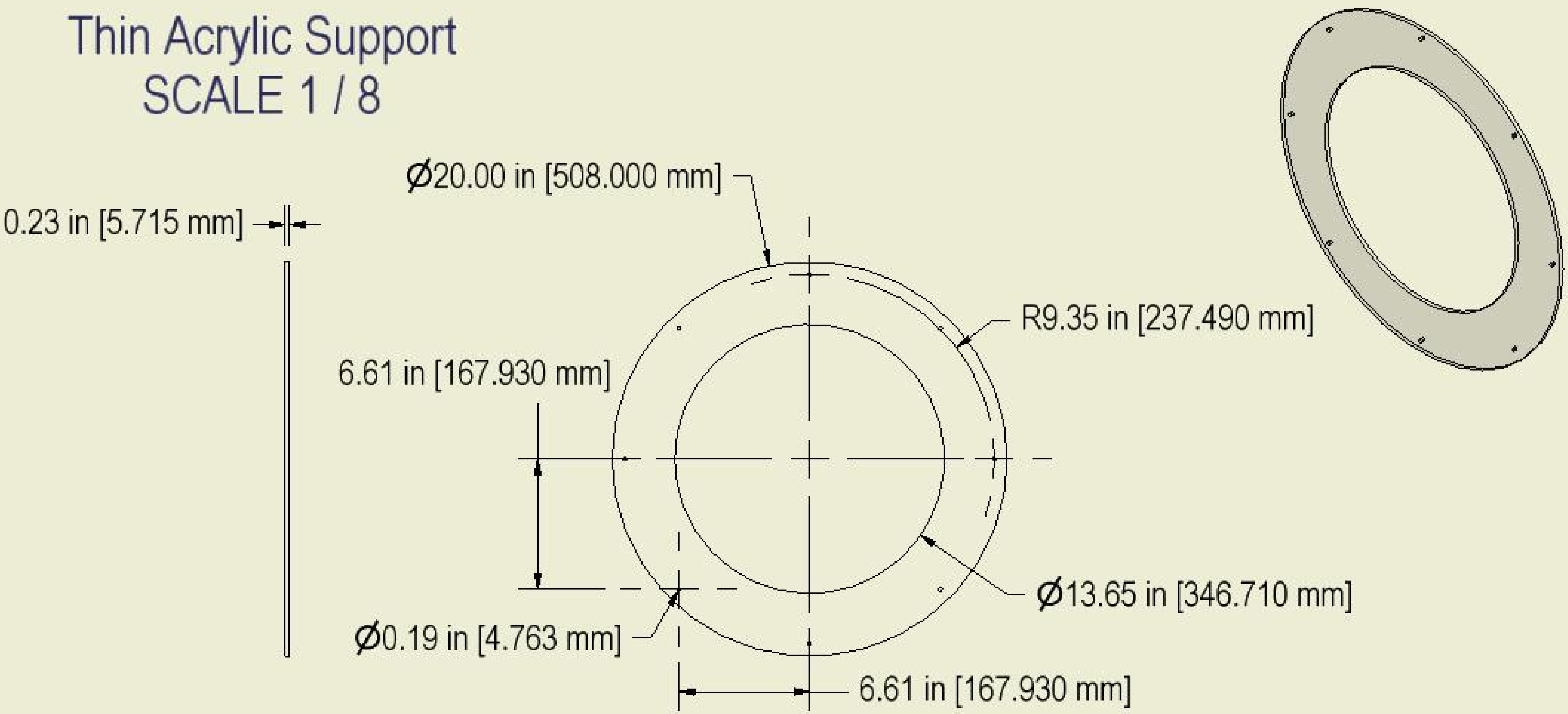
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE **Low-rpm Permanent (NdFeB) Magnet Generator**
QA		
MFG		
APPROVED		SIZE A · DWG NO **Rotor Parts** · REV
		SCALE · SHEET 6 OF 14

Thick Acrylic Support
SCALE 1 / 8



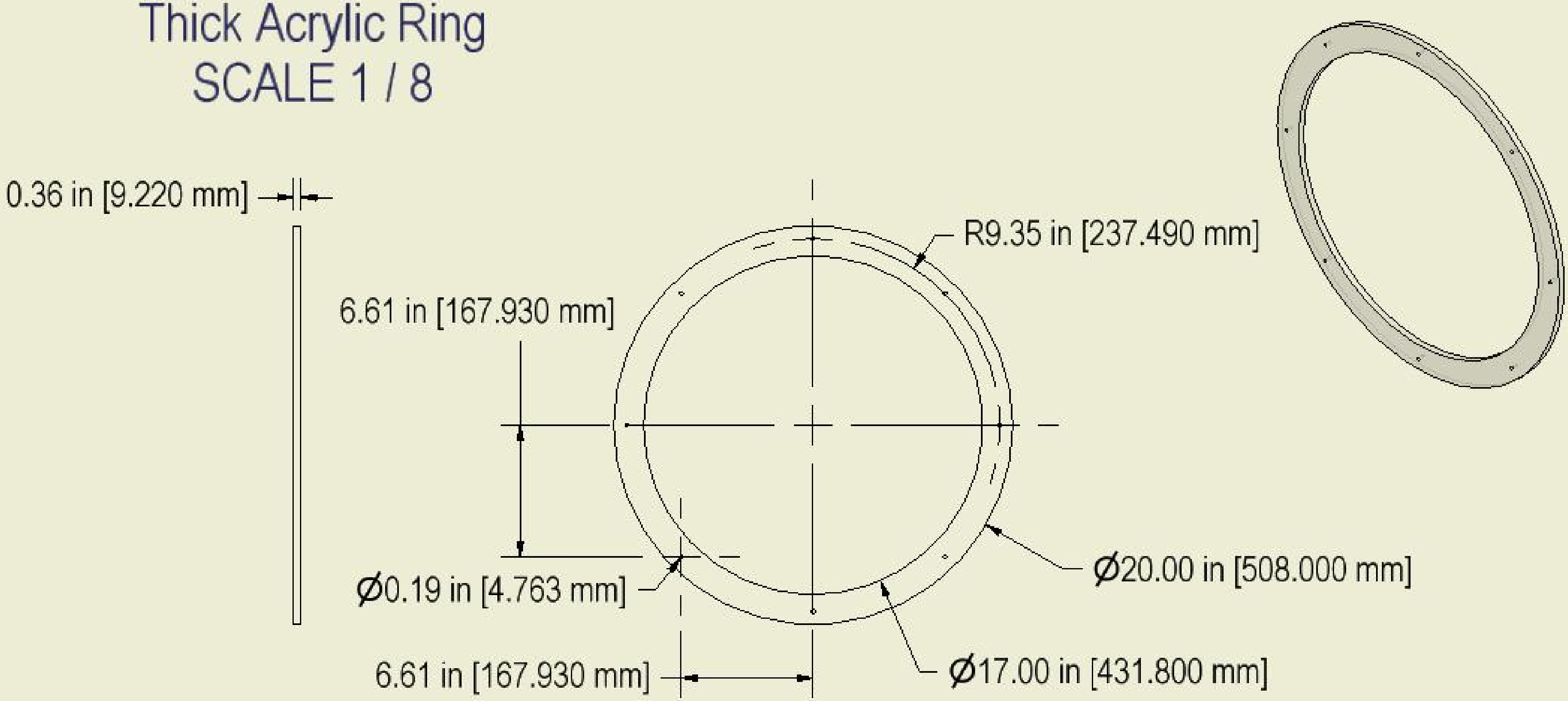
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College		
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator		
QA				
MFG				
APPROVED				
		SIZE A	DWG NO Rotor Parts	REV
		SCALE		SHEET 7 OF 14

Thin Acrylic Support
SCALE 1 / 8



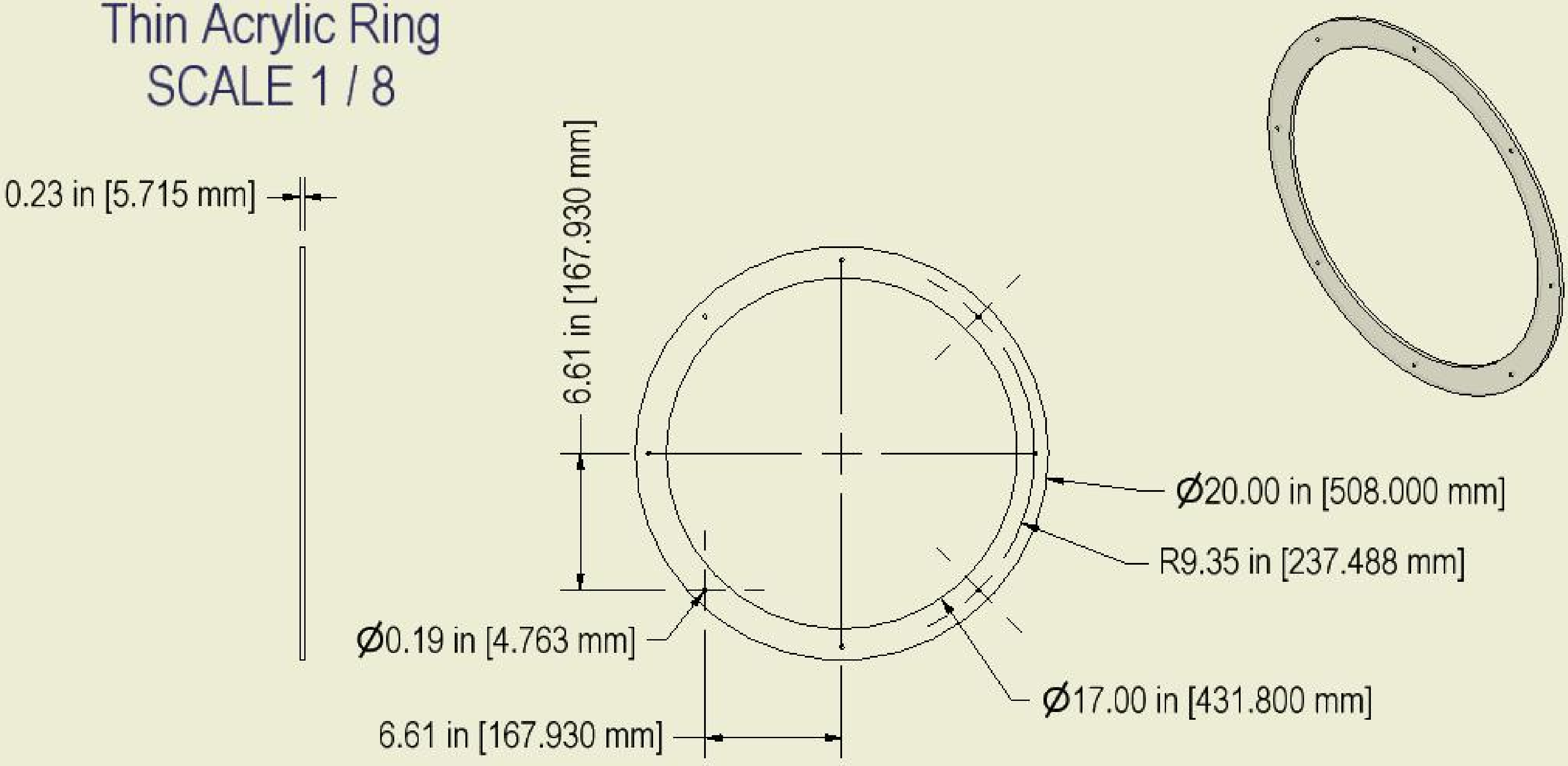
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A | DWG NO Rotor Parts | REV
		SCALE | SHEET 8 OF 14

Thick Acrylic Ring
SCALE 1 / 8



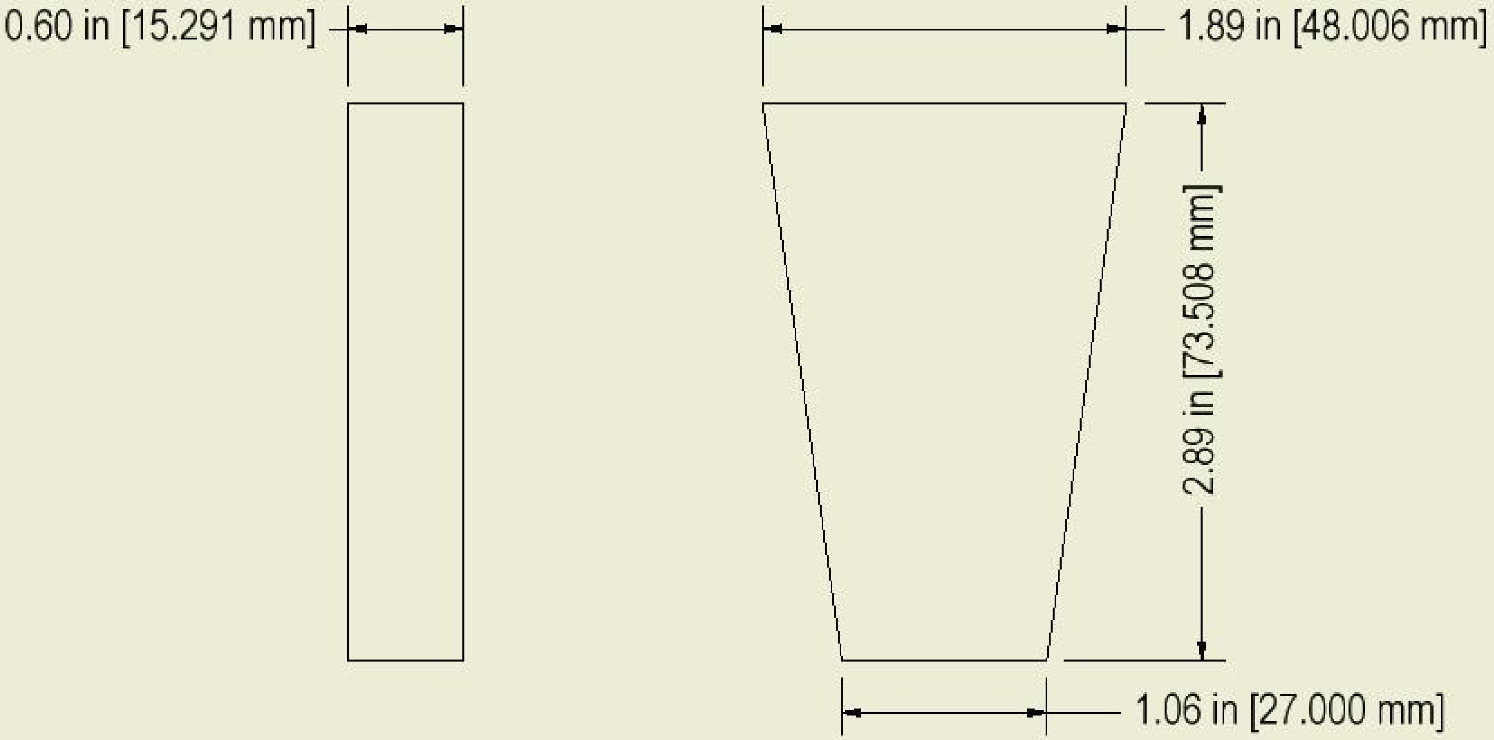
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE **Low-rpm Permanent (NdFeB) Magnet Generator**
QA		
MFG		
APPROVED		
		SIZE A · DWG NO **Rotor Parts** · REV
		SCALE · SHEET 9 OF 14

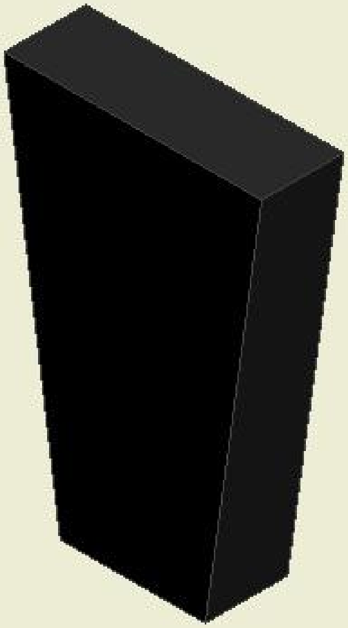
Thin Acrylic Ring
SCALE 1 / 8



DRAWN Donald Merriam Jr.	01/20/2004	Houghton College		
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator		
QA				
MFG				
APPROVED				
		SIZE A	DWG NO Rotor Parts	REV
		SCALE		SHEET 10 OF 14

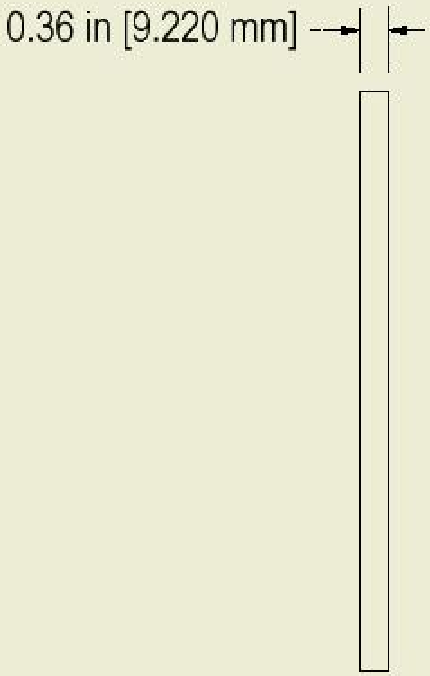
Permanent (NdFeB) Magnet
SCALE 1 : 1

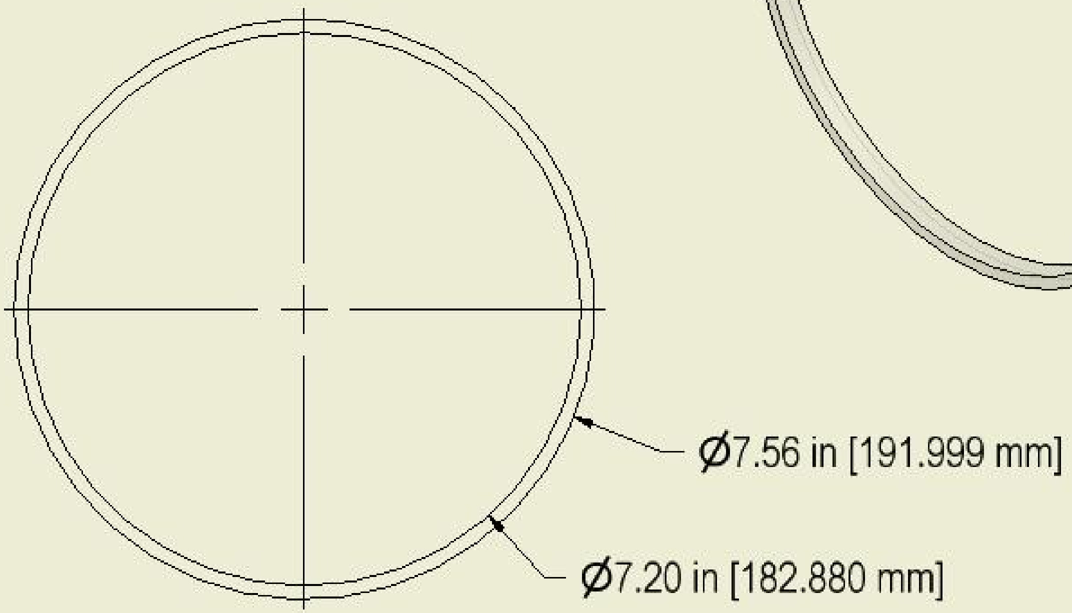


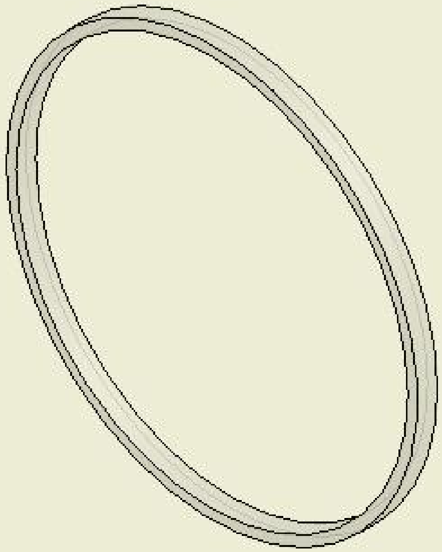


DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A · DWG NO Rotor Parts · REV
		SCALE · SHEET 11 OF 14

Inner Acrylic Support
SCALE 0.40 : 1



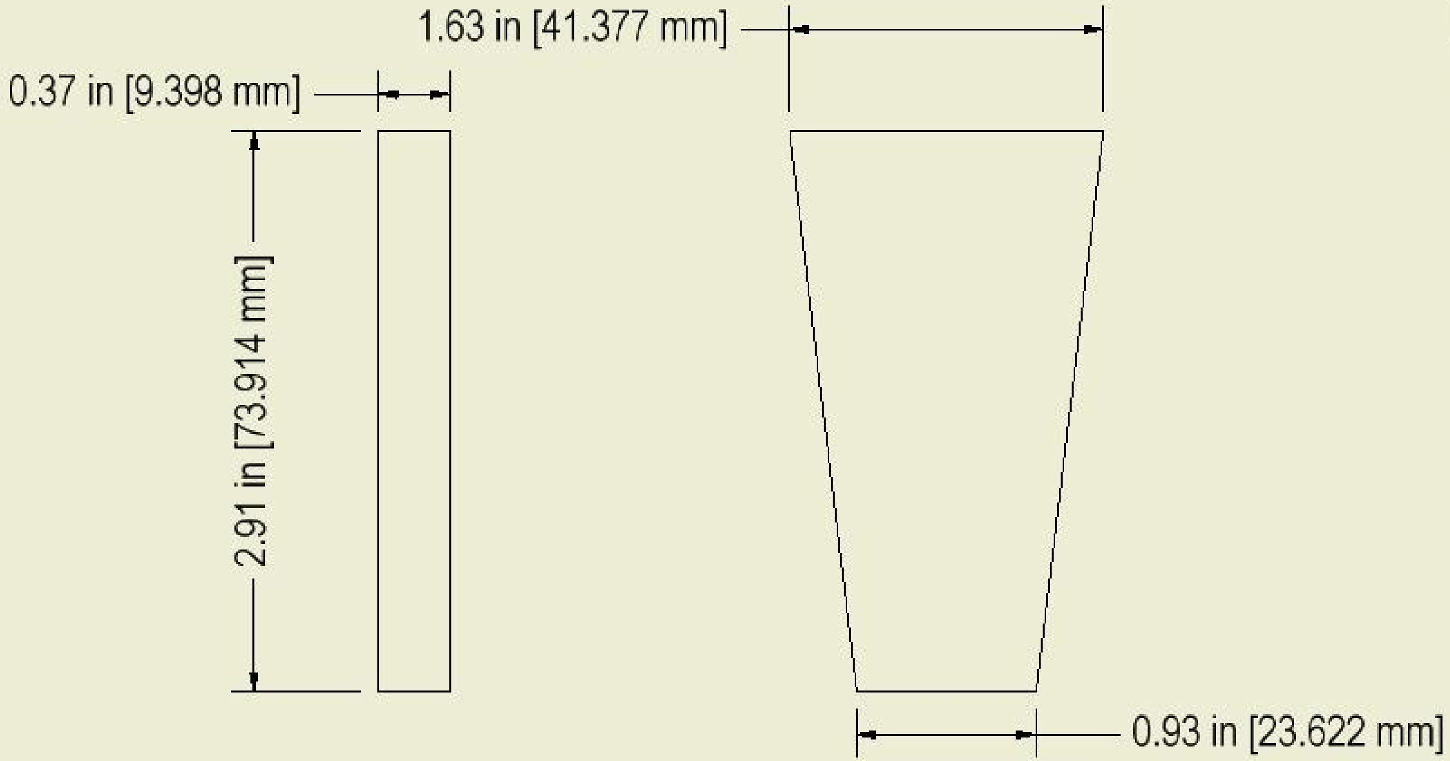


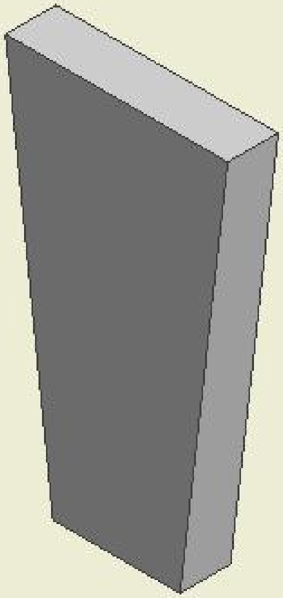


Note: Part is used
for placing magnets
on steel sheets.

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College			
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator			
QA					
MFG					
APPROVED					
		SIZE A	DWG NO Rotor Parts		REV
		SCALE		SHEET 12 OF 14	

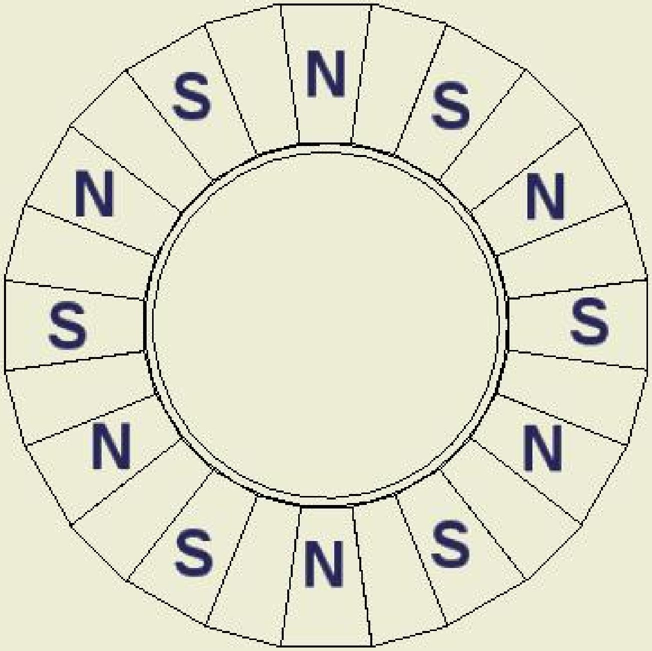
Wooden or Acrylic Place Holder
SCALE 1 : 1

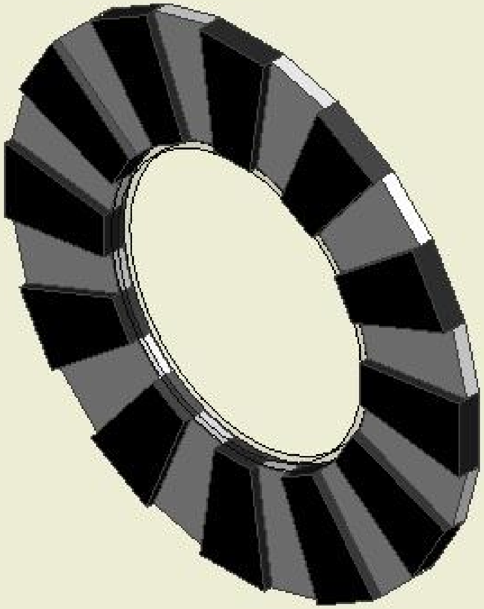




DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A · DWG NO Rotor Parts · REV
		SCALE · SHEET 13 OF 14

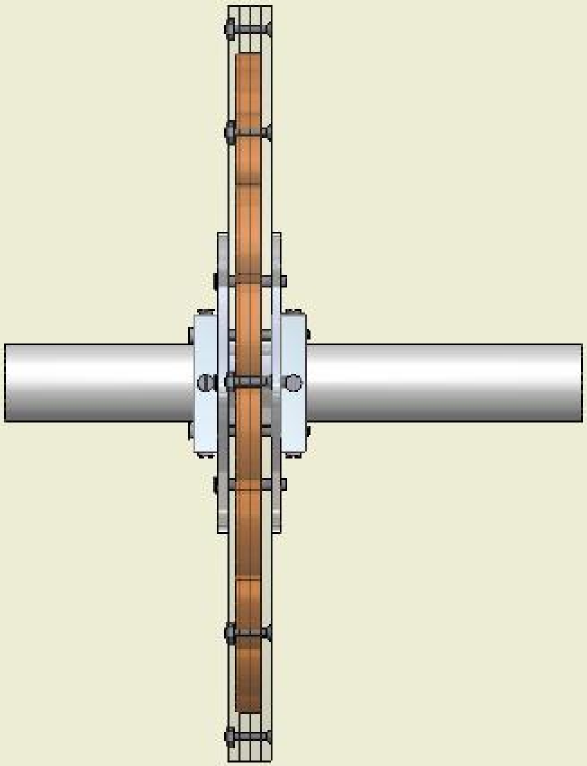
Magnet Placement Pattern
SCALE 1 / 4

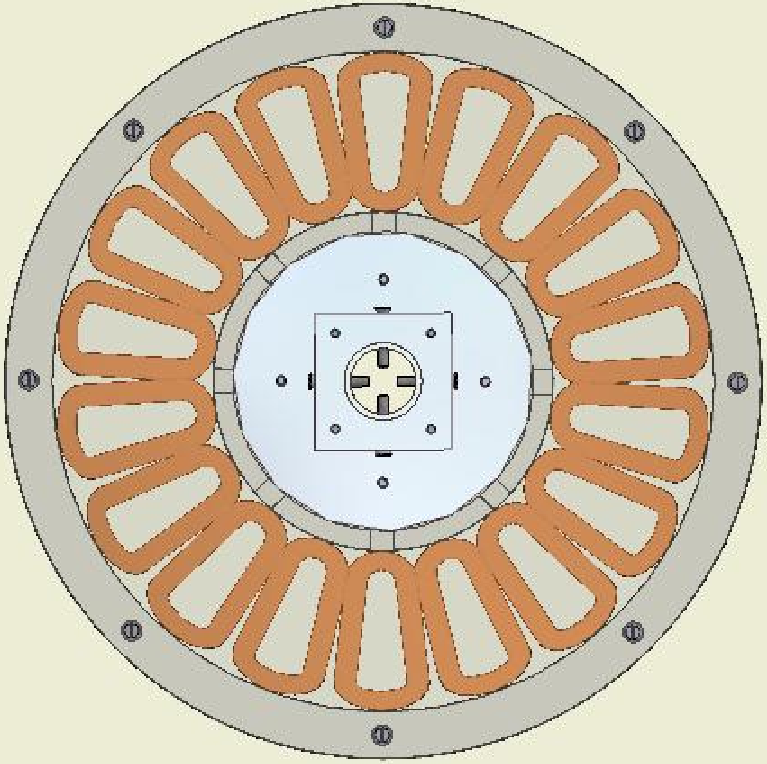




Place magnets
with corresponding
poles facing up,
North (N) or South (S).

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College		
CHECKED	02/06/2004	TITLE Low-rpm Permanent (NdFeB) Magnet Generator		
QA				
MFG				
APPROVED		SIZE A	DWG NO Rotor Parts	REV
		SCALE		SHEET 14 OF 14

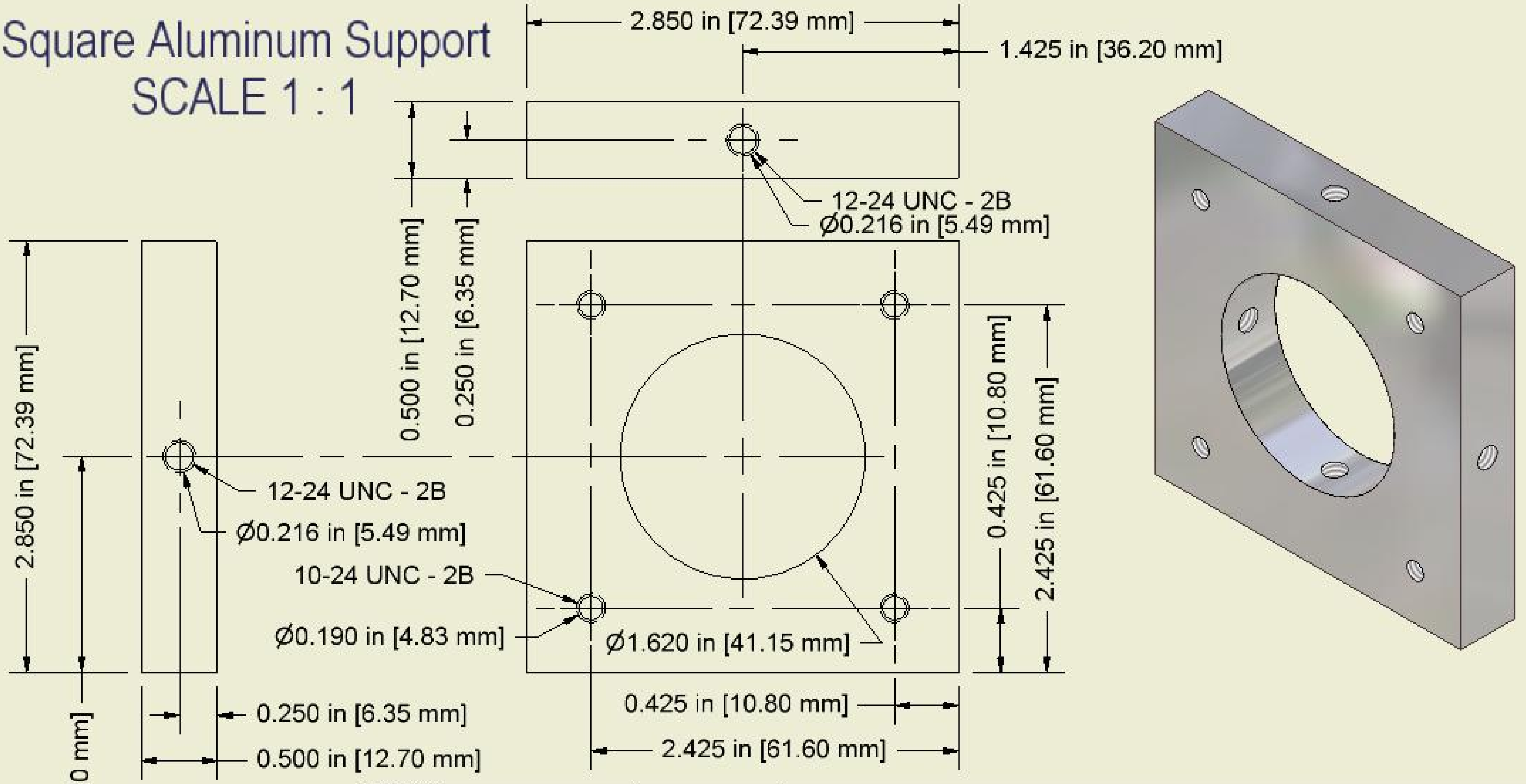




Stator
SCALE 1 / 4

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A · DWG NO Stator Parts · REV
		SCALE · SHEET 1 OF 11

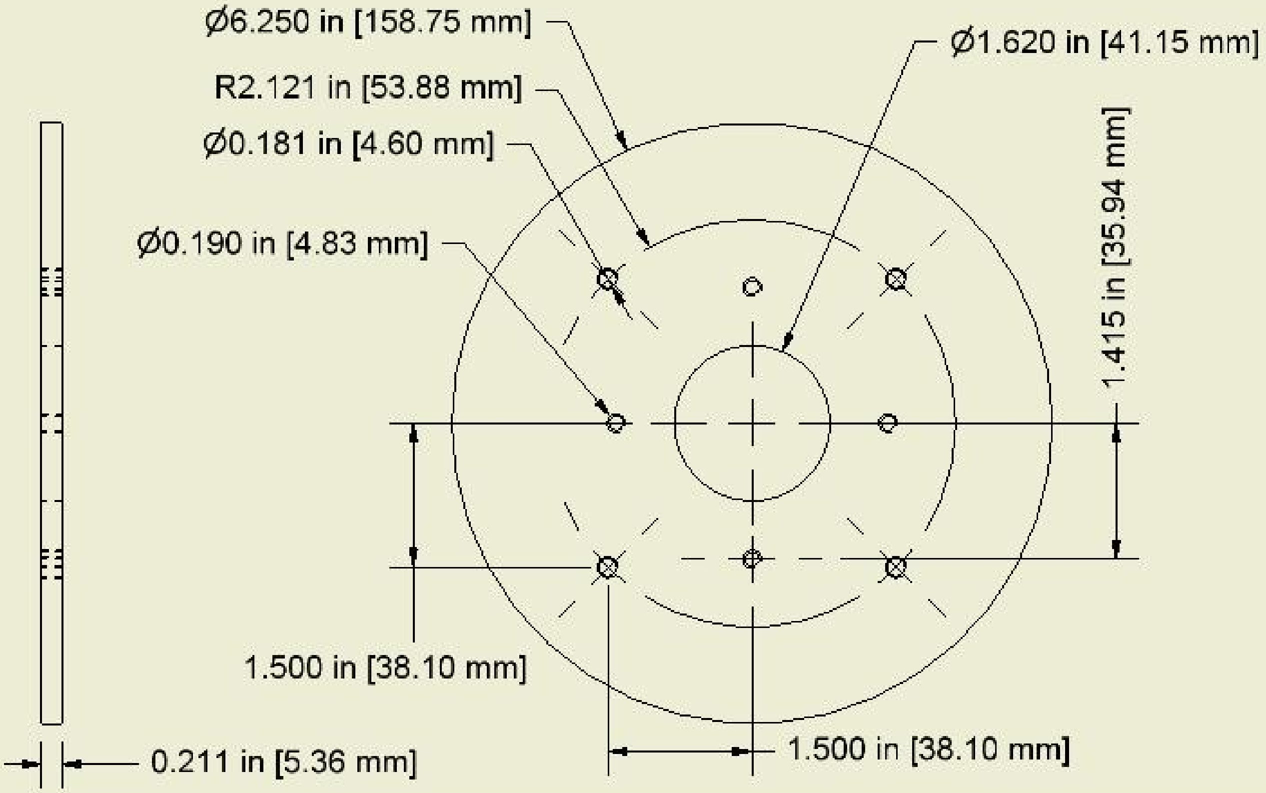
Square Aluminum Support
SCALE 1 : 1

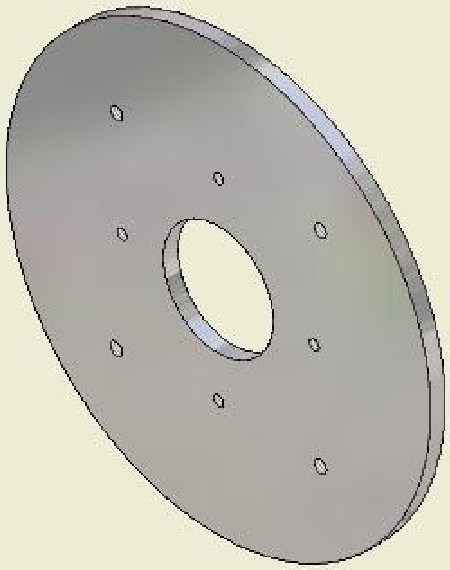


DRAWN Donald Merriam Jr.	01/20/2004	Houghton College	
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator	
QA			
MFG			
APPROVED			
		SIZE A	DWG NO Stator Parts
		SCALE	SHEET 2 OF 11

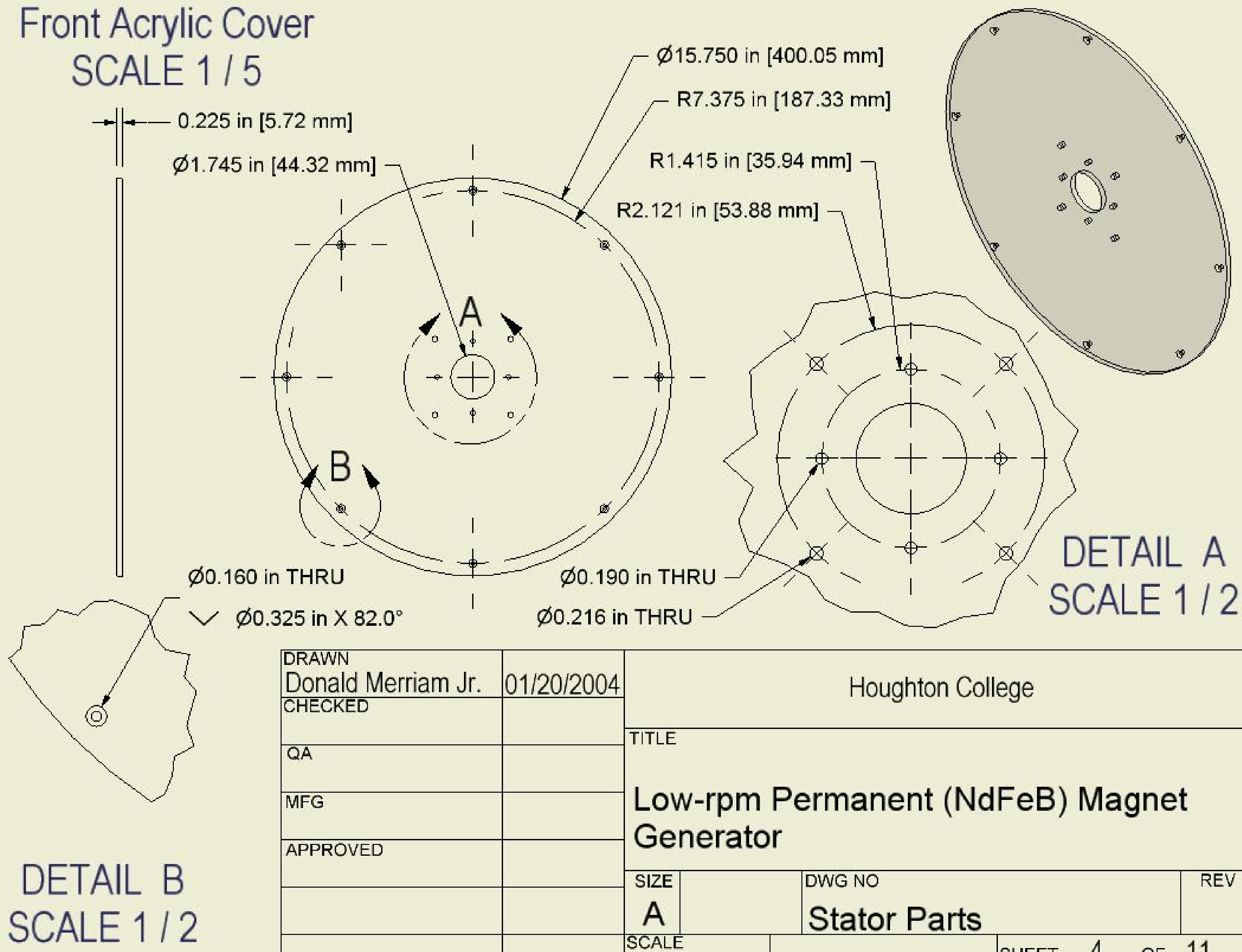
REV

Circular Aluminum Support
SCALE 1 / 2



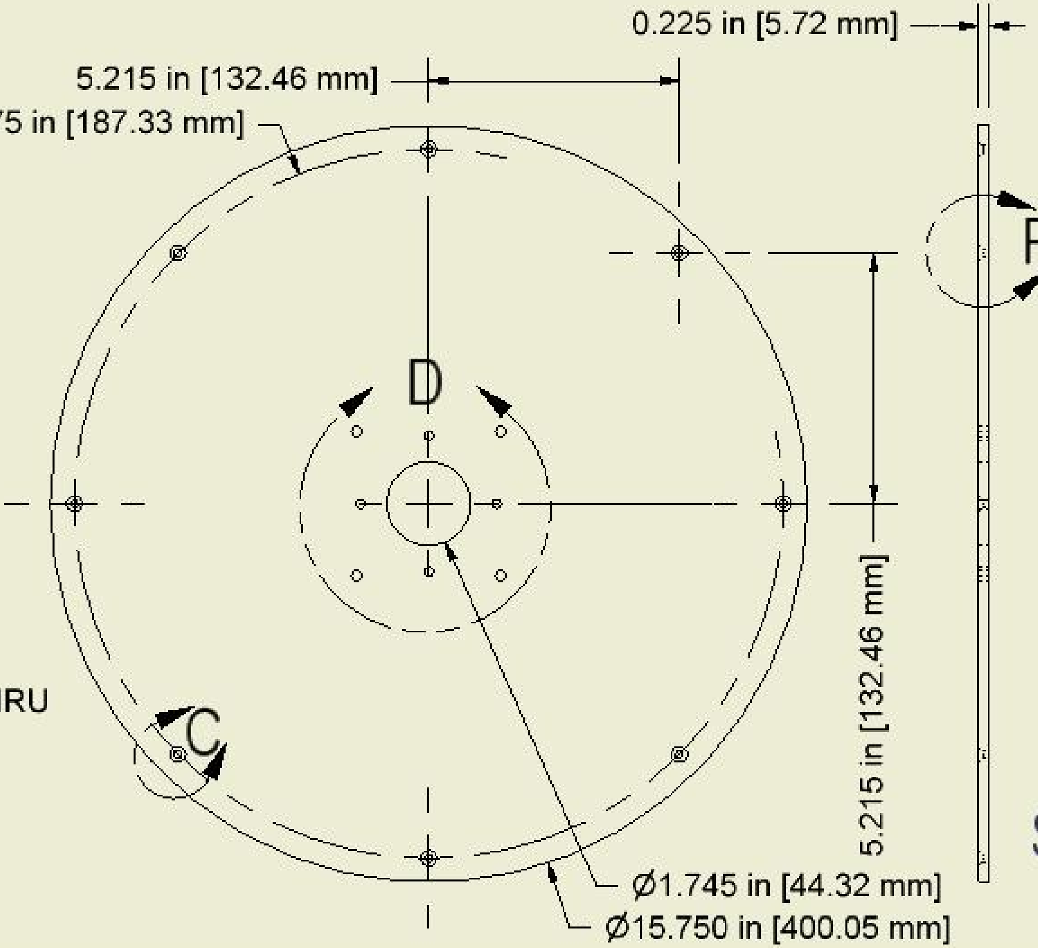


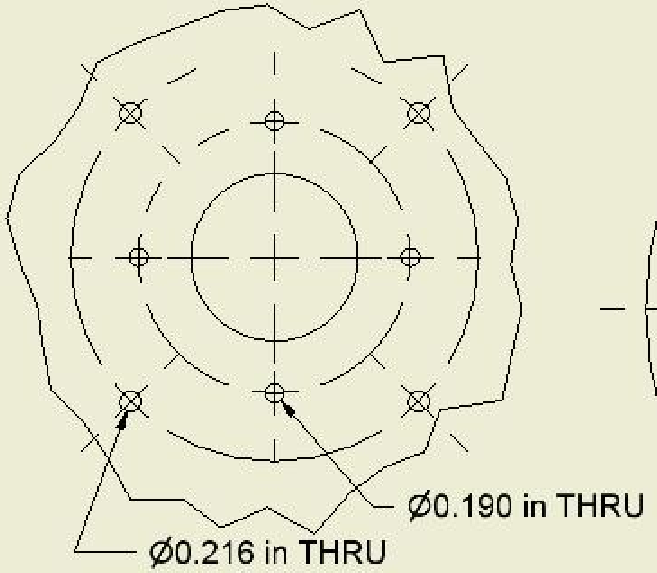
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A — DWG NO Stator Parts — REV
		SCALE — SHEET 3 OF 11



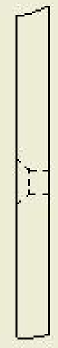
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College	
CHECKED		TITLE **Low-rpm Permanent (NdFeB) Magnet Generator**	
QA			
MFG			
APPROVED			
		SIZE A	DWG NO **Stator Parts**
		SCALE	SHEET 4 OF 11

Front Acrylic Cover
SCALE 1 / 4

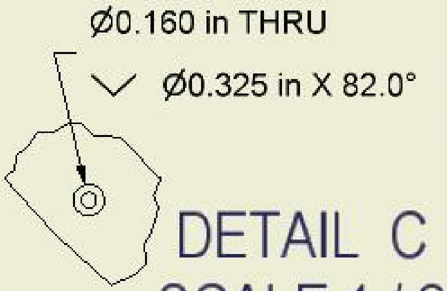




DETAIL D
SCALE 1 / 2



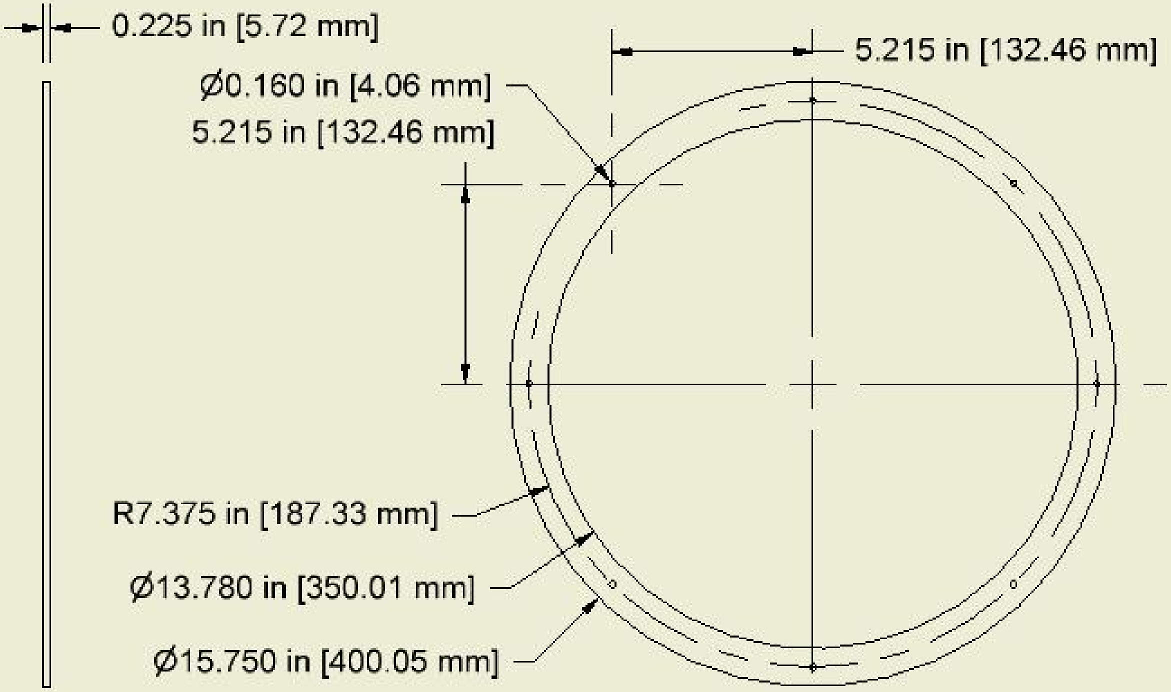
DETAIL F
SCALE 3 / 4

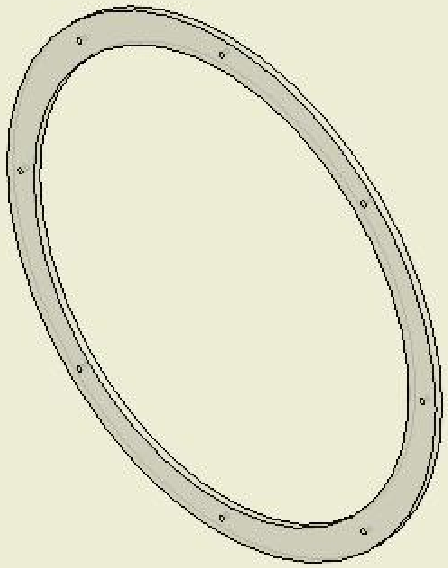


DETAIL C
SCALE 1 / 2

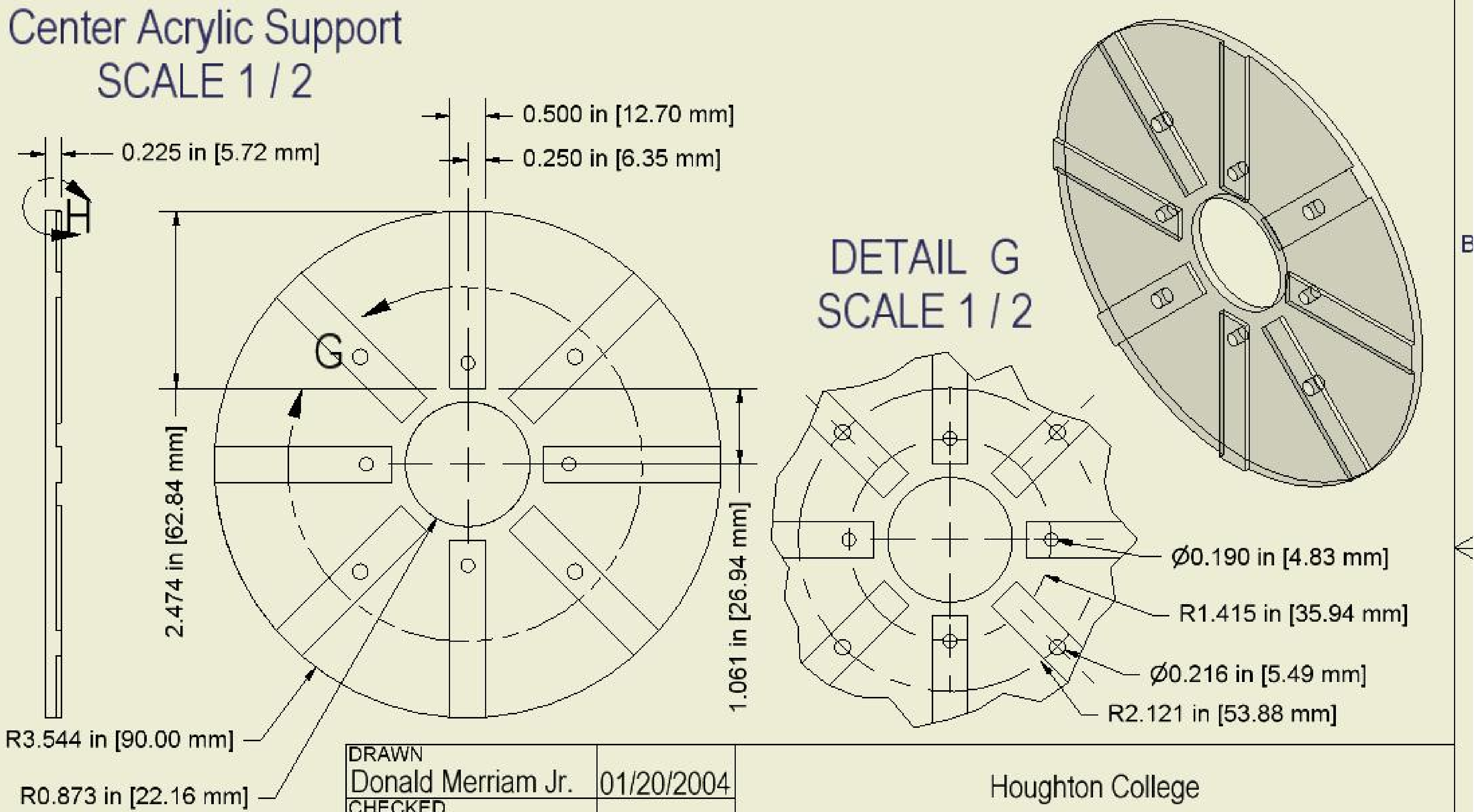
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A · DWG NO Stator Parts · REV
		SCALE · SHEET 5 OF 11

Center Acrylic Ring
SCALE 1 / 5

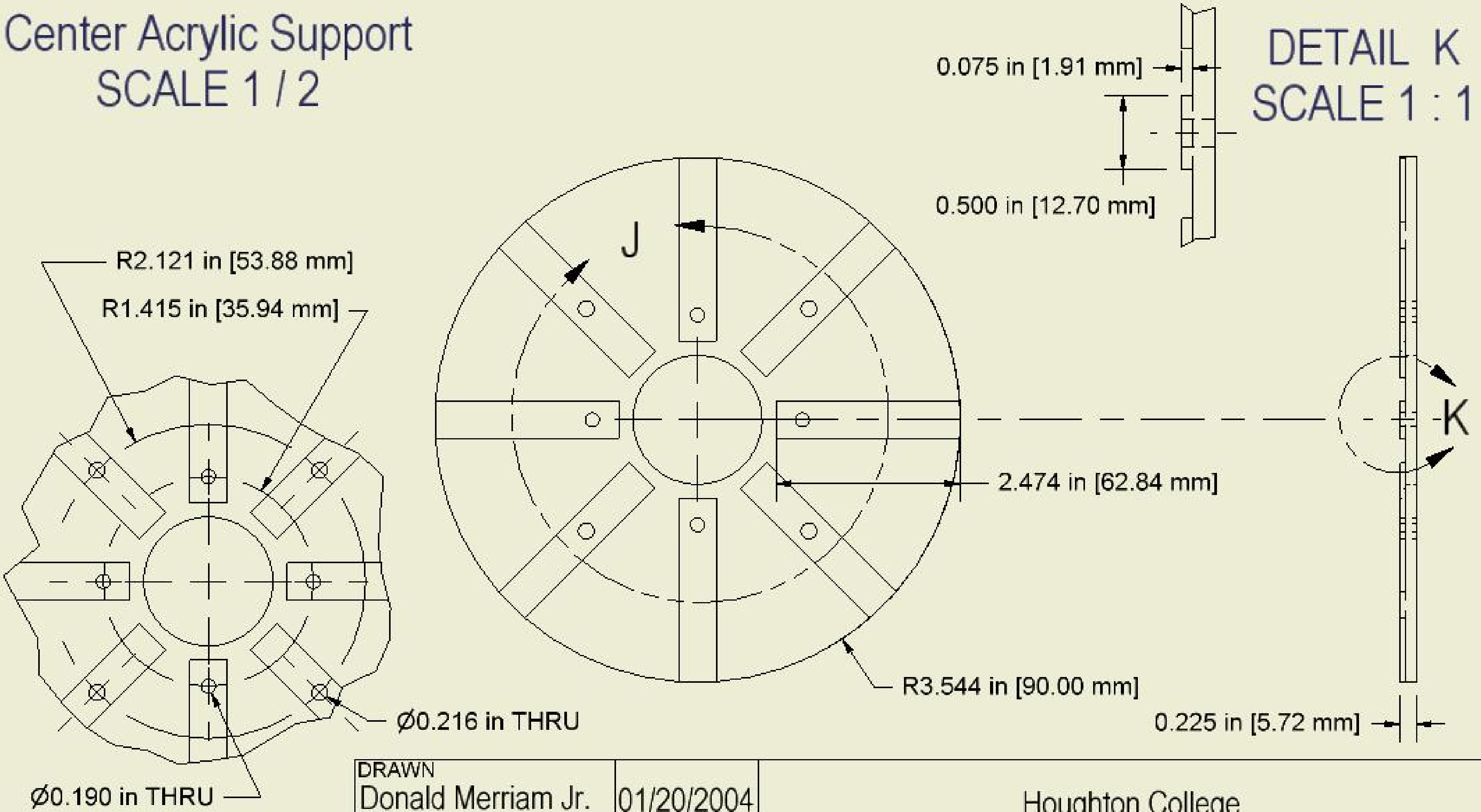




DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A · DWG NO Stator Parts · REV
		SCALE · SHEET 6 OF 11



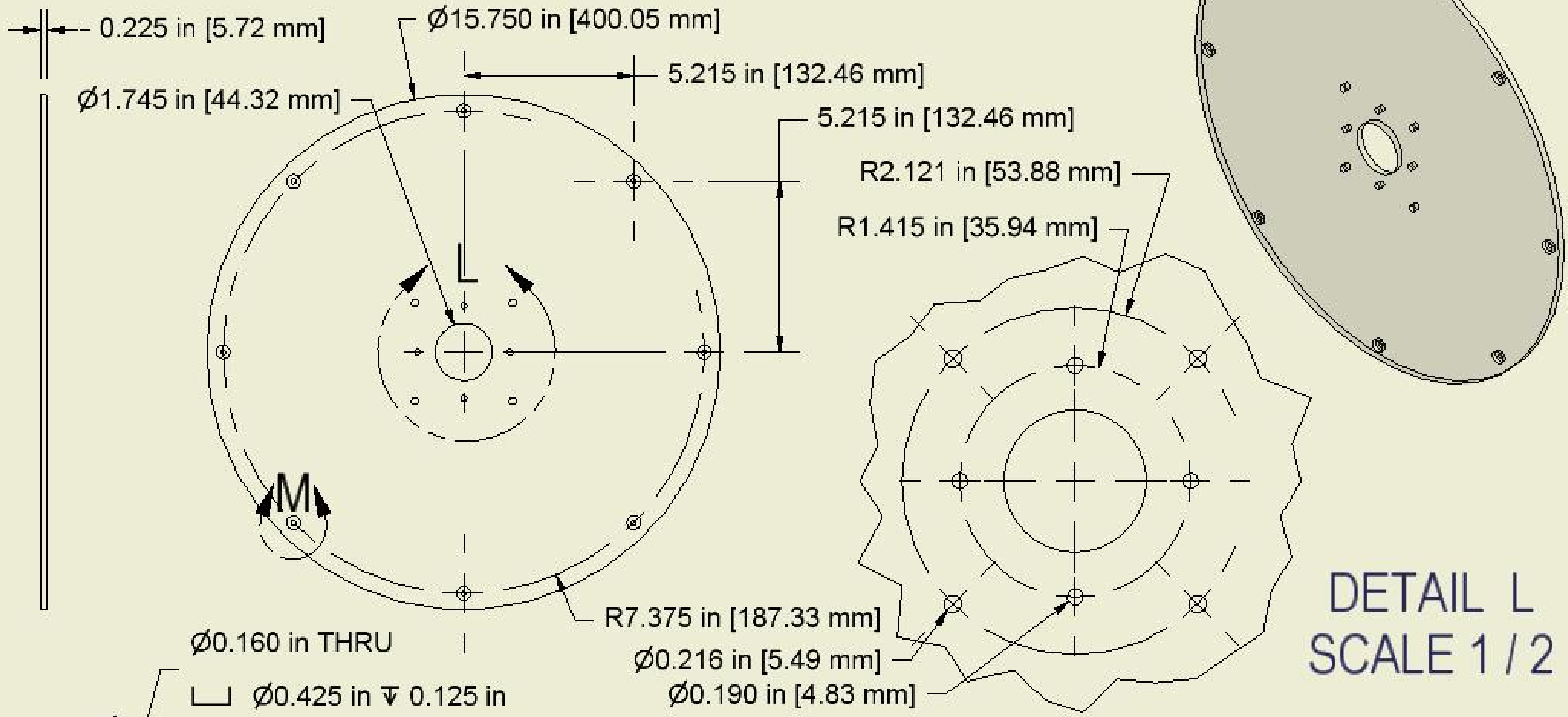
DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		
		SIZE A · DWG NO Stator Parts · REV
		SCALE · SHEET 7 OF 11

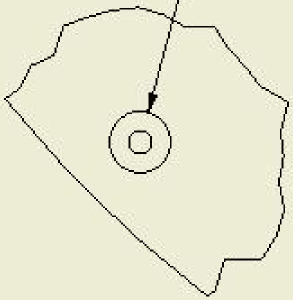


DETAIL J
SCALE 1 / 2

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		
		SIZE A — DWG NO Stator Parts — REV
		SCALE — SHEET 8 OF 11

Back Acrylic Cover
SCALE 1 / 5

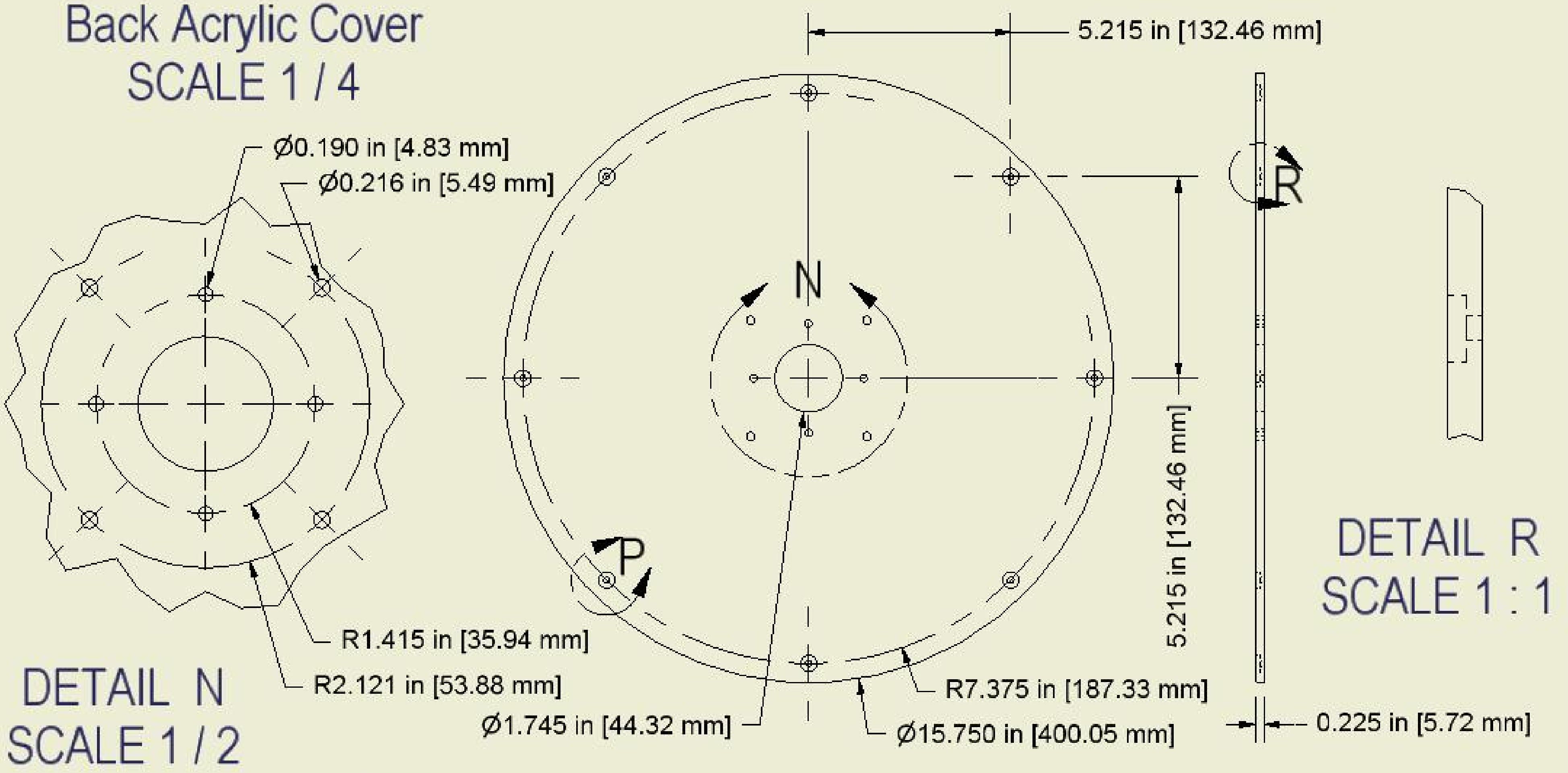


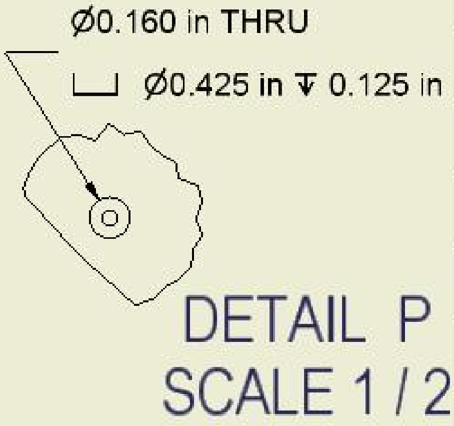


DETAIL M
SCALE 3 / 4

DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE Low-rpm Permanent (NdFeB) Magnet Generator
QA		
MFG		
APPROVED		SIZE A / DWG NO Stator Parts / REV
		SCALE / SHEET 9 OF 11

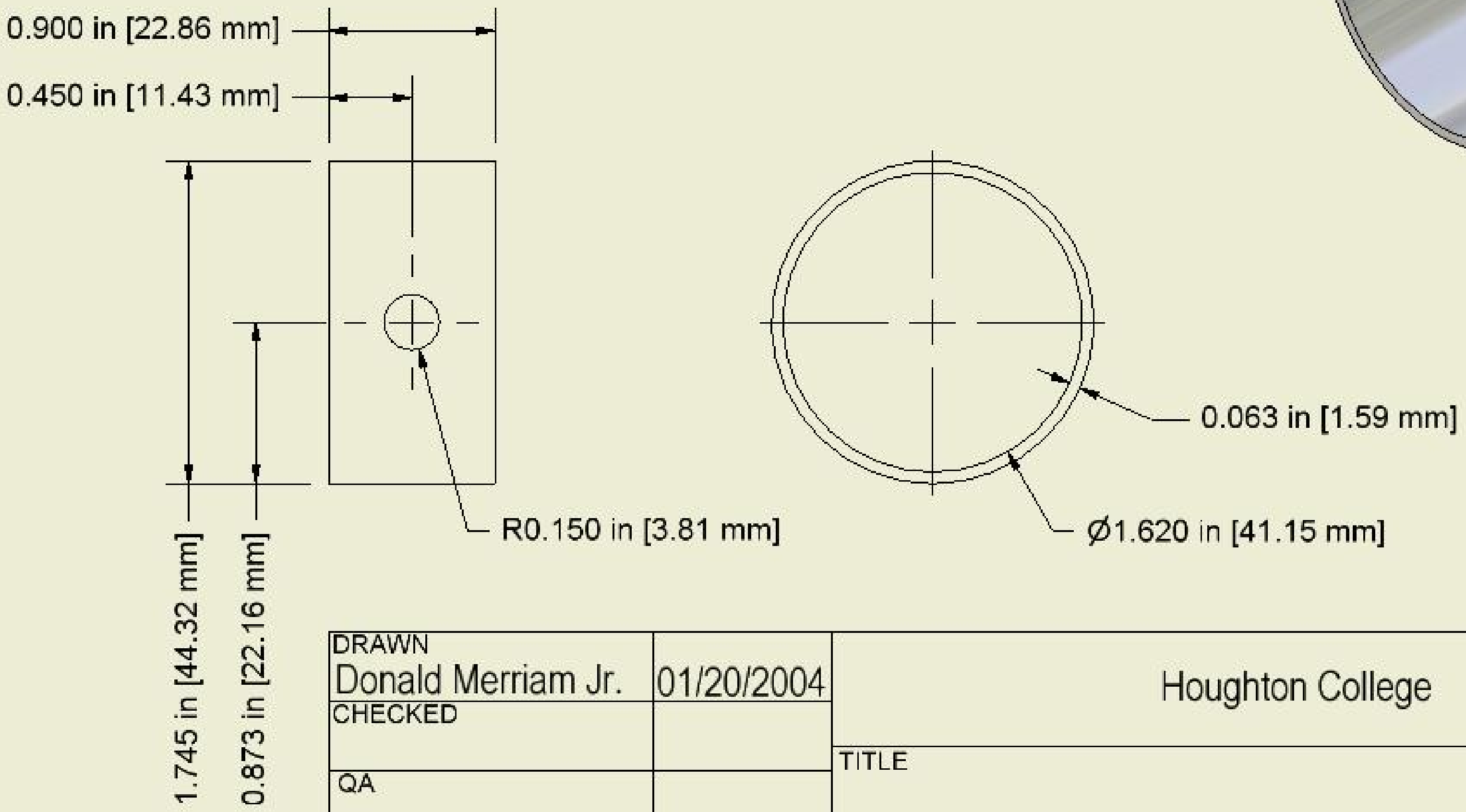
Back Acrylic Cover
SCALE 1 / 4





DRAWN Donald Merriam Jr.	01/20/2004	Houghton College
CHECKED		TITLE **Low-rpm Permanent (NdFeB) Magnet Generator**
QA		
MFG		
APPROVED		SIZE A
		DWG NO **Stator Parts**
		REV
		SCALE
		SHEET 10 OF 11

Pipe Collar
SCALE 1 : 1



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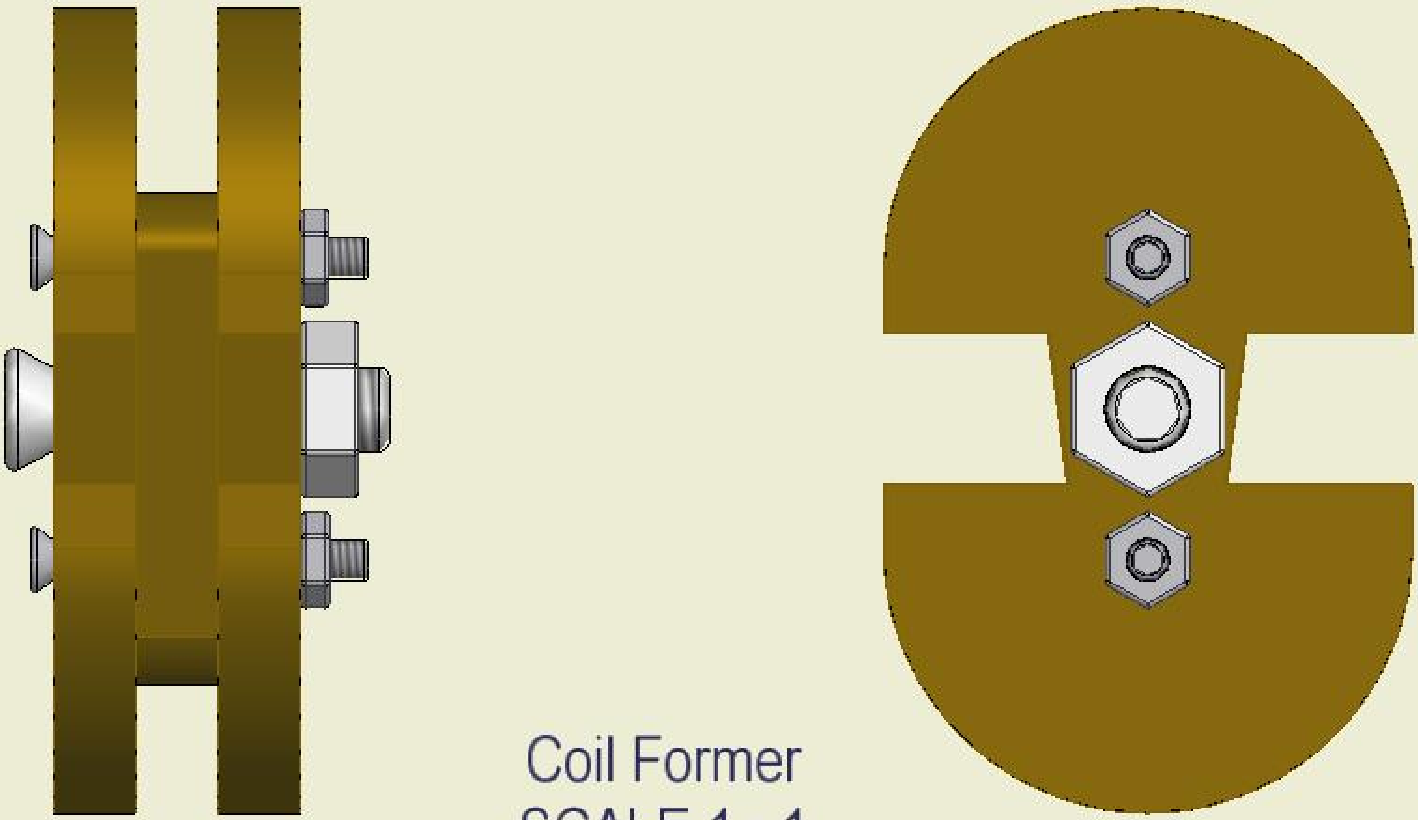
Houghton College

TITLE
Low-rpm Permanent (NdFeB) Magnet Generator

SIZE A
DWG NO Stator Parts
REV
SCALE
SHEET 11 OF 11



Coil Former
SCALE 1 : 1

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TITLE

Low-rpm Permanent (NdFeB) Magnet Generator

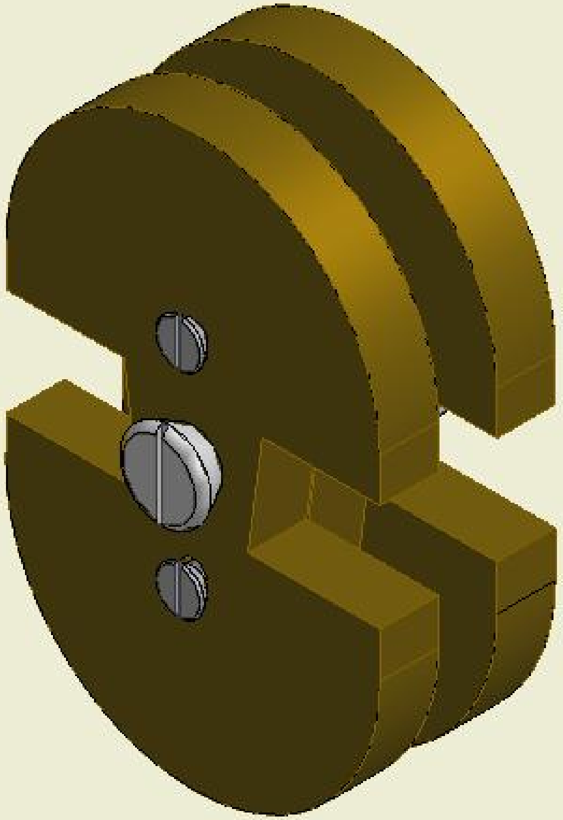
SIZE	DWG NO	REV
A	Coil Former Parts	

SCALE

SHEET 1 OF 7

Coil Former

Parts List				
ITEM	QTY	PART NUMBER	DESCRIPTION	SHEET NUMBER
3	1	No.7.16-14x_in	1.75 in. 7/16 in. screw	
4	2	No.12-24x_in	1.75 in. No. 12 screw	
5	2	No.12 Nut	No. 12 nut	
6	1	No.7.16-14_Nut	7/16 in. nut	
2	2	Coil Former End	Plywood	Coil Former Parts: 3
1	1	Coil Former Center	Plywood	Coil Former Parts: 4



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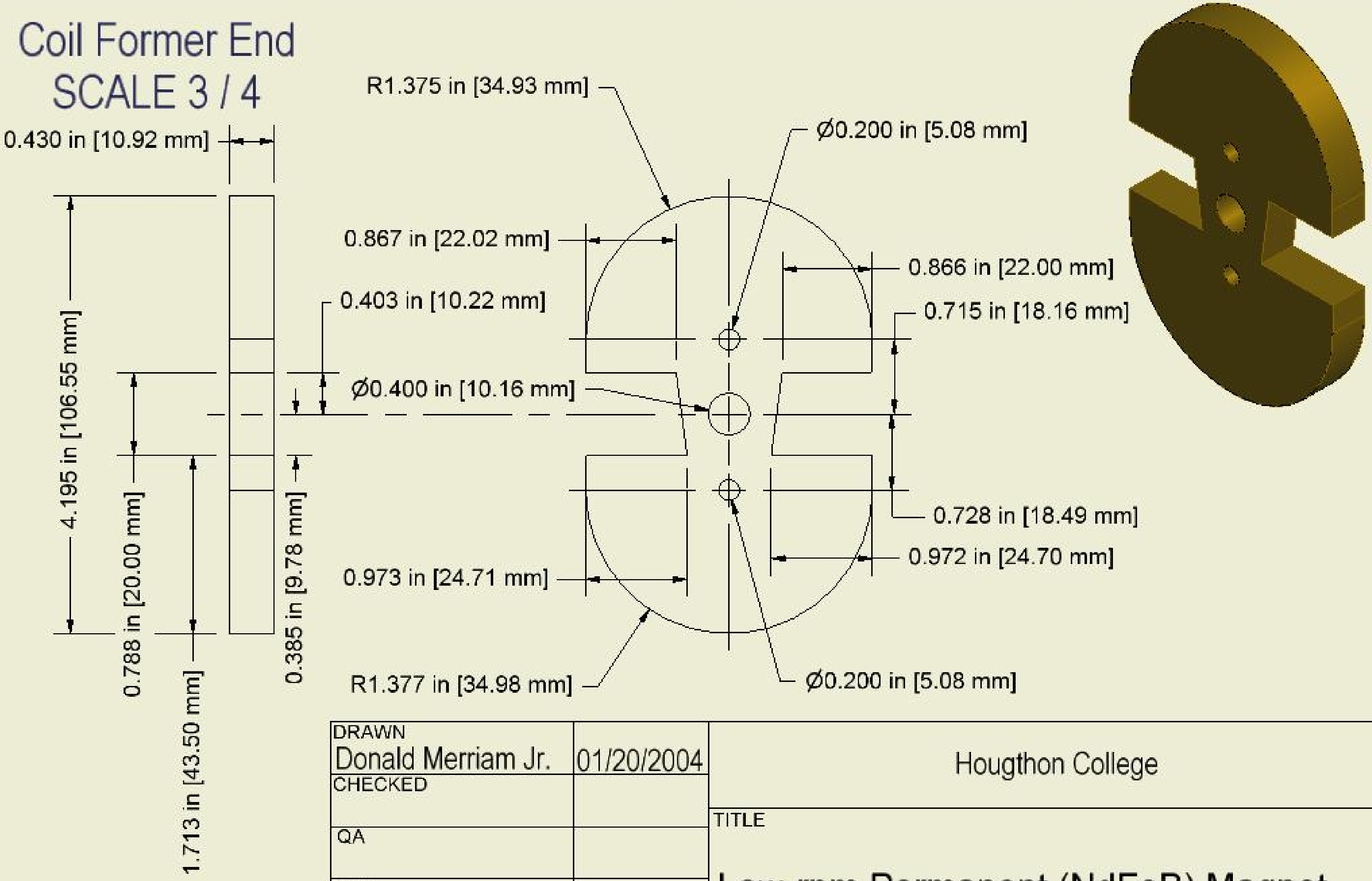
QA		
MFG		
APPROVED		SIZE A | DWG NO Coil Former Parts | REV
		SCALE | SHEET 2 OF 7

Coil Former End
SCALE 3 / 4



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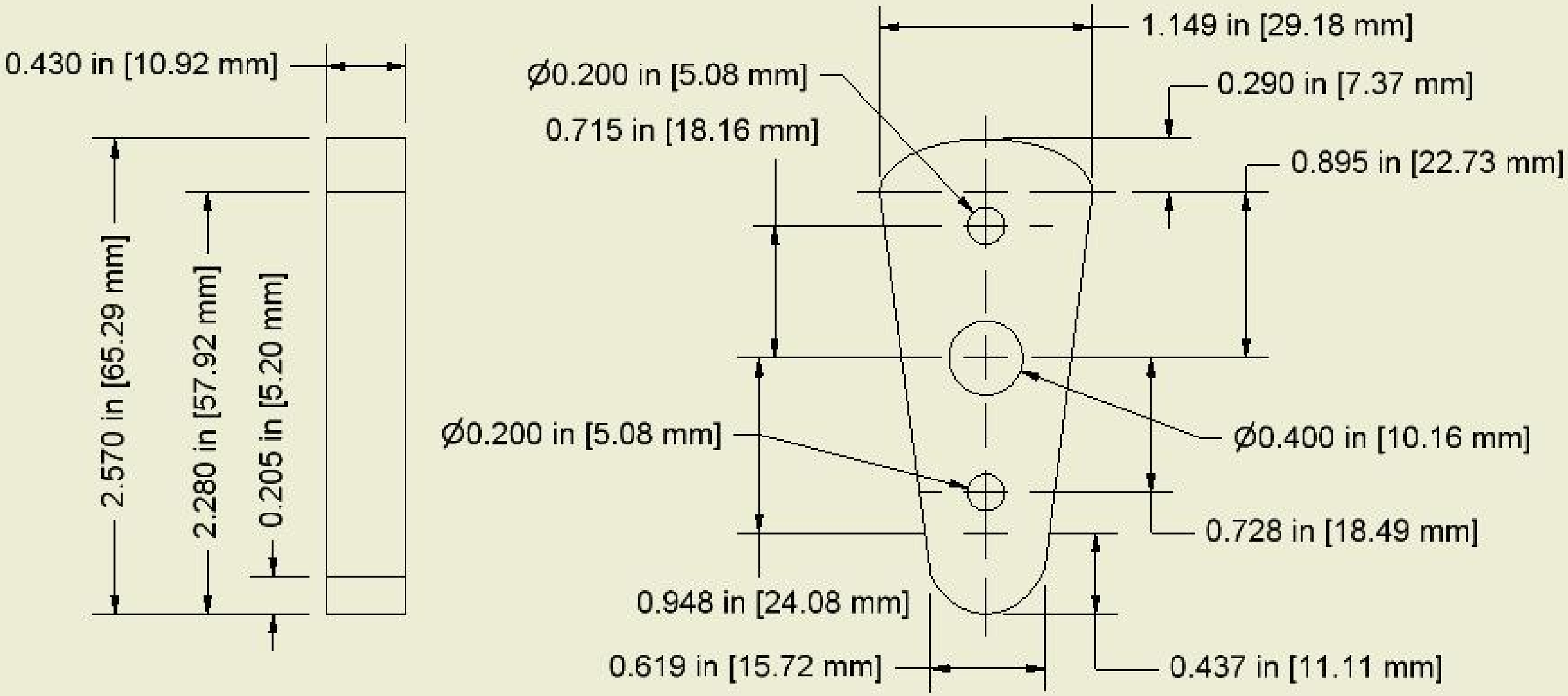
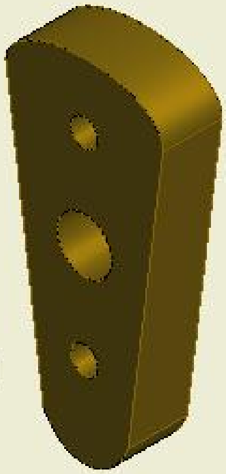
QA		
MFG		
APPROVED		SIZE A · DWG NO **Coil Former Parts** · REV
		SCALE · SHEET 3 OF 7

Coil Former Center
SCALE 1 : 1





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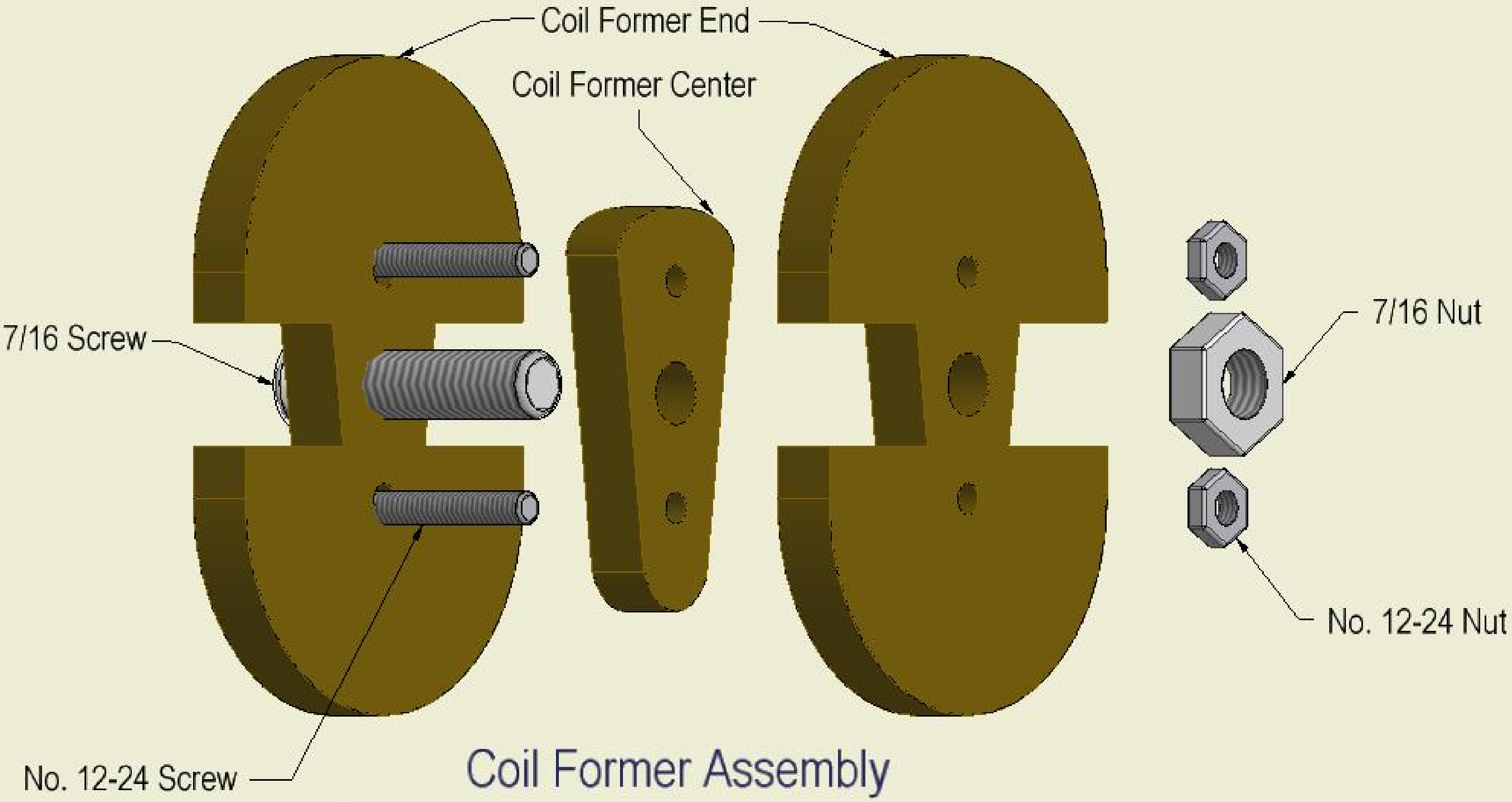
QA		
MFG		
APPROVED		SIZE A · DWG NO Coil Former Parts · REV
		SCALE · SHEET 4 OF 7



Coil Former Assembly

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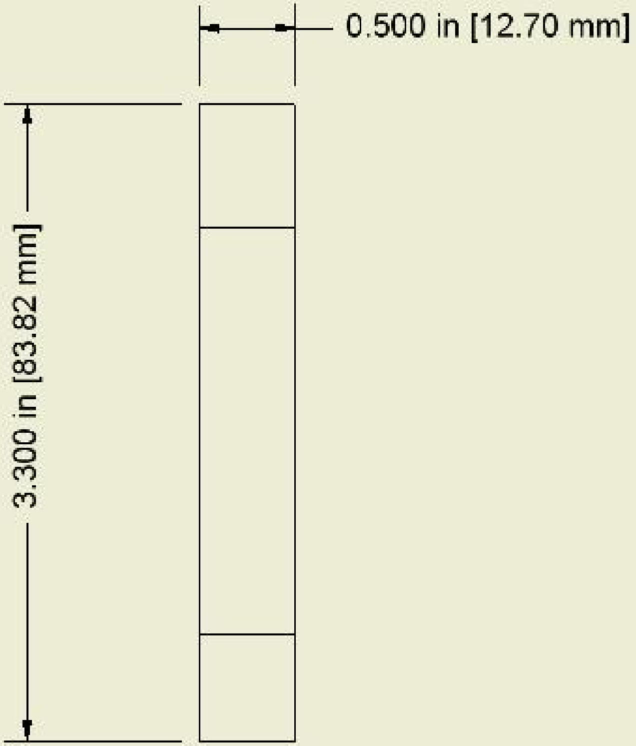
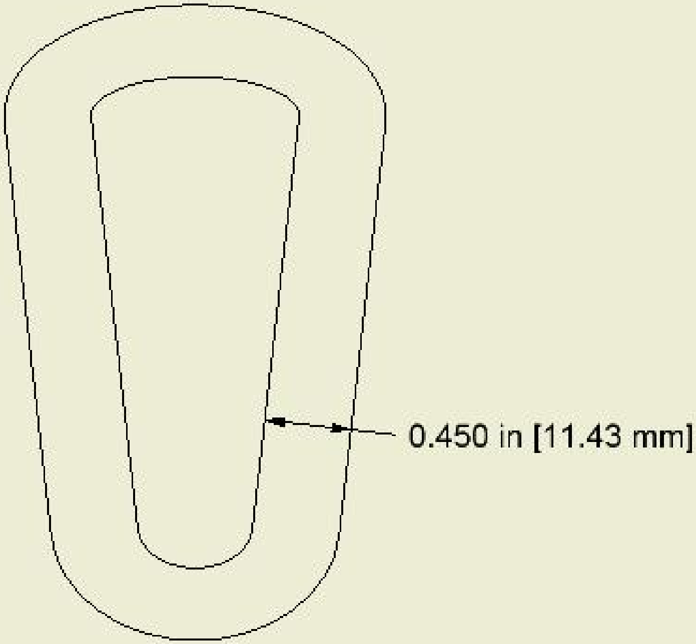
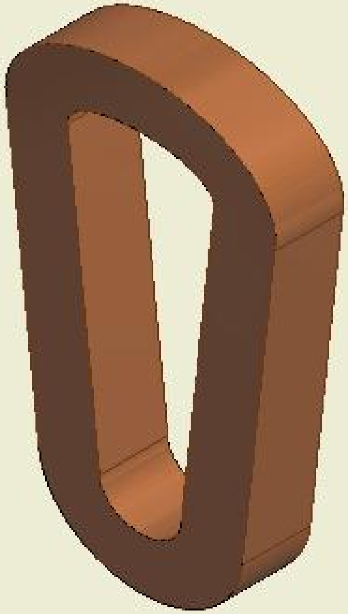
TITLE
Low-rpm Permanent (NdFeB) Magnet Generator

SIZE A
DWG NO **Coil Former Parts**
REV
SCALE
SHEET 5 OF 7

Coil
SCALE 1 : 1







The coil has 110 turns of 19 gauge copper wire.

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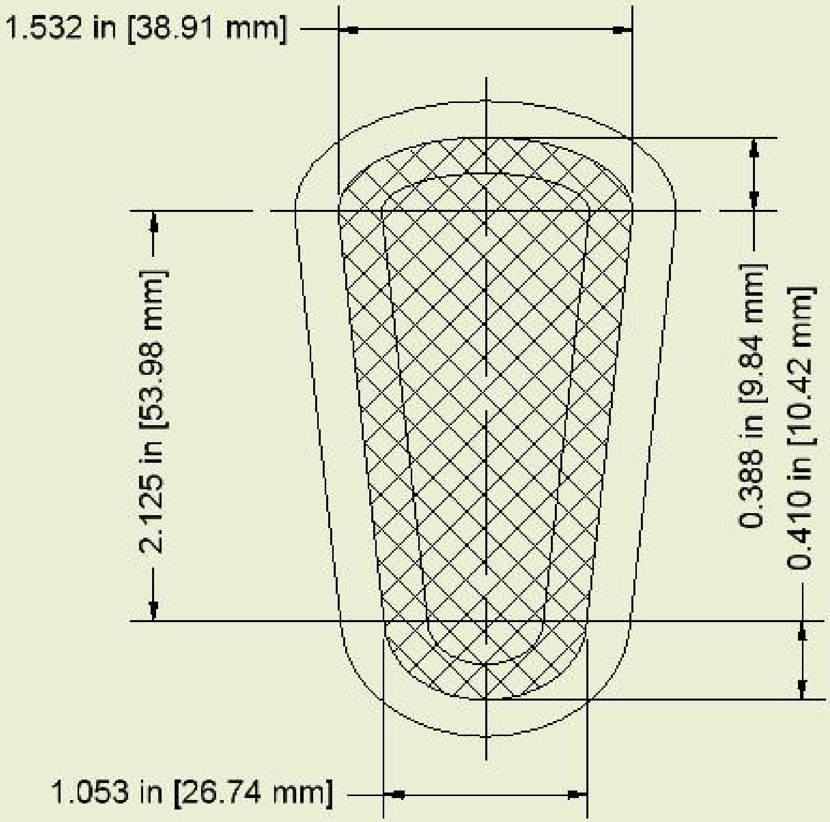
TITLE
Low-rpm Permanent (NdFeB) Magnet Generator

SIZE
A
DWG NO
Coil Former Parts
REV
SCALE
SHEET 6 OF 7

Coil Area
SCALE 1 : 1



The area used to calculate the emf through a single coil covers approximately half of the number of turns in the coil.

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TITLE

Low-rpm Permanent (NdFeB) Magnet Generator

SIZE A
DWG NO **Coil Former Parts**
REV
SCALE
SHEET 7 OF 7

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