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Shrouded small wind turbines

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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SHROUDED SMALL WIND TURBINES

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE
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MECHANICAL ENGINEERING

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Advisor

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Advisor

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Department Chair

SHROUDED SMALL WIND TURBINES

By

Kristen Flannery, Michael Holligan, Joseph Soares

THESIS

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ABSTRACT

The goal of this project is to improve the energy production of small wind turbines (rated less than 100 kW) by increasing wind velocity at the turbine blades through the design of a shroud attachment. The design process involves the analysis of various computer aided design (CAD) nozzle/diffuser shroud geometries. Computational fluid dynamic (CFD) modeling is used to analyze the effect of shroud features on velocity and pressure fields. A 3D printed scale model is tested in a wind tunnel with strain gauges and pressure transducers to validate the CFD data. The resulting design locally increases velocity by a factor of 1.47, and subsequent energy yield by a factor of 3.18 when compared to the performance of an unshrouded turbine. Additionally, the CFD modeling of the shroud was validated through pressure measurements along the shroud.

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Chapter 1: Introduction

1.1 Background Information

Global Energy Deficit

Despite numerous developments in energy technology, there are still over 1.3 billion people without access to electricity and 1 billion more only have intermittent access (see Figure 1 below) [1]. The majority of this population depends on candles, kerosene lanterns, or biomass cook stoves to fulfill the basic needs of nutrition, warmth and light. In addition to their inefficiencies, these energy sources can emit harmful toxins and pose dangers to children who may either burn themselves or ingest toxic fuel stored in soft drink bottles. Beyond household needs, there is an increasing energy demand in developing countries to provide water, health care and education. For these reasons, lack of access to electricity is one of the clearest indications of a country's poverty status.

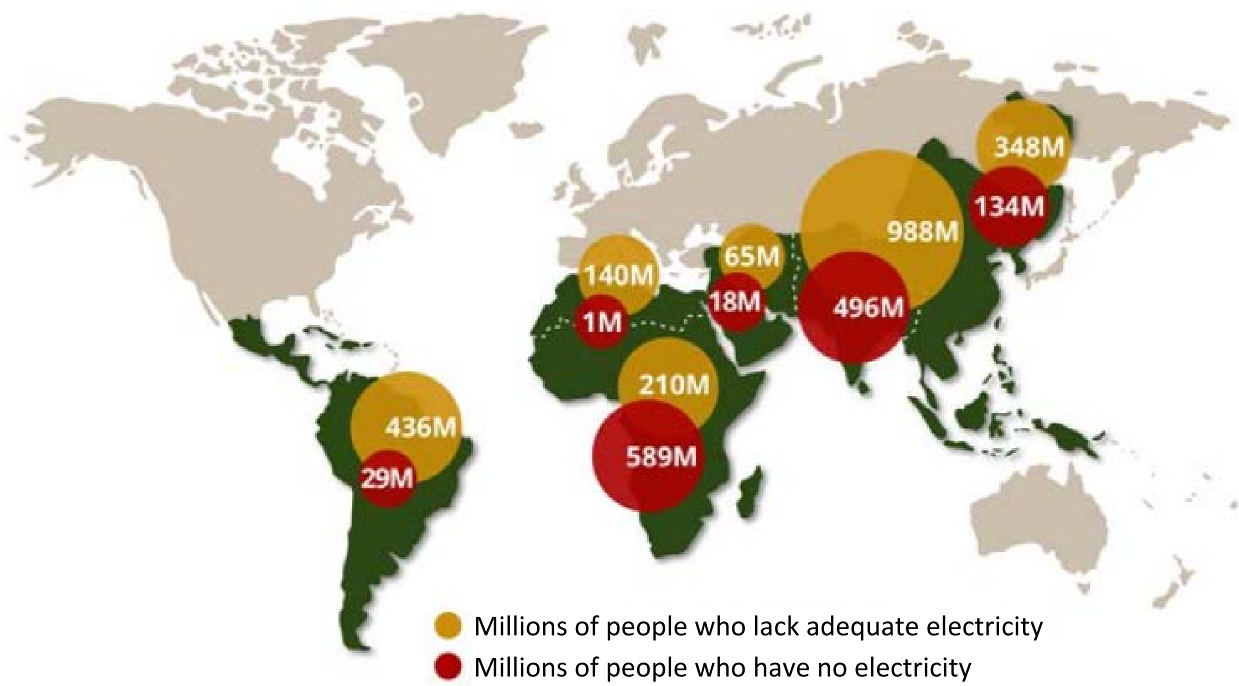

Figure 1: Global energy deficit represented by region [2].

Traditionally, electrical energy is derived from conventional sources such as fossil fuels or nuclear energy. In these systems, electrical energy is generated by a large power plant and transmitted over long distances through distribution lines. While this may be the status quo, there are numerous consequences to using these energy sources. Not only are fossil fuels quickly depleting as a resource, but the process of converting this source into electricity releases greenhouse gases and negatively influences both the quality and availability of water. Nuclear power poses its own threats as it continuously releases dangerous radiation and has been linked to increasing cancer occurrences. In recent decades, there has been a growing effort to derive energy from more sustainable sources, such as hydroelectric plants or solar panels. While they are less damaging to the health of the environment and population, these sources demand either advanced machinery or specialized materials to construct. The majority of the world population without access to electricity lives in rural areas where there is limited access to the specific parts and materials needed to construct technologies such as solar panels. Additionally, they lack the capacity to construct large dams for hydroelectric plants.

Potential of Small Wind Turbines

As an alternative, wind turbine technology may provide electricity in these rural locations. In particular, small wind turbines are an attractive option for developing markets that currently lack electricity or are energy deficient. As a general guideline, small wind turbines are classified within the range of 1 kW-100 kW.

Small wind turbines have many benefits. They are easy and quick to install as they come in small sizes and have a shorter construction lead time than extending the utility grid lines. Small wind turbines can operate for extended periods without attention; with only a few moving parts, these systems have very low maintenance requirements compared to other energy options. Additionally, small wind turbines are not difficult to manufacture. In this respect, local manufacturing is often a suitable option for developing countries that could, in turn, stimulate local economic development and lower production costs. Wind systems replace existing household expenditures for kerosene, candles and dry-cell batteries. Lastly, wind systems require little to no water to operate and do not contribute greenhouse gases or other toxins to the environment.

Figure 2 illustrates the growing cumulative capacity of small wind power across the globe.

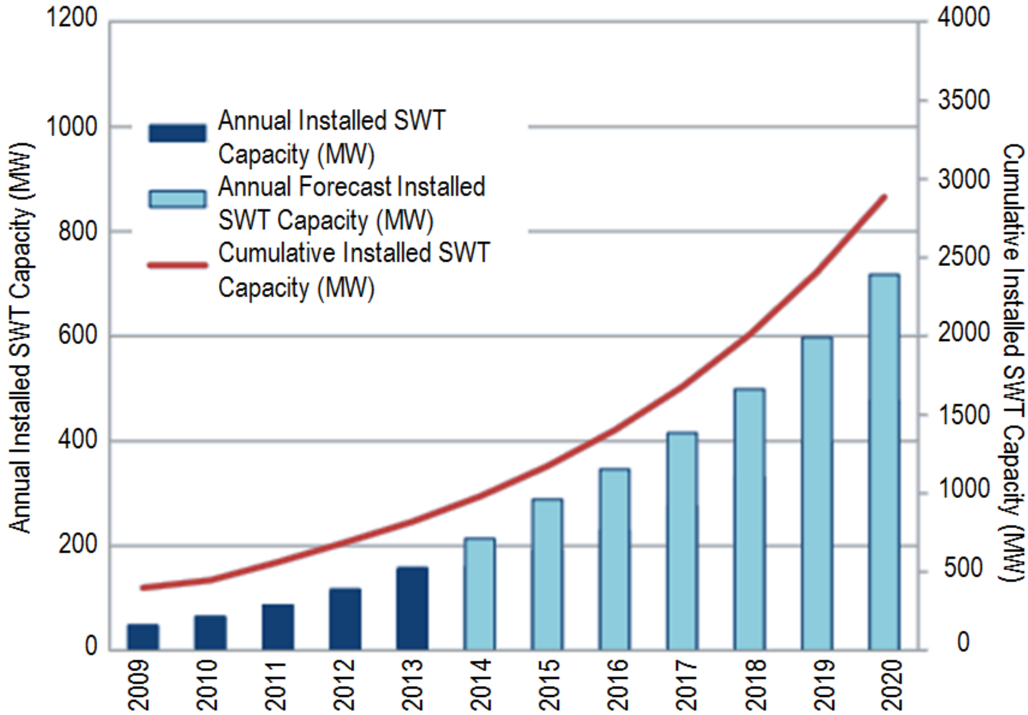

Figure 2: Small wind turbine global installed capacity and forecast [3]

There are about 330 companies in 26 countries manufacturing small wind turbines, and the global market for small wind technologies is forecast to more than double between 2010 and 2015, reaching USD 634 million. The installed capacity could increase threefold in the same period [4]. Much of this growth will take place in developing and emerging markets.

Design Rationale

While small wind turbines are associated with numerous benefits, their market penetration and social impact still faces certain limitations. Because wind turbines operate in a specified ideal wind speed range, locations with lower or unreliable wind speeds are deemed unsuitable for small wind turbine installation. Moreover, locations that are able to justify an investment in small wind turbines often find that their energy demand quickly increases and that energy yield of the wind turbine is no longer sufficient. In these cases, a reliance on unsafe energy such as diesel persists. This project is aimed at developing a solution that will help rural communities both justify a wind turbine installation and accommodate growth in energy demand.

Figure 3 illustrates the annual frequency of wind speeds collected from a rural Nicaraguan village along with the corresponding energy yield of a wind turbine operating at that speed in megawatt-hours.

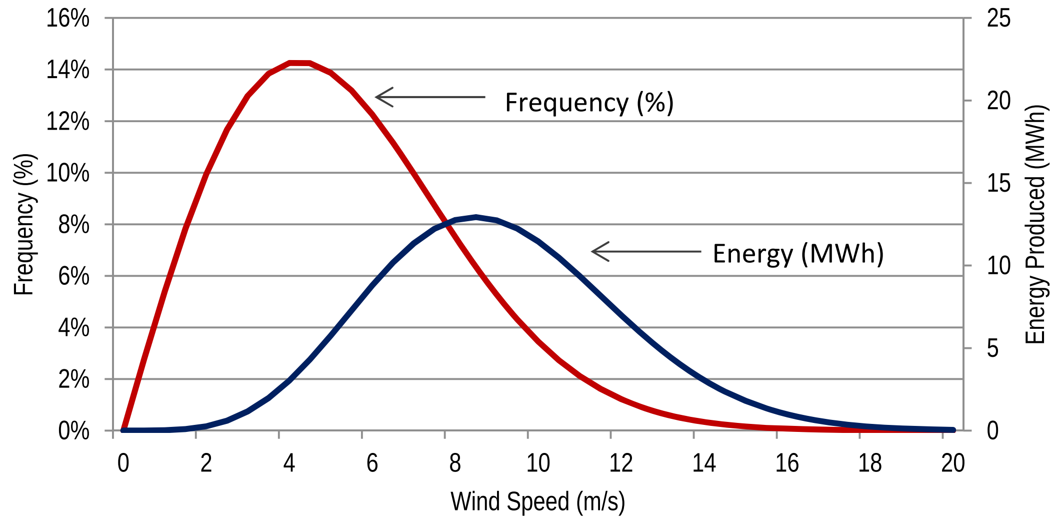

Figure 3: Frequency and energy yield of wind speeds [5]

Conversely, Figure 4 models how the annual energy yield would be influenced by an increase in the frequency of higher wind speeds. This drastic energy boost is associated with a adjusting the average annual wind speed from about 5.11 m/s to about 7.67 m/s, a factor of 1.5.

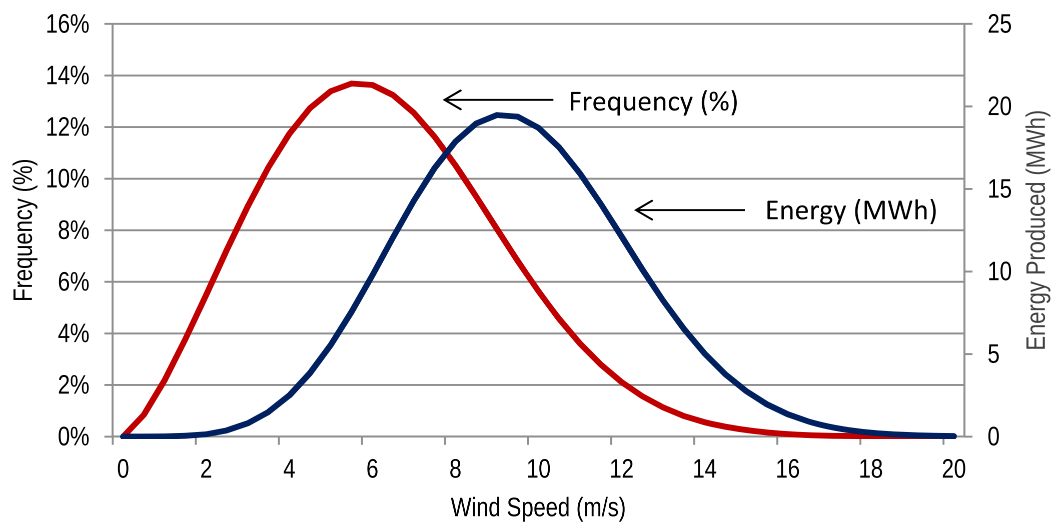

Figure 4: Frequency and energy yield of wind speeds with shroud

Even a minor increase in the frequency of higher wind speeds could result in enough energy yield to justify the construction of a small wind turbine. By revisiting small wind turbine technology and executing design modifications that increase the local inlet velocity, small wind power can become a more reliable and accessible source of electricity for up to 2.3 billion people across the globe.

1.2 Literature Review

The following sources provided a foundation of research and directed the project towards the concept of developing a shroud attachment as a method to increase the productivity of small wind turbines

Bergey Excel 10 Product Brochure

One of the highest performing small scale wind turbines on the market is the Excel 10 kW wind turbine, made by Bergey Windpower (see Figure 5). The performance of this wind turbine provides a baseline for data comparison. It has a 7 meter (23 ft) diameter and an AWEA (American Wind Energy Association) rating of 8.9 kW at 11 m/s (24.6 mph) [6]. In addition to its high power output, other notable aspects of the turbine are its start-up speed of 3.4 m/s (7.5mph) and a cut-in speed of 2.5 m/s (5 mph). Considering that these are relatively low velocities compared to other small wind turbines, an opportunity arises for energy to be produced for a greater duration throughout the day and in locations with inconsistent wind speeds. The AWEA rates the Bergey 10 kW at 13,200 kWh annually at an average of 5 m/s (11 mph).

Figure 5: Bergey Excel 10 wind turbine in operation [7]

A Shrouded Wind Turbine Generating High Output Power with Wind-lens Technology

A new advance in wind technology is the wind lens. It acts as a diffuser, mounted behind the wind turbine, to create a lower pressure area resulting in increased wind speeds through turbine. The diffuser augmented wind turbine (DAWT) was designed for use on a 5 kW, three blade wind turbine that was to be applied on the shore of Hakata Bay in Japan [8]. Initial tests were performed in order to see whether a nozzle or diffuser would better increase wind speeds and, between the two different designs, the diffuser performed significantly better. The data shows that for the prototypes they built, the high pressure area in the nozzle prevented significant flow through the turbine.

This prompted the construction of a model that would increase the wind velocity through the wind turbine that included a slight inlet shroud and a diffuser with a brim. A low-pressure region is generated behind the brim as vortices are created. After this general design, four different designs were created, each with a different cross-sectional area. With each of these models the iterative design process was utilized in order to produce the greatest power coefficient.

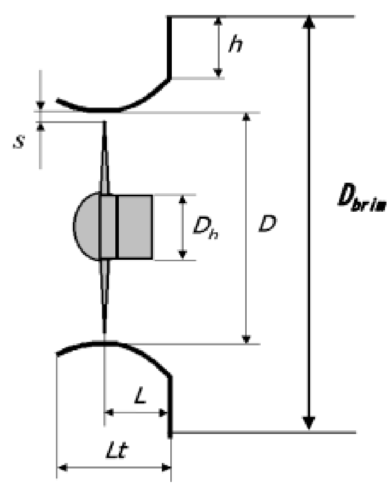

Figure 6: Schematic of wind-lens turbine [8]

Wind Tunnel Tests on a Wind Turbine with Contractor and Diffuser Arrangement

Another system for increasing the wind speed through a wind turbine is a symmetrical nozzle and diffuser. Nine different models were tested in which the main parameters investigated were the ratio of inlet to turbine diameters, the ratio of outlet to turbine diameters, and the length of transition from inlet to contraction and outlet [9]. Through the use of different geometric variations and CFD modeling, it was determined that a mirrored system where the inlet matched the outlet would produce the best results. In order to best analyze the data from modeling and testing, the energy in the airflow and the ratio between energy at the inlet and energy at the turbine blades was calculated by

$$W = 1/2\rho A U^3 \,, \tag{1}$$

$$\frac{W_2}{W_1} = \frac{\rho_2 A_2 {U_2}^3}{\rho_1 A_1 {U_1}^3} = \left(\frac{U_2}{U_1}\right)^2 \tag{2}$$

where W is the wind energy available, ρ is the density of air, A is the cross-sectional area, and U is the velocity of the air. Along with their design, data from the modeling and wind tunnel testing is provided. This data shows the differences in power output from the turbine when provided with a constant wind speed.

Small-Scale Wind Energy Portable Turbines (SWEPT)

Not only is there growth in the wind industry relating to the power production of wind turbines, but also related to the usefulness and portability of turbines. This development of a very small and transportable turbine with the integration of a shroud attachment shows that the improvement of wind speeds can be used in many different circumstances, large or small [10]. In addition, SWEPT shows that researchers are continually finding ways to improve and increase the usefulness and applicability of wind turbines.

CFD Analysis for Optimization of Diffuser for a Micro Wind Turbine

In the hope of lowering the pressure at the outlet of the diffuser even more, the effect of a flange around the outlet and its angle has been researched. Three different setups were tested: a diffuser without a flange, a diffuser with a vertical flange, and a diffuser angled back 10° [11]. From the tests, it was concluded that while the diffuser without a flange increases wind speeds through the turbine by 18.57%, it does not compare with the effects of adding a flange. When the diffuser is vertically flanged, wind speeds are increased by 34.28% and when the flange is angled 10°, speeds are increased by 40.3%. Through a fairly simple test, it was proven that by angling the flange, speeds are significantly affected.

Characteristics of a Highly Efficient Propeller Type Small Wind Turbine with a Diffuser

Specific aspects of wind turbine diffusers were researched in 2006 in order to find an optimal design [12]. One of these characteristics is the angle at which the diffuser opens up from the constricted area to the outlet. The data gathered shows that the ideal expansion angle, the one that provides the greatest speed ratio, is an angle of 6°. The flange height was also studied as a feature of the diffuser, which was determined to have a negligible effect on the wind speed ratio as long as the flange was a tenth of the diameter of the turbine.

1.2 Project Goals and Objectives

The ultimate goal of this project is to first optimize a shroud design and then demonstrate through scaled model testing that the shroud design can increase both the duration for which a small wind turbine can be effectively used at peak efficiency and its total operating time.

Wind turbines have a specified wind speed operating range at which they produce energy at higher efficiencies. A successful shroud prototype enhances the incoming wind speeds with a nozzle/diffuser shroud mounted to the turbine to modify the wind flow convergence. Specifically, the shroud increases wind speeds through the turbine, is structurally sound, and minimizes drag. The design approach consists of:

1) The development of a 3D CAD (computer aided design) model of the turbine and shroud attachment.
2) Testing using CFD (computational fluid dynamic) modeling to provide information on the velocities through the turbine, as well as pressure fields on the shrouded model.
3) A scaled physical 3D model built using a rapid prototyping machine to test in a wind tunnel using strain gauges and pressure transducers.
4) Iterations of the model continued to improve the physical design until the test data fulfilled the stated requirements below.

Feedback from faculty advisors and other qualified professionals was incorporated throughout the process.

Chapter 2: System-Level Analysis

2.1 Customer Needs

The end user of this solution will ultimately be individual energy consumers that are included in the 2.3 billion people with either intermittent or no access to electricity. Because the targeted customer segment is not generally considered to have much purchasing power, non-traditional marketing analysis approaches must be used in order to properly assess its needs. Moreover, the design will be most viable and appropriate in rural areas where distribution poses an added challenge.

The projected wind power capacity should be sufficient to accommodate the needs of an entire community. Opinions from the community as a whole, especially those in leadership positions, must be taken into account before the individual energy consumer can be even reached. Each customer segment is associated with a set of needs that must be carefully addressed as it is imperative to begin the design process with the end user in mind and consider exactly how that end user is defined.

In order to develop a preliminary definition of the customer's needs, research performed by other organizations was analyzed in the context of the project objectives. A prominent case study, involving the implementation of a small wind turbine (Bergey Excel 7.5 kW) in a rural Chilean village, revealed details regarding energy requirements and cost limitations [13]. The pilot energy system consisted of a hybrid small wind turbine-diesel generator system. The project was initiated amongst five organizations with separate functions but a common objective: to evaluate operational performance and social benefits of the system. Interviews with the community led to several conclusions that can guide decisions on the design and implementation of a shroud to the system:

- The study illustrates the possibility of introducing wind energy as a hybrid system with diesel energy or potentially solar energy. Depending on the culture and experiences of the community, this may be the most suitable way to introduce renewable energy.

- The notion of grid-tying must be contextualized to a particular area. Transmission lines across the globe do not operate with the same level of reliability. It is critical to analyze the limitations and requirements of the distribution system so that the perceived value of a technology implementation is not damaged by surrounding issues.

- This particular customer segment is especially frugal and is highly aware of any changes in expenditures. It is important to consider this when developing a payment method to ensure that it is fair and corresponds to the perceived value of the utility.

- It is important for the wind power system to not only accommodate current energy usage, but also enable future development. The current cultural priorities may provide insight into energy applications that are likely to grow in popularity, allowing advanced planning for system expansion.

While the full-scale prototype may not be necessarily implemented in a Chilean village or even in an area with aligning cultural values, this assessment still provides insight into important design considerations.

A market survey report was conducted by reaching out to several industry experts who are familiar with both small wind turbine systems and implementations in developing markets. These interviews guided the following system requirements that are aimed at fulfilling specific customer needs. Refer to Appendix A for transcripts of surveys and interviews.

2.2 System Sketch

Our aim is to research and develop one potential solution to improve the overall utility of a small scale wind turbine. This will be accomplished by attaching a shroud to the turbine and increasing the air flow through the turbine. In its final form, this product would be attached to a small scale wind turbine and used in conjunction with a battery storage unit to provide electricity to a small village. However, this project is focused solely on the design and development of the shroud attachment that will be used on the wind turbine. The sketch below demonstrates the application of a wind turbine that has been equipped with the shroud.

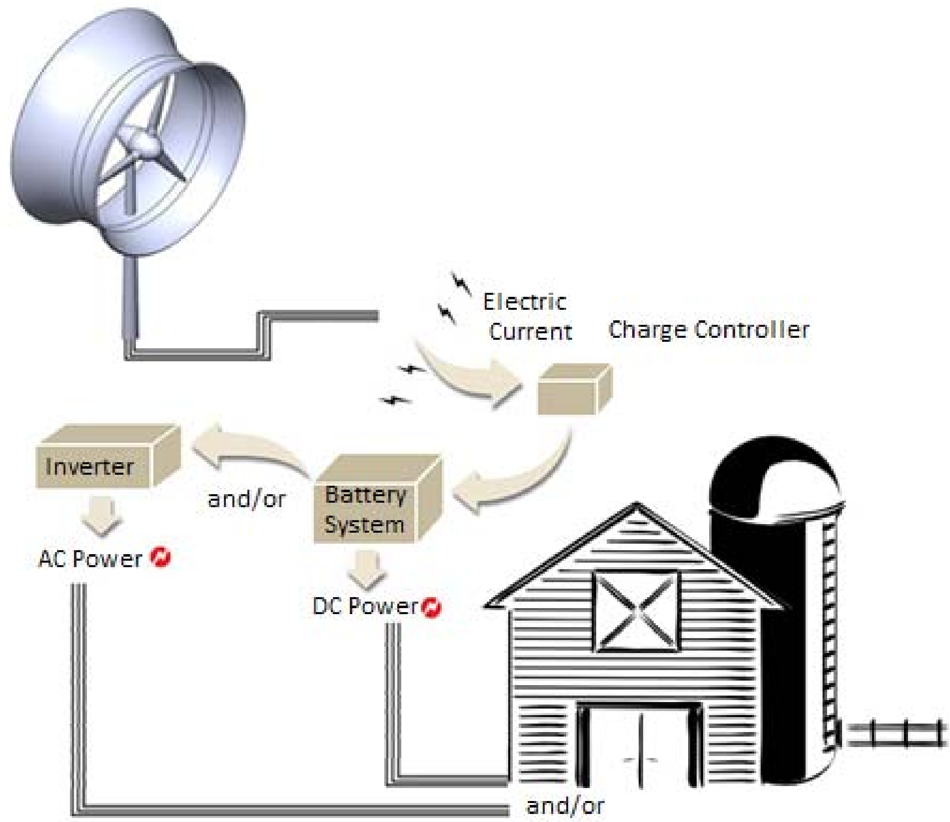

Figure 7: System level sketch of shrouded small wind turbine.

Figure 7 provides a simplified diagram of how the shroud design can integrate with an electrification system. The electric current may be sourced to either a DC storage system such as a battery bank or through an inverter to provide AC power to an electrical grid. This effectively demonstrates that introduction of the shroud to the system does not interrupt the normal operation of the wind turbine, which suggests the possibility of implementation on both new and existing electrification systems.

2.2 System Level Requirements

The Performance and Design Requirements were used as criteria of success for this project while the Economic and Implementation Requirements can provide guidance for full-scale implementation decisions.

Performance and Design Requirements

1) Shroud must be attached around the wind turbine without interfering with the blades or other mechanisms of the turbine.
2) Shroud should increase the wind speed through the turbine by a factor of 1.5.
3) Energy production should be improved by a factor of 3.375.
4) The system should minimize increased load to the turbine post due to drag forces while still meeting other performance requirements.
5) Shroud design should emphasize manufacturability to lower production costs.

Economic and Implementation Requirements

6) Lifetime of shroud must meet or exceed that of the turbine, approximately 20 years.
7) Shroud should not require maintenance at higher frequency than every three years.
8) Payback period should be less than five years.
9) System should be aesthetically pleasing within the context of the local culture.
10) Shrouded turbine should not generate any more noise than an unshrouded Bergey 10 kW turbine, 42.9 dB.

The Verification Matrix in Section 5.4 evaluates the measured results of the selected shroud prototype against the stated Performance and Design Requirements.

2.4 Functional Analysis

The shroud design consists of three main features: the shroud inlet is essentially the nozzle portion of the design and will be used to increase the incoming velocity by decreasing the cross sectional area of the shroud, the shroud outlet is a diffuser which causes the air to experience a decrease in pressure, which creates a pressure differential between the inlet and outlet air, thus causing an increase in wind speed through the turbine, and the shroud flange is located at the back edge of the shroud and creates a low pressure point that also increases the wind speed through the shroud. Below, both an assembly and exploded view of a representative wind turbine shroud are shown.

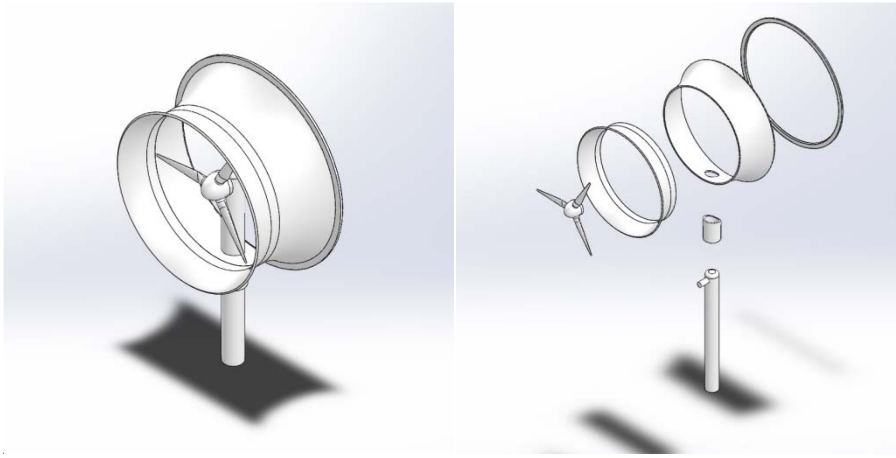

Figure 8: Sketch of assembled shroud (left) and exploded view of shroud system (right).

Our team aims to develop an optimized shroud design by examining geometric features from each component and integrating them for the best possible performance. The geometric features that will be analyzed are broken down by component below.

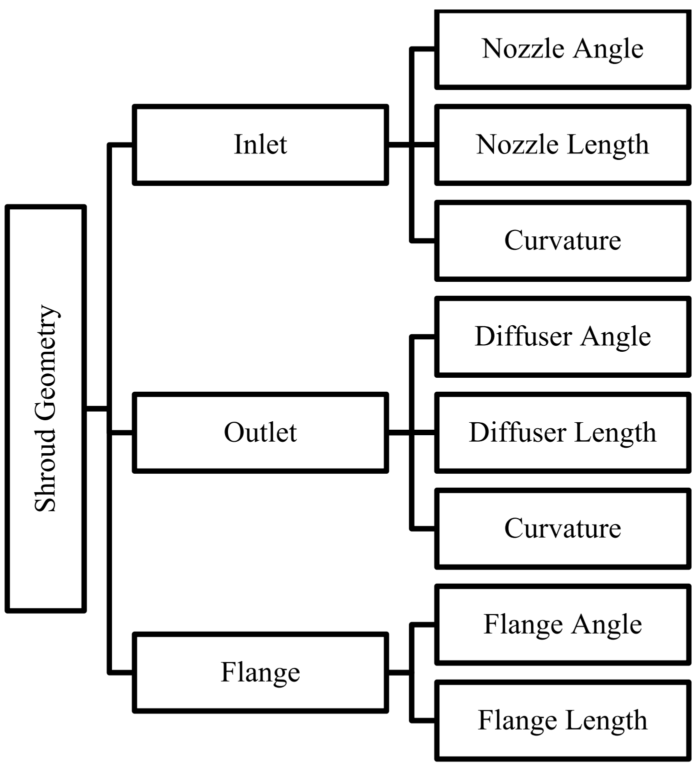

Figure 9: Subsystem breakdown chart.

2.5 Benchmarking Results

There are several companies that produce shrouded wind turbines for grid-tied systems at rated power greater than or equal to 100 kW. One emerging company, Ogin, integrates a unique shroud design to a conventional mid-size wind turbine [14]. Annual energy output per kW of rated capacity is increased by 50%, while peak energy output from the rotor is increased by up to three times per unit of swept area. The result is a quiet, compact 100 kW turbine that has proven to be competitive in the utility scale market. Ogin adopts the shroud design at a more sophisticated and larger scale than is intended for this project. However, the company's demonstrated success in improving mid-size turbine performance provides encouragement to extend wind turbine shroud technology to an even smaller scale.

Currently, the only commercial shrouded small wind turbine is available through licensing by an Irish company called Airsynergy [15]. Airsynergy owns the intellectual property rights to a certified 5 kW shrouded small wind turbine and is in the process of certifying models with larger power capacity. The reported performance of Airsynergy's 5 kW wind turbine provides further guidance of design targets for this project. A key differentiator, however, is that Airsynergy's product is the entire shrouded wind turbine system, rather than just a shroud design that may be adapted to existing turbines.

There are no commercial products that isolate the shroud itself but rather only experimental products used for research. These various diffusers typically only analyze one aspect of the design in an effort to determine the effect of one geometric feature. Some of the products created for research, like the shroud with flange presented in the article "CFD Analysis for Optimization of Diffuser for a Micro Wind Turbine" [11] have seen wind speed increases of about 40% during a simple comparison of the effectiveness of a flange and its angle. The results from this particular shroud provide backing for the possibility to increase wind speeds by 50% while minimizing the drag forces.

Although there is limited research about the integration of all the different geometric aspects, there are various journal articles that provide more useful data useful for the project. This does not provide enough detailed information to directly compare to, however, due to the fact that this design integrates several factors to increase local wind speed.

2.5 Project Scope

Budget

In summer of 2013, the project team applied for grant funding in the amount of $24,000 from Lawrence Berkeley National Laboratory through the Max Tech and Beyond Competition. Funding was not provided due to discrepancies between the competition and project objectives. However, the process of writing this proposal was greatly beneficial in narrowing the focus of the project.

At the beginning of the 2013-2014 academic year, grant funding was sought from the Center for Science, Technology, and Society (CSTS), ASME Santa Clara Valley Section (SCVS), and the Undergraduate Engineering Program at Santa Clara University. Each of these organizations contributed financial resources to this project. Appendix C provides a detailed budget for this project, including the specific amounts committed by each group.

The funds received in support of this project allows for the completion of testing with a 3D printed prototype in the Santa Clara University wind tunnel. However, if the project came to a point where the logical next step is testing a larger scale model in a larger wind tunnel, a substantially larger budget would be necessary both to reserve time in the wind tunnel and produce a larger prototype with a high level of precision. Considering the available resources and time constraints of the project, the team decided to focus the financial resources on prototyping materials and test equipment for use at the wind tunnel at Santa Clara University.

Timeline

While initial concepts for the project were discussed at the end of the 2013-2014 academic year and continued over the following summer, the project formally began in September of 2013 when an appropriate scope and timeline was established.

The initial timeline was deliberately aggressive in order to encourage productivity, but it did not anticipate the complexity of several challenges, such as modeling the wind turbine in ANSYS. The team adjusted the timeline and ultimately selected a shroud design for prototyping before it was modeled with the turbine blades in ANSYS.

The construction of the scale model testing apparatus also required more time than was initially estimated. Manufacturing was delayed as detailed drawings needed to be completed and approved. There were also unforeseen issues related to machine shop access.

One of the primary constraints of the project was driven by the size of the wind tunnel that was available for use. The results of preliminary testing are intended to justify the use of a larger wind tunnel. However, an unrealistic schedule would be required in order to complete testing in a larger wind tunnel by the end of the 2013-2014 academic year. Given this challenge, the team chose to focus on producing high quality results at Santa Clara University's wind tunnel and promote the continuation of testing in a larger wind tunnel as an option for future senior engineering projects. Refer to Appendix C for the project Gantt Chart.

Risks and Mitigations

Aside from the previously stated risks and proposed mitigations, another risk for this project is that the CFD modeling only allows a limited number of elements to be tested. In order to use a finer mesh for more precise results, both a faster computer and more advanced software package would be required. Table 1 summarizes the risks involved with this project, potential impact, and proposed mitigation strategies.

Table 1: Risk matrix with mitigation strategies

(Probability [0-1] x Severity [1-10]=Impact→P x S= I).

Risks	**Consequences**	**P**	**S**	**I**	**Mitigation Strategy**
Insufficient Wind Tunnel Size	Physical model cannot accommodate scaling parameters	0.6	7	4.2	Measure tunnel in advance and plan model accordingly Consider a back-up wind tunnel
Time	Results inconclusive Project incomplete	0.4	8	3.2	Develop realistic timeline Frequent (weekly) check-ins
Limited Software Capacity	Available version cannot accommodate mesh requirements.	0.3	5	1.5	License or purchase an upgraded software package
Limited Availability of Machines or Wind Tunnel	Cannot complete further iterations.	0.3	4	1.2	Reserve space in advance and build in buffer time if possible

The size of the available wind tunnel was identified as a risk early in the project as initial Reynolds number scaling calculations were performed. The probability of this risk affecting the project was considered the highest, as there was little that could be done to circumvent the sizing constraints. However, the severity of this risk is less than the severity of failing to complete the project by the end of the academic year. While the limitations posed by the software capacity and machine availability were identified as risks, the project could still be completed by using a coarser mesh in the CFD software and by outsourcing to an external machine shop if necessary.

Team Management

In order to verify that the design team was acting ethically within itself and in relation to sponsoring institutions, consistent meetings were held with qualified advisors to discuss and document the important decisions related to this project. Before advancing with any stage of the project, permission from both the advisors and related sponsor was granted to validate that the team was both capable and justified in the use of any funds. Fair treatment among team members was promoted by encouraging frequent discussions related to workload and responsibilities. The team agreed to address this project in the same way was they would a professional project in industry and adhere to the same expectations of workplace interactions.

Chapter 3: Shroud Design

Several features of the shroud were designed to optimize performance, including the geometry of the diffuser, nozzle, and flange attached to the diffuser. Figure 10 shows representations of each component of the shroud design. While each component can be independently manipulated, the integration of the shroud as a system must be carefully considered.

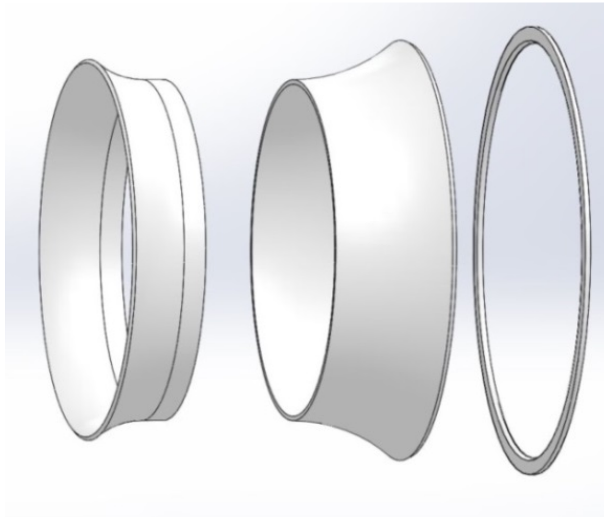

Figure 10: Exploded view of shroud components: diffuser (left), nozzle (center) and flange (right).

3.1 Component Requirements

3.1.1 Shroud Inlet

The shroud inlet is the first part of the shroud and acts as a nozzle for the air that passes over the wind turbine. At the most basic level, the inlet must act as a nozzle and have a decrease in cross sectional area of the shroud as it approaches the blades of the wind turbine. Additionally, the inlet must be large enough to direct a sufficient amount of air into the shroud without being so large that it causes an unmanageable amount of drag on the structure of the wind turbine. Other aspects that must be determined include the length of the inlet and the curvature of the interior of the inlet. The inlet has to be designed with size, weight, and manufacturability in mind in order to meet the system requirements relating to drag forces, cost, and durability. The shroud inlet was tested at different lengths and angles of opening in order to determine the appropriate size that will help meet the above aforementioned requirements.

3.1.2 Shroud Diffuser

The shroud's outlet portion, or diffuser, is the second feature that the wind interacts with as it passes through the turbine system. The diffuser acts in conjunction with the shroud's nozzle and flange to create a higher pressure field on the outside of the shroud system and a low pressure zone on the inside. This difference in pressure is necessary in order to increase the wind speed locally through the shroud and past the turbine blades. The main requirement is that the diffuser helps increase the wind speed through the turbine by a factor of 1.5 of the ambient wind speed. Another important criterion that the diffuser must meet is that its design minimizes the drag on it while still increasing the wind speed. The last consideration is the cost of the diffuser. Material use and simplicity of the design in regards to its manufacturability will both affect the cost of this component. The outlet was tested at different lengths and opening angle in order to determine suitable dimensions that allow it to meet requirements.

3.1.3 Shroud Flange

The shroud flange is an extrusion of the shroud that exists on the back outer edge of the diffuser. Its purpose is to create a pressure differential between the air that flows around the outside of the shroud and the air that flows through the shroud. The flange increases the pressure outside the shroud and lowers pressure behind the shroud. This forces the air to increase in velocity as it passes through the shroud and across the turbine blades. The flange contributes to the performance requirement of increasing ambient wind speeds by a factor of 1.5. The addition of the flange causes an increase in the drag forces on the shroud; therefore the flange also has to be designed to help minimize these drag forces. This could be done by angling the diffuser so that it is no longer perpendicular to the flow of air.

3.2 Options and Tradeoffs

3.2.1 Shroud Inlet

The first tradeoff that must be considered is the cross sectional area of the front of the inlet as compared to the acceptable amount of drag that is imposed on the structure of the wind turbine. A large enough cross sectional area is required so that the air does not simply flow around the inlet, but as the size of inlet increases, so does the drag it creates on the system. Additionally the cost of the part increases. In order to determine an appropriate sized inlet, CFD modeling was used to iteratively design the inlet until all of the criteria for the system requirements are met. Secondly, the desired amount of curvature on the inside of the shroud was determined against the manufacturability of making curved sections for the shroud. A curved surface would increase the cost of the part, which means that any benefits that are garnered from having a curved inside surface have to be weighed against the additionally costs to manufacturing. Both of these decisions were also influenced by the results of the CFD analysis to see how each change alter the airflow through the shroud. One issue that was faced with the design of each subsystem is that their performance is closely tied to the design of the other subsystems. Extensive testing is required to isolate each subsystem and see how changes to that subsystem directly affect the function of the entire system.

3.2.2 Shroud Diffuser

There are many different options for designing the geometry of the diffuser. The change in cross-sectional area, length, angle of opening, and curvature of opening all can be varied in order to change the pressure difference created by the diffuser. While there is an ideal shape of the diffuser for the greatest amount of pressure differential, and therefore velocity increase, many of the aspects that increase the wind speed also increase the drag on the system. As the length of the diffuser is increased, the pressure differential increases, but so does the drag on the system. The angle of opening and change in cross-sectional area are also greatly dependent on the length and therefore, they all need to be balanced together in order to increase the velocity in the most effective manner. Like the shroud nozzle, the diffuser is also part of an iterative CFD modeling process where the various lengths are tested, along with the opening angle and curvature of the diffuser.

3.2.3 Shroud Flange

The shroud flange has two important characteristics that likely affect its contribution to the shroud attachment. These two features are the length of the flange and the angle at which the flange is attached. The basic trade off with the flange is the longer and more perpendicular to flow the flange is, the greater the pressure differential between the inside and outside of the shroud. This leads to an increase in wind speed through the shroud, but also an increase on the drag of the entire system. Because the flange seems to have relatively clear correlation between its geometry and the performance of the shroud, the flange can likely be used for adjusting the design to make any small changes that allows the design to meet the system requirements.

Chapter 4: Computational Fluid Dynamic Modeling

4.1 Shroud Selection Methodology

A four factor two-level Design of Experiments (DoE) approach was used to analyze sixteen different scaled shroud geometries and the impact that selected factors had on the performance of the design. This was the chosen methodology because it reduced design costs by speeding up the design process, reduced late engineering design changes, and reduced product material and labor complexity.

The primary analysis included four factors: flange angle, angle of openings, nozzle length, and diffuser length. The factors were measured at a maximum and minimum value selected based on insights provided in available literature. In this case, wind velocity at the location of the turbine blades was used as the output for each iteration. The two levels analyzed for each factor were as follows:

Table 2: High and Low Values of Four-Factor DoE

Isolated Factor	High Value	Low Value
A) Flange Angle	25^o	0^o
B) Opening Angle	25^o	5^o
C) Nozzle Length	0.20 in.	1.50 in.
D) Diffuser Length	0.50 in	4.0 in.

A secondary three-factor two-level DoE analysis was performed in an attempt to identify optimum values of the opening angle and the influence of curvature on the system. The isolated factors and values are shown below.

Table 3: High and Low Values of Three-Factor DoE

Isolated Factor	High Value	Low Value
A) Curvature	1 (curved)	-1 (straight)
B) Nozzle Angle	5^o	10^o
C) Diffuser Angle	5^o	15^o

4.2 ANSYS Fluent

Three levels of CFD analysis were performed in order to optimize the modeling design process of the shroud geometry. The ANSYS Fluent 14.5 Student suite was used for each level of modeling. The first stage was to model the fluid pressure and flow velocity profiles inside the shroud geometries that would be used for the two DoE iterations. This process enabled a more rapid analysis of shroud geometries without requiring a physical prototyping of each candidate design. A quarter section of the shroud was analyzed under the assumption of symmetrical flow which allowed a finer mesh to be applied in and around the modeled shroud for greater precision. The second level of analysis within the CFD program was to model the chosen shroud geometry with a focus on recreating the pressure and velocity profiles that would be present during the experimental testing. The final level of CFD analysis involved the modeling of the shroud with a rotating turbine blade in order to simulate the system under actual testing conditions.

4.3 Assumptions and Boundary Conditions

Sixteen distinct scaled shroud geometries were designed in SolidWorks and were tested using ANSYS Fluent Computational Fluid Dynamics (CFD) software. Because the CFD models were compared to a scaled physical model tested in a subsonic wind tunnel, the CFD model used the same sizing constraints that would be applied to the scaled physical testing. Specifically, the CFD testing had the geometries being modeled in a box with the same dimensions as the wind tunnel apparatus available at Santa Clara University.

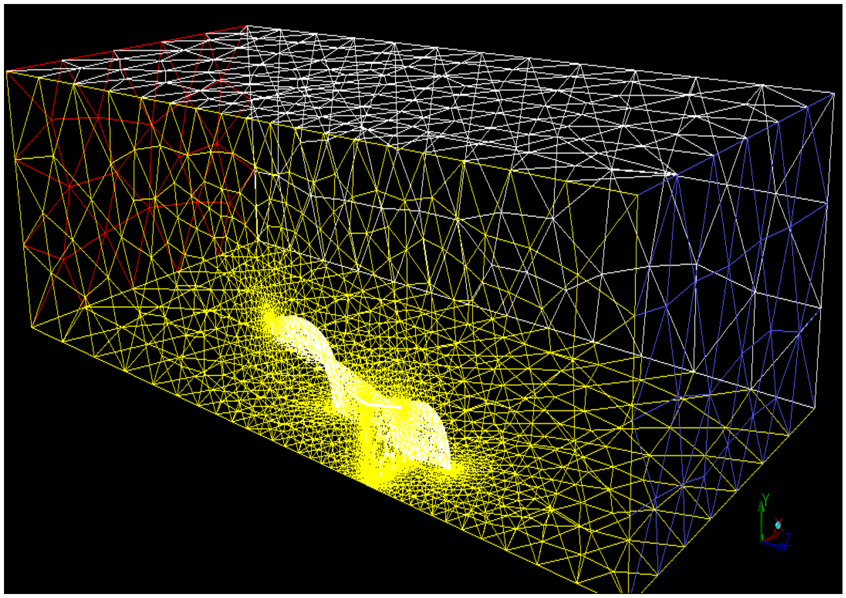

Figure 11: Tetrahedron mesh used to model a quarter of the shroud geometry.

A tetrahedron mesh was used in the CFD modeling of the shroud geometry as can be seen in Figure 11. Table 4 shows the modeling conditions that were used for the DoE trials run in ANSYS Fluent.

Table 4: Modeling Parameters used for DoE iterations in ANSYS Fluent.

CFD Modeling Conditions	
Mesh Type	Tetrahedron
Number of Elements (Final Shroud)	369679
Number of Nodes (Final Shroud)	93781
Air Density (kg/m^3)	1.225
Air Viscosity (kg/m*s)	1.79E-05
Turbulence Model	Realizable k-epsilon
Inlet Velocity	55 m/s
Turbulent Intensity	5%
Turbulent Viscosity Ratio	10
Outlet Pressure	0
Number of iterations per trial	200
Shroud Shear Conditions	No Slip

In order to increase the detail of the mesh and simplify the calculations done by the CFD analysis, only a quarter of the geometry was modeled assuming the flow would be symmetrical through the shroud. The maximum achievable wind speeds in Santa Clara University's wind tunnel are approximately 55 m/s. Because of this, the CFD model was run assuming an inlet velocity of 55 m/s.

The most ideal material for the full size product is still undecided. However, the scaled models are 3D printed in ABS plastic, so for more accurate comparison, the CFD analysis used a similar type of plastic to model the shroud. However, in the case of examining flow through the shroud, the type of the material used is of relatively low significance.

This software was especially useful in that it allows a visual comparison of how geometric factors affect the performance of the shroud through the analysis of velocity and pressure contours. For example, Figure 12 displays quarter view pressure contours of two shrouds geometries that differ only in that the one on the right is curved.

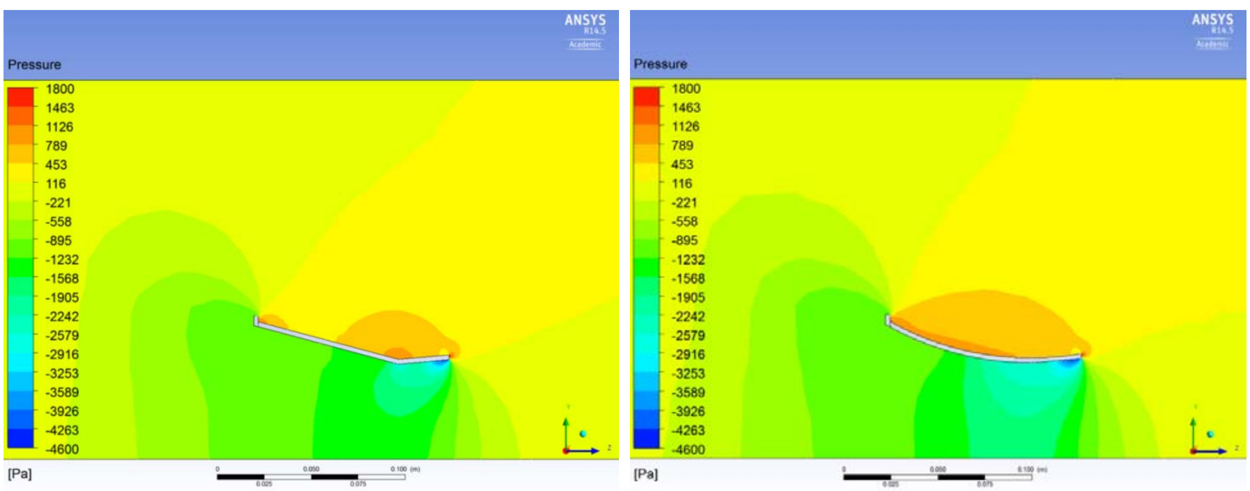

Figure 12: Cross sectional view of a quarter shroud geometry showing pressure contours around shroud without curvature (left), and with curvature (right)

In this comparison, it can be seen that the curvature of the shroud induces a larger region of lower pressure inside the shroud, which corresponds to higher velocity and better performance. Figure 13 displays quarter view velocity contours of the same shroud geometries.

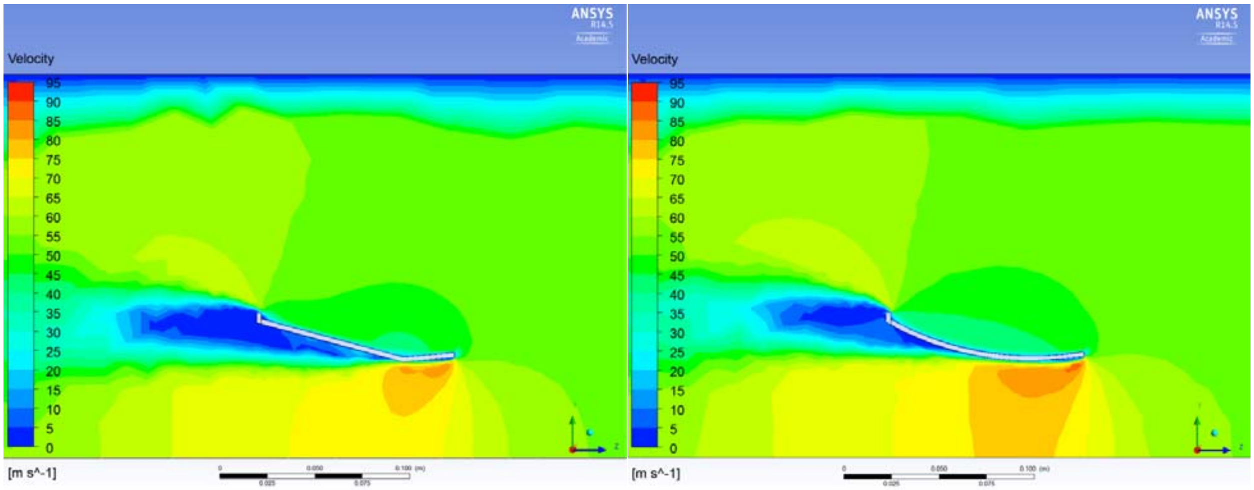

Figure 13: Cross sectional view of a quarter shroud geometry showing wind velocity contours around shroud without curvature (left), and with curvature (right)

4.4 Results and Analysis

The DoE table below was used to gather an array of outputs that determined the significance each factor has on the output. By testing each factor individually as well as in combination, the factors with the most influence can be identified.

Table 5: Four-Factor Two-Level DoE Results

Standard Run Order	Flange Angle (A)	Opening Angle (B)	Nozzle Length (C)	Diffuser Length (D)	Output Velocity
1	0	5	0.2	0.5	64.25
2	25	5	0.2	0.5	64.53
3	0	25	0.2	0.5	65.21
4	25	25	0.2	0.5	71.37
5	0	5	1.5	0.5	61.98
6	25	5	1.5	0.5	62.91
7	0	25	1.5	0.5	62.9
8	25	25	1.5	0.5	62.31
9	0	5	0.2	4	69.91
10	25	5	0.2	4	71.38
11	0	25	0.2	4	68.41
12	25	25	0.2	4	68.12
13	0	5	1.5	4	88.47
14	25	5	1.5	4	88.12

A Pareto chart (Figure 14 below) enabled a visual representation of the significance of each factor or combination of factors. Test scenarios with the higher impact are associated with a higher coefficient, plotted on the vertical axis. Scenarios with coefficients reaching above the blue line are considered to have a significant impact on the performance of the system.

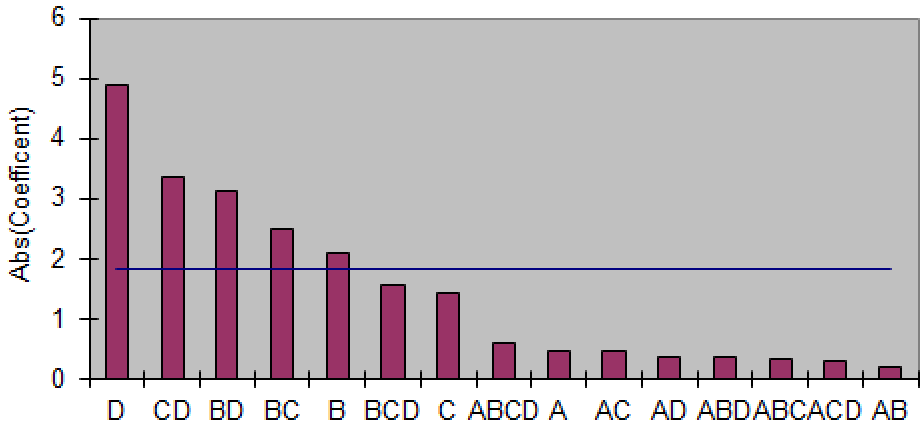

Figure 14: Pareto chart demonstrating influence of four shroud features

As seen in Figure 13, the shroud geometry factors that had significant impact on the performance of the shroud were the length of the diffuser, the opening angle and the nozzle length. The length of the diffuser alone had the most significant impact on the performance; a longer diffuser creates a higher velocity through the shroud. The flange angle was determined to be relatively insignificant in affecting the velocity through the shroud. Figures 15 – 18 demonstrate the impact that each factor had on the performance of the shroud based on the average velocity of the sixteen trials that were run.

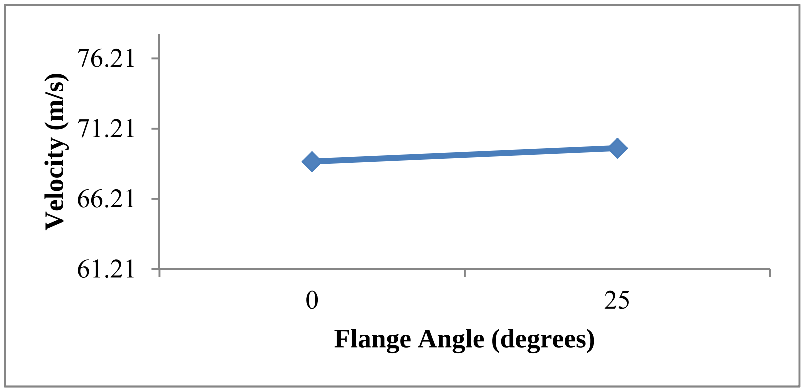

Figure 15: Effect of the flange angle on the average velocity.

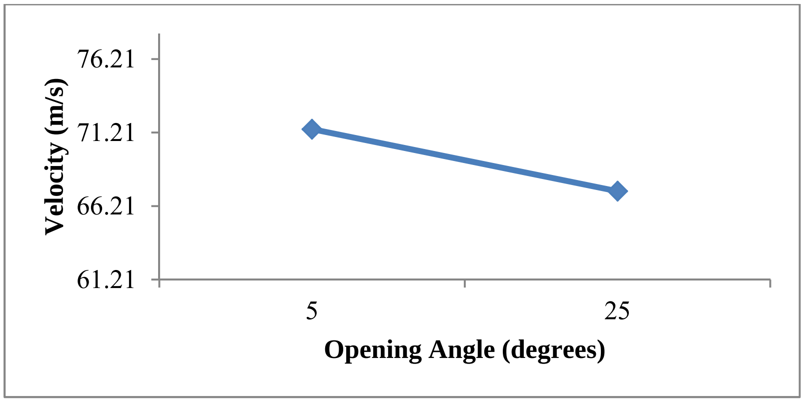

Figure 16: Effect of the opening angle on the average velocity.

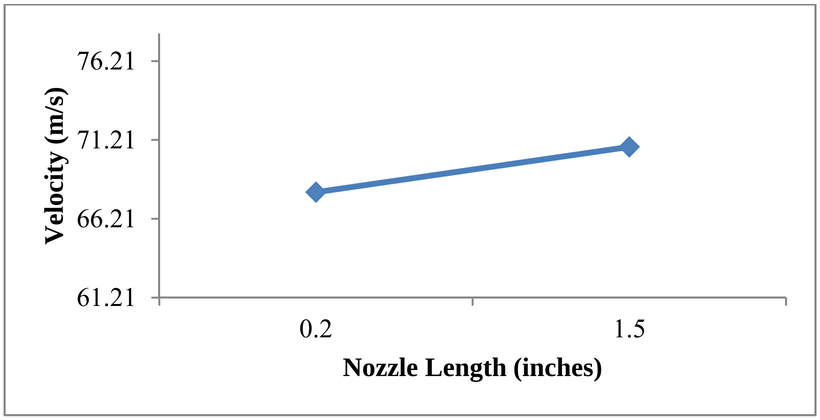

Figure 17: Effect of the nozzle length on the average velocity.

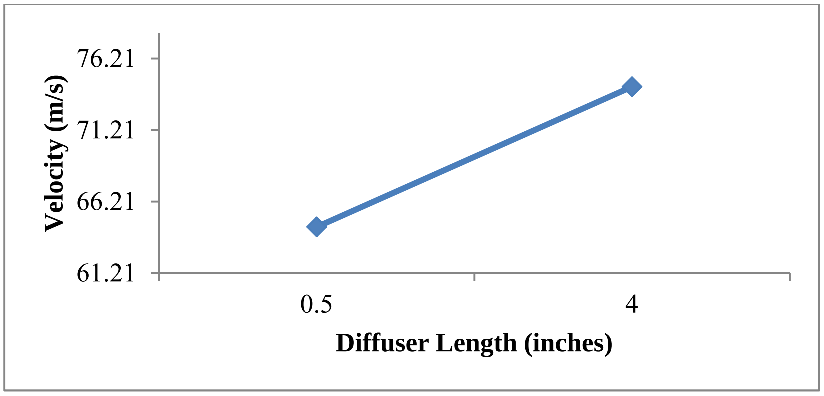

Figure 18: Effect of the diffuser length on the average velocity.

The results were reasonable and agree with the expected outcomes. However, the significance of each factor is the true value that was gained from this design of experiments. The results were all within the expected range, with the highest wind velocity calculated to be 1.60 times the free stream velocity and the lowest being 1.13 times the free stream velocity.
The run order and output values for the three-factor DoE can be observed in Table 6.

Table 6: Three-Factor Two-Level DoE Results

Standard Run Order	Curvature (A)	Nozzle Angle (B)	Diffuser Angle (C)	Output Velocity
1	-1	5	5	81.78
2	1	5	5	82.77
3	-1	10	5	79.25
4	1	10	5	79.92
5	-1	5	15	78.35
6	1	5	15	83.92
7	-1	10	15	80.51
8	1	10	15	82.00

The significance of each factor on the system is represented by the Pareto chart shown in Figure 19.

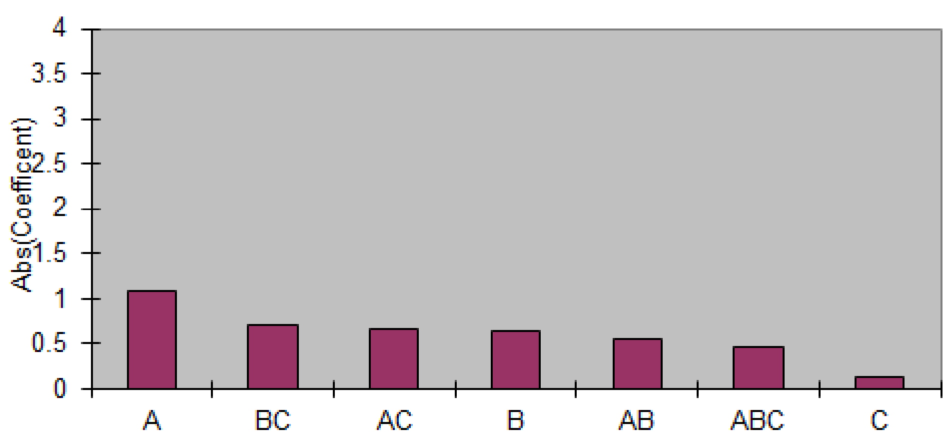

Figure 19: Pareto chart demonstrating influence of three shroud features

The results from this analysis implied that the curvature of the shroud had a positive influence on the system, closely followed by a combination of the nozzle and diffuser angle.

Using the data collected, the final version of the shroud was selected that uses the most performance enhancing aspects of each factor. A 3D rendering of the selected shroud is displayed in Figure 20.

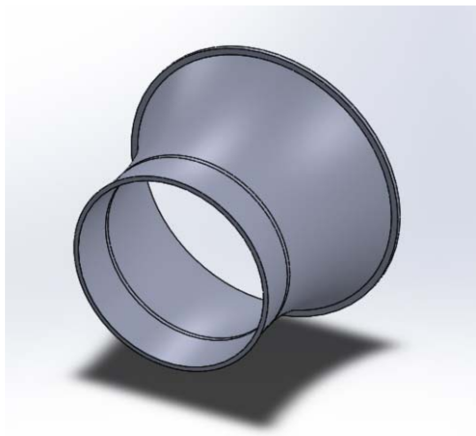

Figure 20: 3D rendering of selected shroud

The geometric specifications of the selected shroud are shown in Table 7. The final design features a 3:1 ratio between diffuser length and nozzle length as well as a 3:1 ratio between the opening angle of the diffuser and the opening angle of the nozzle.

Table 7: Geometric specifications of selected shroud

Flange Angle	90°
Nozzle Length	1”
Diffuser Length	3”
Curvature	Yes
Nozzle Angle	5°
Diffuser Angle	15°

According to the CFD modeling results, this shroud design effective in reaching the performance requirements of increasing the velocity by a factor of 1.5, which theoretically would result in a power increase greater than 3.37. The 90° flange angle helps maintain the requirement of manufacturability as perpendicular angles are common in machining and therefore easier to produce. These results justified the construction of a 3D printed scaled model to be tested in a wind tunnel for data validation.

4.5 Wind Turbine Modeling

The shroud geometry that was selected for use in the wind tunnel testing was based on CFD analysis that analyzed only the flow through the shroud without incorporating any representation of the blade interacting with the shroud. However, as part of the experimental data collection process, pressure was measured along the inside of the shroud with and without a blade present. Taking this into consideration, one of the goals was to produce a CFD analysis that could be validated by the experimental data.

A number of methods were considered for creating an accurate representation of the effects that a spinning turbine blade would have on the pressure and velocity fields as air flowed through the shroud. Ideally, the method used would create a pressure and velocity at the location of the turbine blades to mimic the extraction of energy that occurs when a wind turbine in producing power. The approaches considered were:

1. Using a semi-permeable membrane at the location of the turbine blades
2. Modeling a perforated disk instead of turbine blades
3. Using a rotating frame of reference with a turbine blade modeled.

The semi permeable membrane was the first option considered because it allowed for the potential of accurately modeling the turbine blades effect without affecting the detail of the modeling mesh. Due to the restrictions on the student edition of the ANSYS suite that was available, the level of mesh detail was limited. The membrane is represented as a fluid section within the CFD model in which the porosity can be set as a parameter. By using a semi permeable membrane to model the turbine blade, the model would be able to cause a uniform pressure and velocity drop inside the shroud that would be equivalent to the effect of the turbine blade. One benefit to this system is that the porosity could be changed to retroactively match the data collected in the experimental testing in order to determine the parameters that most accurately correspond to the collected data. This method was unsuccessful due to the inability to limit the porous fluid section to only the inside of the shroud without affecting the flow around the outside of the shroud. Issues also arose with controlling the porosity of the membrane.

The second approach was to model a perforated disk within the shroud that would essentially achieve the same goal as the semi permeable membrane. Different disks were used with the size and the spacing of the holes varied for each attempt, however the results were not successful in creating the desired effect on the airflow. Figure 21 shows a screenshot taken during this modeling attempt.

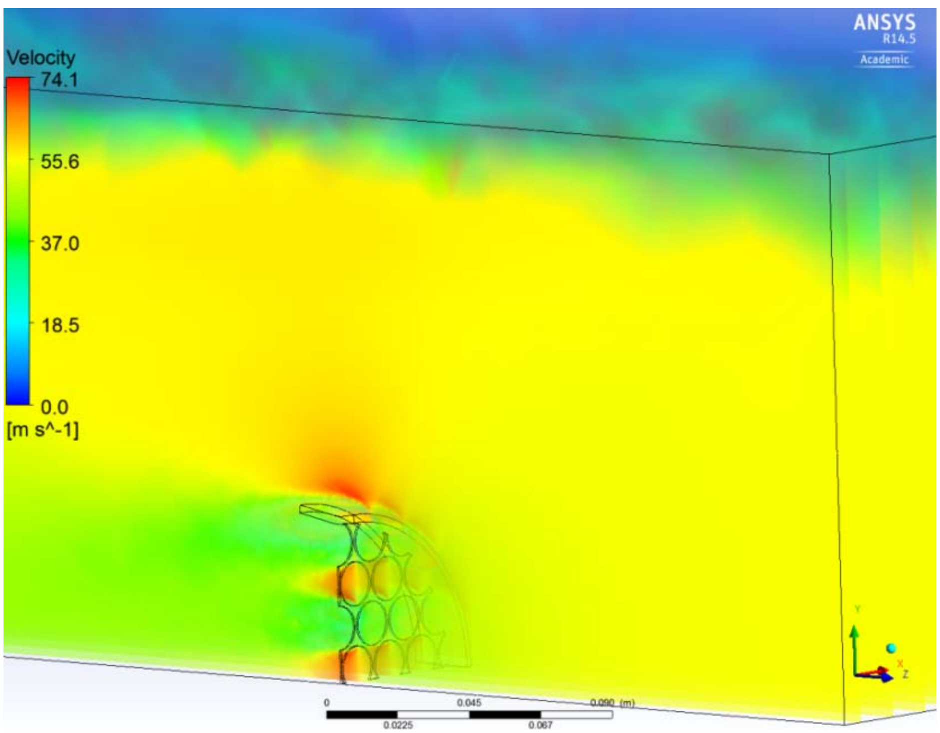

Figure 21: Attempt to model turbine as perforated screen

Wind speed was increased locally around the edges of each hole, and areas of high pressure were present at the rest of the areas. Additionally, for some cases, the flow was redirected around the shroud because the disk created too much blockage. The addition of the disk also caused a decrease in the overall level of detail in the shroud because there of the addition of complex geometry.

The third approach is to use the actual blade design from the experimental testing and create a rotating frame of reference so that the CFD model will analyze the flow with a rotating blade. This method was only partially successful. While a rotating blade was successfully modelled within the shroud, the rotation was set at a fixed speed instead of being a function of the inlet wind speed which resulted in the model not having the same drop in pressure and velocity that was present in the experimental testing.

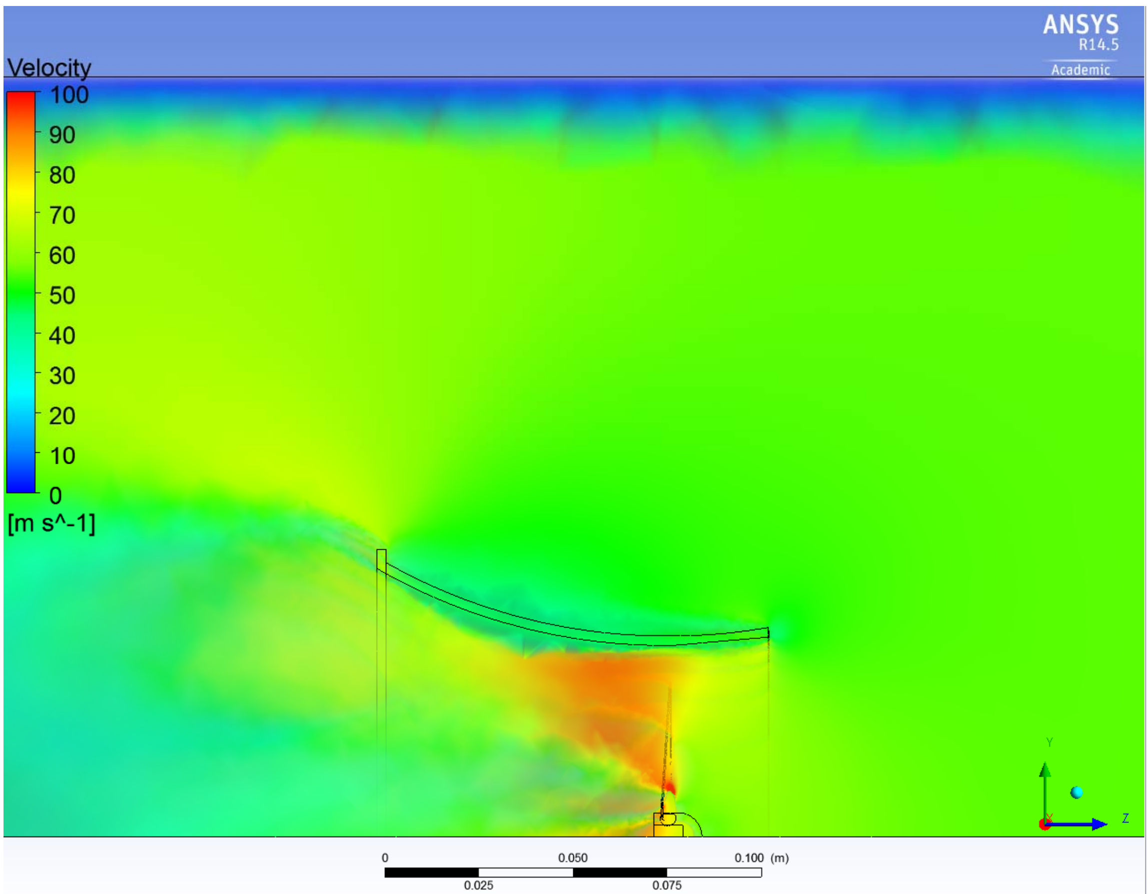

Figure 22: Volume rendering of wind velocity as air flows past a spinning blade.

As can be seen above in Figure 22, the general velocity profile is similar to the simulations run without the blade, but there are clear disturbances in the wake caused by the rotating blade. In this regard, the modeling attempt was successful in that it gives a better indication of the flow pattern through the shroud than the models without the turbine blade.

Chapter 5: Wind Tunnel Testing

5.1 Experimental Apparatus

The next step in the analysis process was to run scaled wind tunnel testing to compare the results of the CFD analysis and determine how accurately the CFD modeling represents physical data. Wind tunnel testing also provided a means to measure the drag coefficient of the shroud and compare the power output of shrouded and unshrouded turbine.

The initial testing system of the horizontal axis turbine consisted of a three blade system, mounted to a rotating shaft. Attached to the opposite end of the shaft was a pulley, driven by the rotation of the wind turbine. The turbine, shaft, and pulley were supported by two towers, with a ball bearing system mounted in each, allowing for a low friction rotation of the shaft. In order to prevent free-wheeling of the turbine and to measure power output, the pulley at the end of the shaft was linked to a weight, which it lifts during operation. By introducing a resistance to the wind turbine's system, a more significant amount of energy was required to rotate the blades. This extraction of energy mimicked how a full-scale wind turbine functions. The three blade turbine system was 3D printed utilizing the equipment in Santa Clara University's Machine Shop in order to rapidly produce different models accurately and consistently. Refer to Appendix D for detailed drawings of the wind tunnel testing assembly.

Figure 23 illustrates the assembled experimental apparatus that enabled wind tunnel testing. The pulley system ran from inside the wind tunnel, along the axis of rotation of the blades and up to two other axles where the direction of motion is changed in order to successfully lift the mass.

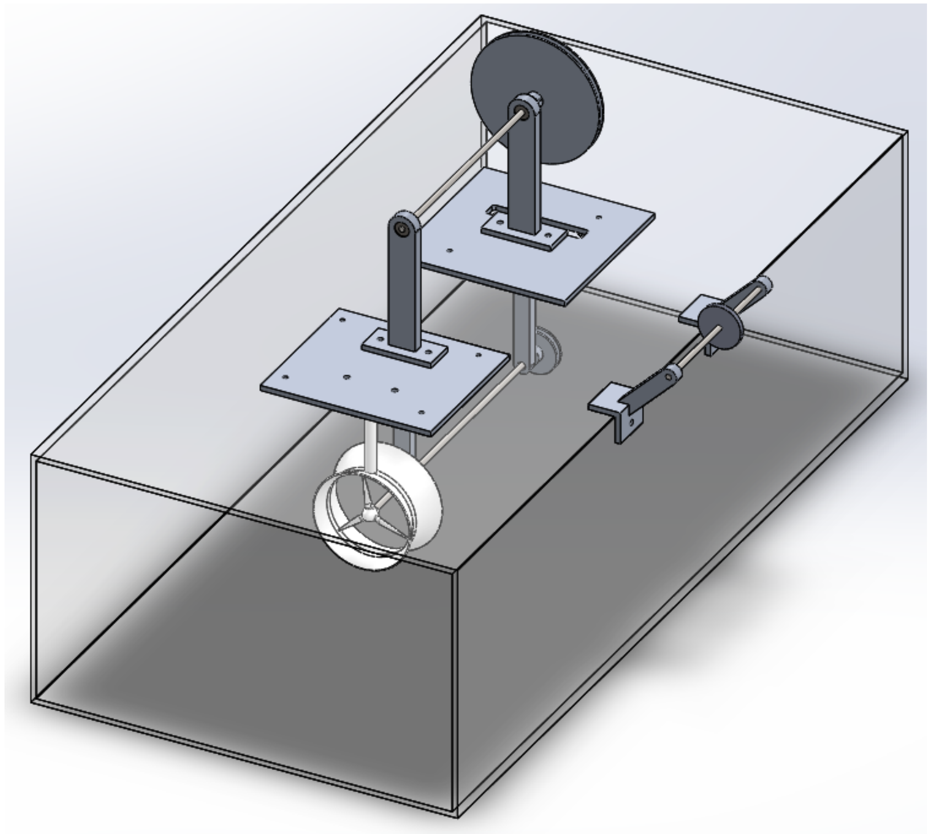

Figure 23: Wind tunnel experimental apparatus

5.2 Experimental Protocol

The performance of the shroud was measured through comparison between the shrouded and unshrouded power output of the turbine, as well as the pressure distribution along the shroud and the drag force on the shroud. In order to measure and calculate these values, the shroud and turbine system was placed in the Santa Clara University, Mechanical Engineering Department wind tunnel and run at approximately 55 m/s (the maximum of the wind tunnel).

To set a baseline value for the power output of the unshrouded turbine system, the wind tunnel was operated at 55 m/s while measuring the power output. The power output was measured via a pulley contraption, lifting a mass as the turbine axle rotates. This displacement of a mass over time was used to calculate the power output of the turbine system. A Pitot tube was used to measure the pressure field behind the turbine, creating a simple pressure profile. The Pitot tube also allows for an accurate measure of wind velocity to be calculated by measuring the difference of the stagnation and static pressures.

After setting a base for performance of the turbine, the shroud was mounted around the turbine blades, attached to the wind tunnel with a post to the baseplate. In order to measure the drag on the shroud, four strain gages of initial resistance of 120 Ω were used. These four were set at the front and back and bottom and top of the shroud post and connected to a data acquisition device in a full Wheatstone bridge. Figure 24 below displays the location of the four strain gages on the shroud post.

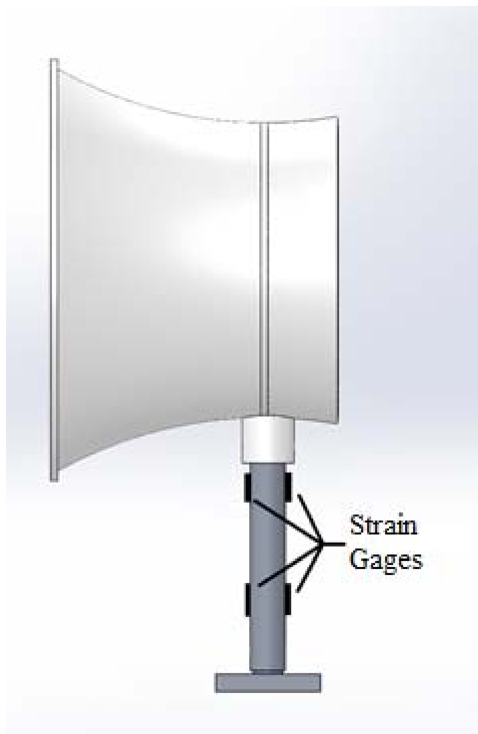

Figure 24: Location of strain gage sensors on the shroud post

The strain gage output was calibrated by reading an average voltage output with no load on the shroud and then a voltage output with approximately 5 lbs. The data that was used to calibrate the strain gages and generate a relationship between voltage and force can be observed below in Table 8.

Table 8: Strain gage calibration data

Force (grams)	Average Potential Difference (Volts)	Standard Deviation of 100 trials (Volts)
0	-2.70E-07	6.36E-05
1455	-1.00E-04	1.06E-04
2890	-2.87E-04	1.04E-04

These values were used to create a linear equation for the voltage difference in the bridge. It is assumed that, for the majority of operational ranges of the strain gauges, the change in resistance has a linear relationship to the deflection within the range of anticipated force.

To measure the pressure along the shroud, pressure ports were tapped along the bottom of the shroud and connected to the Scanivalve system. A pressure transducer then evaluated the pressure and outputs a voltage. The Scanivalve system allowed for one pressure transducer to take readings along all of the ports. Table 9 summarizes the experimental protocol for both the unshrouded and shrouded tests. The Person-Hours column reflects the collective amount of time spent by the team to gather raw data for each evaluation.

Table 9: Summary of experimental protocol

Evaluation	**Equipment**	**Accuracy**	**Trials**	**Expected Outcome**	**Formulas and Assumptions**	**Person-Hours**
Power	Pulley System	0.1 Watts	50	Power increase w/ shroud attachment, w/o shroud = 10 W	Pure vertical motion, P = m*g*Δh/t	25
Drag	Omega 350Ω Strain Gages, NI-9219 Module	1E-6 Volts or 1E-3 kg	5	Drag = 5.1 kg	Drag = 24489*V - 21.901	12
Pressure Field	Wind Tunnel, Scanivalve, Pressure Transducer	0.001 Volts or 1E-4 Pa	4	high pressure in front and low pressure in back half of shroud	Pressure = 863.31*V-1908.4	8

With everything connected to the shroud to test and measure power output, drag, and pressure distribution, the wind tunnel was run near 55 m/s and data was taken. The collected data informed the performance of the turbine with and without the shroud and can confirm whether the shroud increases the power output of the system.

5.3 Results and Analysis

5.3.1 Power Test

Power output was determined by measuring the time taken for the system to raise a mass by a known distance. Through a comparison of results from both the shrouded and unshrouded system, it was determined that the power was increased by a factor of 3.18. This is correlated to a velocity increase by a factor of 1.46. The power coefficient of each system was also evaluated. Table 10 below summarizes the results of the power testing, inclusive of 50 trials.

Table 10: Summary of power testing results

Parameter	Unshrouded	Shrouded
Mass Lifted	0.0145 kg	0.0327 kg
Average Lift Time	3.83 s	2.25 s
Power Coefficient	$1.05 \cdot 10^{-4}$	$3.36 \cdot 10^{-4}$
Standard Deviation of Power Coefficient	$6.16 \cdot 10^{-6}$	$2.67 \cdot 10^{-5}$
Velocity at Turbine	53.74 m/s	78.57 m/s

The results did not quite meet design targets of increasing the velocity by a factor of 1.5 and power by a factor of 3.375. Given possible error sources in data collection at this scale, however, it may be that the shroud design could meet the requirements if tested at a larger scale. Error in data collection for this test may include an incorrect estimation of frictional losses, as the losses were calculated by timing the rate at which a mass dropped a known distance with no wind. This provided a power lost in the system and allowed for more accurate results, but may not take into account the kinetic frictional losses correctly when compared to the static friction losses.

The power coefficients that were measured in the system are significantly lower than power coefficients that are measured in industry. Commercial small wind turbines have a power coefficient ranging from 0.3 to 0.4. The lower values of the turbine power coefficients can be primarily attributed to the fact that a standard small wind turbine blade profile could not be accommodated by the size constraints of the wind tunnel. The NREL S834 airfoil is commonly used in industry and is an appropriate benchmark, though it was also too thin in relation to its length at the small test scale. The resolution of the 3D printer was not high enough to accurately model the turbine blades' contour.

5.3.2 Drag Force Test

Preliminary research on fluid dynamic drag suggested that a realistic range for a drag coefficient would be 0.9-1.5 [16]. Based on this estimation, appropriate strain gages were selected and attached to the shroud post in the wind tunnel in order to experimentally measure the drag force on the shroud and determine the drag coefficient. The strain gauges were connected in a standard full Wheatstone bridge and the voltage difference across the bridge was used to measure a force on the shroud. Table 11 summarizes the data collected over five trials.

Table 11: Summary of drag testing results

Parameter	Value	Standard Deviation
Reynolds Number	347,000	N/A
Average Drag Force	15.8 N	0.235 N
Average Drag Coefficient	0.906	0.013
Estimated Full Scale Drag Force	474 N	7.06 N

While an initial estimation of the Reynolds Number was made based on the available range of wind speeds in the wind tunnel, the value in the table incorporates the actual velocity at which the drag force testing was performed, 53.741 m/s. The average drag force was correlated to a drag coefficient of 0.906, which is on the low end of the expected range of 0.9-1.5. While this is encouraging, the added drag force on a full scale wind turbine of a 12 foot diameter was estimated at 474 N. This may exceed the structural limits of the wind turbine post, depending on its height and the moment created by the additional force. For this reason, further structural analysis of the wind turbine post is strongly suggested before the shroud is implemented at full scale.

While load cells were considered as a drag force instrument, the decision to use strain gages was made in order to limit the blockage ratio in the wind tunnel. The existing blockage ratio of 0.126 may contribute to uncorrected error of a different free stream pressure upwind of the turbine system than downwind, where the free stream pressure was measured. Further study in a larger wind tunnel with more sophisticated instrumentation could increase both accuracy and precision of these tests with a lower blockage factor.

5.3.3 Pressure Test

The pressure was compared to CFD calculations and validated that the computer dynamics simulations are accurate models of the system. This proved that CFD modeling can be used to accurately predict the performance of variations of the shroud at larger scales. The pressure along the shroud was measured in the wind tunnel by attaching a Scanivalve pressure transducer to ten equally spaced linear ports along the length of the shroud. The results from this test were compared to the CFD modeling by evaluating pressure at corresponding geometric points along the length of the shroud. Both the wind tunnel measurements and CFD evaluations are plotted in Figure 25.

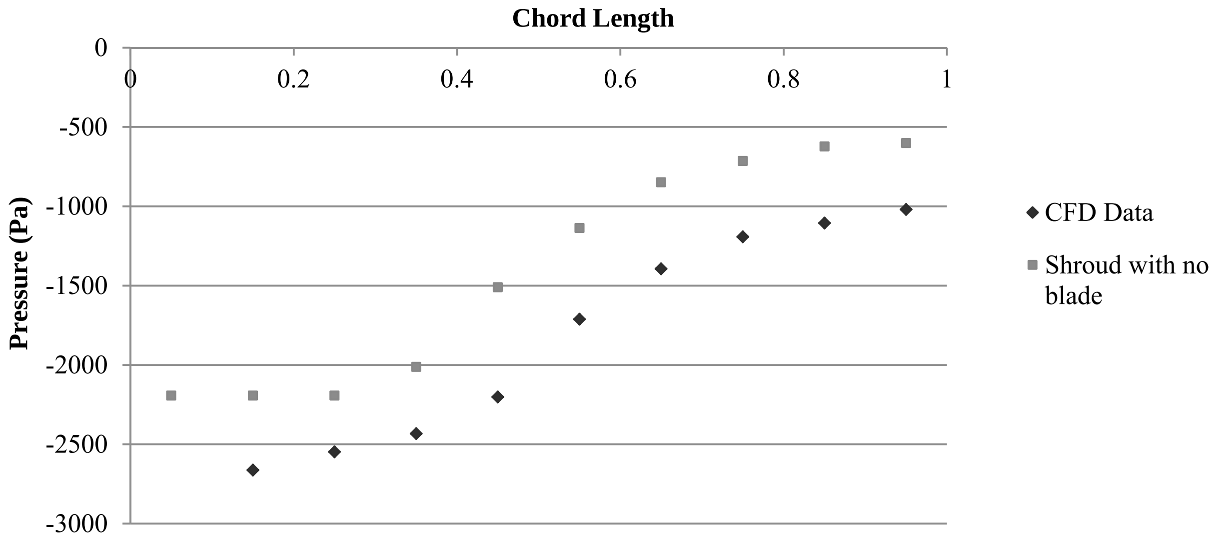

Figure 25: Pressure values along the shroud for CFD and physical testing

The pressure was measured in relation to the free stream pressure which resulted in negative pressures along the shroud. The free stream pressure was measured by the pitot tube, which was setup downwind of the turbine and shroud system. While not identical, the two results follow a similar pattern and most measurements taken at the same chord length vary by approximately 400 Pa. This discrepancy can likely be attributed to several factors related to the wind tunnel experiment. While an effort was made to align the Scanivalve ports exactly perpendicular to the oncoming flow, this may not have been the final result in the setup. In addition, continual vibration in the system could have altered the readings. Further, the free stream pressure in the wind tunnel was measured using a Pitot tube. It is possible that the pressure may not have fully returned to free stream where the Pitot tube was located and could cause further discrepancy in the data and calculations. Despite these potential error sources, the consistency in the pattern of both data sets validates the CFD modeling and encourages its use in predicting results at a larger scale.

Below, a graph of the pressure along the shroud, with and without a rotating turbine can be seen. As predicted, the two follow a similar trend, but with the inclusion of the turbine blades, you see a pressure, and energy, drop. This is due to the extraction of energy from the wind that the turbine system creates, in order to generate power. The drop in available wind energy behind the blades is consistent with what was expected and further supports the testing methods.

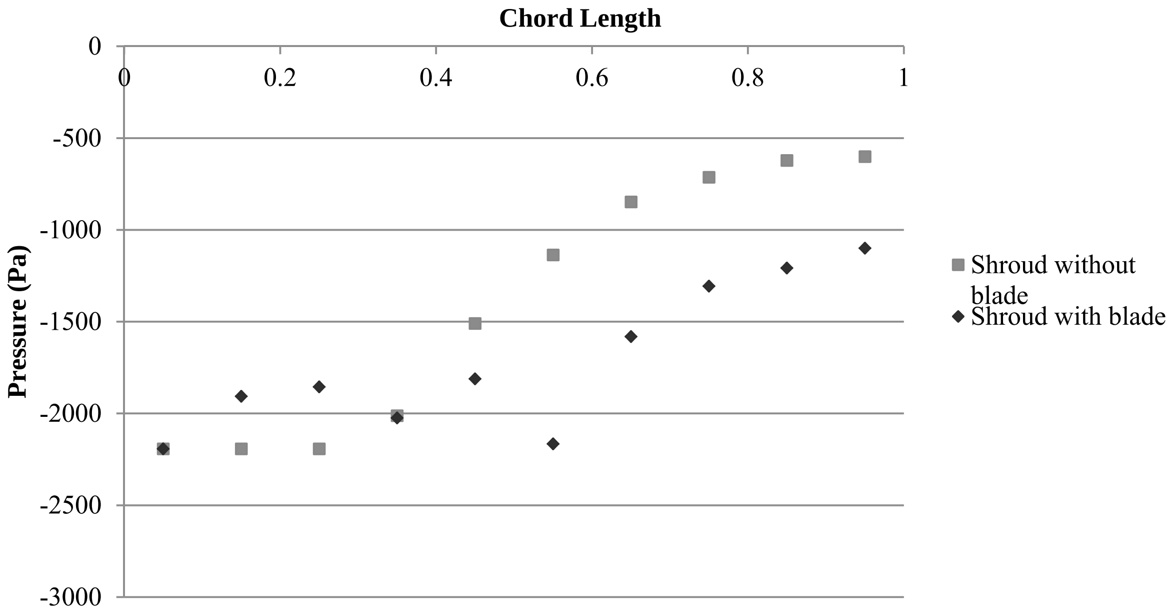

Figure 26: Pressure values along shroud with and without rotating turbine

5.3.4 Tip Speed Ratio Analysis

Additional testing was performed to analyze the power curve of the unshrouded turbine blade in order to determine the correlation between the tip speed ratio, λ, and the power coefficient, C_p. This was done in order to determine if there was an optimal mass to be raised that would produce the highest coefficient of power for the turbine system. Most turbine blades have an optimal tip-speed ratio in which they will produce the most power. However, the testing done on the non-standard blade was inconclusive in determining this optimum ratio. A range of masses were lifted to determine the maximum power coefficient based on the tip speed ratio. An increase in the tip speed ratio, which corresponds to a decrease in the mass being lifted, did show an increase in the power coefficient, but the increase was still mostly negligible.

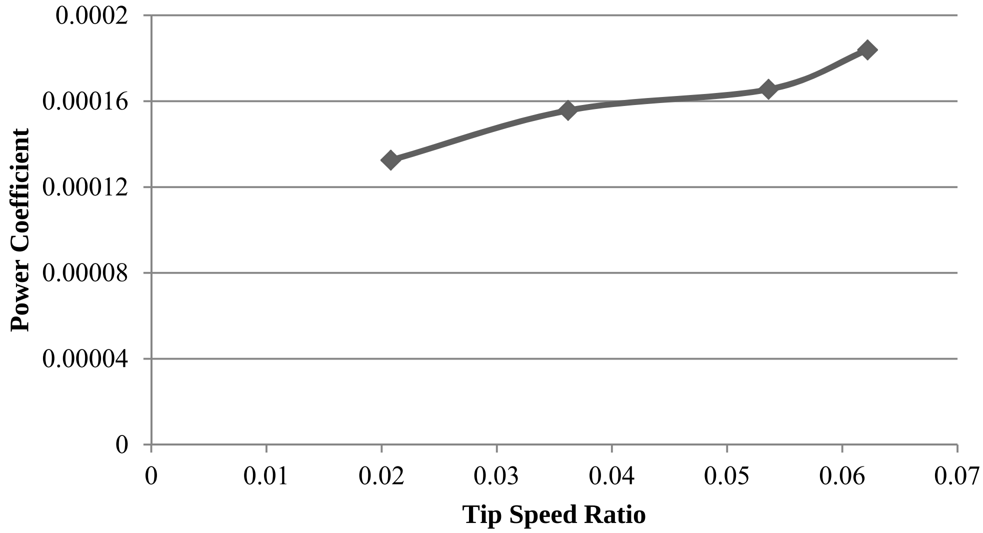

Figure 27: Power coefficient based on the tip speed ratio of the turbine blade.

These results may be due to the fact that even at the lowest masses, the tip speed ratio was still very low compared to standard turbine blades. This test would be more conclusive in further testing when using a more standard airfoil at a larger scale.

5.4 Verification of Performance Requirements

The results gathered by the each test were evaluated based on established Performance and Design requirements. By demonstrating that each requirement was met, the design of the shroud can be considered successful and further testing can be justified at a larger scale. The Verification Matrix in Table 12 provides a comparison of the performance of the shroud to the stated requirement.

Table 12: Verification Matrix of Performance and Design Requirements

Requirement	Method of Verification	Result of Analysis
Shroud must be attached around the wind turbine without interfering with the blades or other mechanisms of the turbine.	• Inspection through CAD Modeling • Demonstration through wind tunnel testing	• CAD modeling enabled appropriate visualization of the shroud's interface with the turbine. • Wind tunnel confirmed that normal operation of the turbine was not interrupted by the shroud.
Shroud should increase the wind speed through the turbine by a factor of 1.5.	• Testing and analysis from wind tunnel data.	• Addition of the shroud increased velocity at the turbine blades by a factor of 1.46.
Energy production should be improved by a factor of 3.375.	• Testing and analysis from wind tunnel data	• Addition of the shroud improved energy production by a factor of 3.18.
The system should minimize increased load to the turbine post due to drag forces while still meeting other performance requirements.	• Measurement of drag coefficient and comparison to expected range according to literature.	• Measured drag coefficient was 0.906. • Literature provided an expected range of 0.9-1.5
Shroud design should emphasize manufacturability to lower production costs.	• Analysis of manufacturability of each subsystem	• Flange angle established at 90^0. • Opening angle of both nozzle and diffuser kept below 20^0. • Material selection kept flexible.

The verification matrix confirms that the Performance and Design requirements were mostly fulfilled. Potential sources of error during data collection can practically account for the results that fall nearly short of the design criteria, namely those related to power and velocity increase.

In general, the success of the selected shroud in meeting or coming reasonably close to each design criteria provides both a foundation and encouragement for continued research on the design.

Chapter 6: Engineering Standards and Realistic Constraints

6.1 Environmental Impacts

This approach to improving a small wind turbine helps reduce the environmental consequences of nonrenewable energy sources. Wind energy is clean energy that produces no emissions. It does not contribute to acid rain, global climate change, smog, regional haze, mercury contamination, water withdrawal or particulate related health effects. In the context of the developing world, most of the population still relies on the use of harmful kerosene lamps or other dangerous energy sources that are related to oil extraction or deforestation and the emission of toxic fumes and greenhouse gases. The introduction of a small wind turbine could provide safe, clean energy while further limiting the demand for fuel sources that damage the environment.

However, many small wind systems in the developing world still rely on hybrid diesel systems to compensate during times of insufficient wind speeds. In these energy systems, environmental risks from diesel emissions still exist. By adding a shroud attachment that improves the operating range and energy efficiency of a wind turbine, the dependence on non-renewable energy may be eliminated completely. The manufacturing of the shroud attachment incorporates this focus on the environment by limiting the use of equipment or materials that involve environmentally harmful processes. Furthermore, wind energy generation uses a negligible amount of water. Especially in the communities with limited access to water, increasing the amount of energy that can be derived by wind energy will help preserve this resource.

6.2 Social Impacts

In addition to the environmental benefits, the societal impact of enabling more productive applications of electricity could have a substantial effect on the quality of life of villagers in rural areas. A pilot study involving the installation of a small wind turbine-hybrid diesel generator system in an 82 person Chilean village suggested potential social benefits of small wind. By implementing the shroud attachment on this system, the social benefits would be magnified.

After the payback period of the shroud, the money that would normally go towards the purchase of diesel fuel would hopefully trickle into the pockets of the villagers. Assuming a direct and even savings among all households, this amount would equate to about $230 USD. This is equivalent to about 2.5 weeks of income at minimum wage in Chile. In addition to a more consistent availability of electricity, the attachment of the shroud could result in additional capital that would encourage productive activity in the community.

The shroud implementation would also produce an estimated additional 4535 kWh per year. By incorporating the average fuel consumption per person, this could potentially provide energy to an additional ten people. Given the projected population growth of this particular village, this additional energy could help accommodate the additional demand.

While the full-scale prototype may not necessarily be implemented in a Chilean village or even in an area with aligning cultural values, this assessment still provides insight into important societal impacts of this project. There are currently over 30 countries that have installed hybrid small wind turbine systems and many of the installation sites have experienced an increase energy demand. In many cases, a reliance on harmful resources such as diesel or kerosene resurges. However, the addition of this shroud attachment provides an alternative that is both environmentally friendly and beneficial to the growth and development of the society.

6.3 Manufacturability

Manufacturability is a concern for any product that is anticipating commercial production. In the case of the wind turbine shroud, the manufacturability is particularly important due to the target market of rural, often minimally industrialized regions of the world. This constraint means that material selection, part manufacturing, and product assembly must be considered carefully. Generally speaking, the design used must be affordable, durable, easy to produce, and relatively uncomplicated to assemble.

The first issue that must be considered is material selection. The material must be lightweight in order to be supported by the existing structure of the turbine as well as durable in order to have a lifespan that is at least as long as that of the turbine. The material must also be cheap enough to meet the cost requirement as set out in the system requirements.

The second issue that must be addressed is the manufacturing of the individual components of the shroud. The more complicated each piece is the more it will cost to produce. However, the cost of the piece must be considered against the benefits that can be gained from having the ideal geometry for the shroud. The parts manufactured must be simple enough to allow for a relatively straightforward assembly and attachment process for the shroud. Ideally, the shroud would be able to be assembled and attached without the need for high tech machinery that would likely be unavailable at the desired locations of installation.

Lastly, if the shroud is integrated with an existing small wind turbine, the structural impact of the shroud on the turbine base must be carefully analyzed. The full scale drag force based on the preliminary testing in this project was estimated at about 500 N. Depending on the structure of the turbine base, which can range from a simple post to a lattice structure, this may induce a moment that cannot be withstood by the existing support. With this in mind, the design of the shroud may need to be adjusted to limit drag at the expense of performance to improve manufacturability.

As the design of the shroud progresses towards a larger scale, an appropriate commercial manufacturer should be consulted to allow further optimization of the design and prevent costly or time-consuming rework.

6.4 Health and Safety

Health and safety is always a paramount concern for engineering products. Not only does the final product have to be safe for the end users, but the process of design and building the product must also be safe for everyone who is involved. For this senior design project some of the main safety concerns were the structural integrity of the wind turbine, the safe operation of machining equipment to create a scaled model, and effects that the shroud will have on the cut off speed of the turbine.

A primary issue of health and safety relates to the structural integrity of the wind turbine post and its ability to withstand the added drag force of the shroud. This can be dealt with by performing structural calculations on the system to determine how these forces affect the wind turbine tower. Specifically, the deflection that these forces causes on the wind turbine tower should be analyzed on a case by case basis as the strength of the tower can vary greatly both by location and by design.

During scaled model wind tunnel testing, some of the parts for the wind tunnel test had to be machined by students on the senior design team. Safe operation of the machining equipment is extremely important so that no one is injured during the process. It is important to enforce safe construction of larger prototypes, especially in the field, as heavy machinery will almost certainly be required to construct a full scale shroud.

The shroud design is made to increase local wind speeds through the turbine by a factor of 1.5 so that more power can be generated by the turbine. One of the side effects of this design is that the maximum wind speed that the turbine can undergo before breaking is now lowered to two thirds of its nominal rating. While these wind speeds are generally in the range of 160 mph, it is still an issue that needed to be considered. This concern can be dealt with by siting the potential location for the shroud in areas where extreme wind speeds are very uncommon, thus mitigating the likelihood of this particular issue being a problem.

6.5 Ethics

The United Nations recognizes “the right to a standard of living adequate for the health and well-being of himself and of his family” as a basic human right. As global citizens, we must recognize modern energy access as essential to this standard and strive to resolve the energy deficit as a moral imperative. Rural electrification, however, presents an ethical dilemma unto itself: How can short term social costs, born largely by developing nations, be balanced against the long term benefits of moving towards a more sustainable society and protecting the environment? This is an extremely complex question and the answer depends on careful analysis of the costs and benefits at local, national, and global levels. In short, the ethics of energy must concern the whole energy cycle, from extraction and distribution to consumption and waste disposal.

Our particular solution will require the support of an entire community, not just an individual or even an agency. A wind turbine will require maintenance, which ties into a sense of ownership. Before any sort of lifestyle-altering technology is implemented, substantial research must be performed to ensure that the community is both willing and prepared to accommodate the changes that are associated with it. This team's only role is to develop a functioning design and inform the appropriate people of its capability. From an ethical standpoint, any decision to adopt the design must be made by the community itself. It will also be important to comply with any existing legal or political implications as this will be a long term solution that is devised for a culture very different from the one where it was developed.

Chapter 7: Business Plan

7.1 Product Description

The SWT Shroud can be originally installed or retrofitted on an existing small wind turbine in order to improve the overall energy production of the turbine. It accomplishes this through an optimized nozzle/diffuser geometry that locally increases the wind velocity at the turbine blades. Because wind speed is cubically related to the energy production of a wind turbine, the addition of this shroud has a dramatic effect on energy output. Preliminary studies show that energy production can be improved by a factor of over 3 times. As energy demand in rural areas increases, this product provides a suitable alternative to the costly installation of another wind turbine and is more environmentally friendly than increasing diesel usage in a hybrid system.

7.2 Potential Markets

It is rather difficult to estimate the number of end-users or even communities that could be potentially included in the potential market for this product. However, given the established strategy to pursue a licensing agreement with existing small wind turbine manufacturers, it is possible to size the market based on the number of manufacturing companies. There are over 300 registered small wind manufacturers that offer a complete commercialized generation system. Approximately 80% of those companies offer standalone off-grid systems that may be appropriately adapted for this product [4]. This suggests a current global market size of about 240 companies.

Initial sales will likely be concentrated on companies with a presence in South America, as the viability of small wind has been extensively explored in particular areas, such as Peru, Chile and Nicaragua. This brings the initial market size to about 40 companies. By strategically selecting leading companies and adapting prototypes to interface with their specific wind turbines, initial license agreements can be established and the brand recognition of the licensee can lead to discussions of expanding with additional licenses.

7.3 Competition

Airsynergy is an emerging Irish renewable energy company that licenses the first commercially available shrouded wind turbine to successfully augment wind speed in both high and low wind conditions. They are waiting on final certification of their 5kW turbine that has been prototyped at full scale in Ireland. They plan to eventually scale-up to 1 MW pending the success of the 5 kW model.

The company is still in early stages and has several certifications pending. Only one licensed partnership has been disclosed with U.S. based Aris Energy, LLC. However, they report to be in “serious” discussions with six companies in the U.S., U.K., Ireland and China. They estimate a product payback period of 3 to 5 years and estimate that larger models will produce power ranging from $45-$50 per megawatt-hour.

Their strategy of licensing their patented designs to qualified partners seems to be a primary strength, as it allows for a global roll-out while still allowing the employees to focus on product design and engineering. Their licensing partners act as agents in securing other licenses.

A key weakness in their approach, however, is that their design cannot be retrofitted and therefore cannot be leveraged on existing small wind turbines. Additionally, their marketing is focused on countries that already have well established grid lines. Because SWT Shroud was designed specifically for off-grid rural electrification, the target markets intersect very little, if at all.

7.4 Sales/Marketing

Rather than entering the market directly or even outsourcing sales, the most profitable marketing strategy for this project seems to be a licensing model similar to the one used by Airsynergy. This would require the procurement of a patent. However, as a differentiator from Airsynergy, SWT Shroud is an appropriate product for existing small wind turbine manufacturers. In this regard, leading small companies such as Bergey Windpower and Xzeres Wind can be viewed as potential partners rather than competitors. This will also leverage the existing brand recognition of these companies in the rural areas where they have already installed small wind turbines. Distribution and manufacturing will also ideally be handled by the licensee. It may also be appropriate to partner with an NGO, such as blueEnergy Group or the Alliance for Rural Electrification as the partnership may aid in procuring grant funding or sponsorship for pilot studies.

7.5 Manufacturing Plans

Considering the experience and vendor relationships of the small wind turbine manufacturers, the license agreement should stipulate that the licensee is responsible for manufacturing under normal circumstances. In order to establish an initial license agreement, however, it is likely that a full scale prototype will have to be manufactured and implemented. This would ideally occur in a target area of South America, though the proof of concept could be established in numerous areas, including sites in the U.S.

Manufacturing of the shroud attachment is estimated to take about a week, assuming a fiberglass composite material is used and full scale prototype costs are estimated between $7,000-$20,000, with location and proximity to manufacturing tools being the most influential factor. The prototype will likely be in operation from 6-months to 1-year to demonstrate functionality before serious licensing discussions begin.

7.6 Product Cost and Price

It is expected that the initial license agreements will favor the licensee; at least until the perceived value of the shroud attachment becomes more widely established. With this in mind, it is realistic that the first license will be sold at a fraction of the actual cost of the product. While product cost is highly variable, rough cost estimations, using rural South America as the implementation sites, are to about $20,000.

Airsynergy reports that their 5 kW prototype can generate energy at about $60 per megawatt-hour in a grid-tied system. While off-grid systems are subject to a different set of factors for pricing, this benchmark will be used to appropriately price the license in order to stay relatively competitive. However, this cost is once again highly dependent on location related factors.

7.7 Service or Warranties

The target lifetime of the shroud attachment is equivalent to the lifetime of the wind turbine it is fitted with. However, this cannot be directly proven as wind turbines have an estimated lifetime of 20-40 years. However, as part of the licensing agreement, a warranty of the attachment will be issued that guarantees the viability of the shroud for the length of the payback period, which is estimated at a range of 3-5 years.

Service on the wind turbine will be arranged by the licensing partner, with the intention of establishing local employment through the regular maintenance schedule. Monthly condition monitoring and appropriate preventative maintenance should be performed, as well as corrective maintenance as needed. The shroud attachment is designed with the intention of not adding any additional maintenance requirements beyond that of the wind turbine.

7.8 Financial Plan/Investor's Return

Startup costs for this venture would include application fees in pursuit of a patent as well as the construction of a full-scale prototype and operation for approximately 1 year. Table 13 below details the startup cost estimates.

Table 13: Estimate of venture start-up costs

Full-Scale Shroud Prototype	Materials Cost	$3,000.00
	Construction Cost	$500.00
	Installation Cost	$2,000.00
	Total Shroud Cost	**$5,500.00**
Pilot Year Operation	Site Service	$3,240.00
	Transportation to site	$1,200.00
	Technical Administration	$2,500.00
	Local Operator	$3,600.00
	Total Pilot Year Costs	**$10,540.00**
Patent Application	Patentibility Assessment	$1,600.00
	USPTO Application Filing Fee	$800.00
	Nonprovisional Application	$6,500.00
	Total Patent Fees	**$8,900.00**
TOTAL START-UP COSTS		**$24,940.00**

Given the social benefit of this product, it may be feasible to obtain investments from an impact investor that would allow a longer return on monetary investment in exchange for the social impact. Other potential investors include NGOs or renewable energy laboratories such as NREL.

The return on investments or profitability of this venture depends on the nature of the license agreement and therefore is highly variable.

Chapter 8: Conclusion

8.1 Summary

This project investigated one approach to improve the utility of small wind turbines. By attaching a flanged nozzle/diffuser shroud, the wind velocity at the blades is locally increased, thereby improving the energy production at lower wind speeds. The design of the shroud was accomplished through CFD modeling in ANSYS Fluent by isolating geometric factors and determining their influence on the performance. The most influential factor on the performance of the shroud was determined to be the length of the diffuser. Several attempts were made to model the effect of rotating turbine blades in ANSYS but none were able to accomplish this accurately.

A shroud design that met the design and performance criteria was selected and a scale model was 3D printed for wind tunnel testing at Santa Clara University. The factor by which wind turbine power production was increased by the addition of the shroud was measured to be 3.18, which is associated with a wind speed increase of 1.47. The added drag force on the turbine post due to the shroud was also measured in order to determine an experimental drag coefficient of 0.906. When scaled to full-size, this raises concerns for the structural integrity of the turbine base. Further structural analysis will be required as the turbine used for full scale implementation is selected. Pressure measurements along the length of the shroud during wind tunnel testing validated the CFD modeling results. This encourages the use of ANSYS Fluent as a tool to model the system at a larger scale.

8.2 Suggestions for Further Study

The immediate next step for this project would primarily involve the construction of a larger prototype to be tested in a larger wind tunnel. Given the location of Santa Clara University, the facilities at NASA Ames or Stanford University may be considered. The results from this study can provide a foundation to apply for grant funding to procure the necessary resources.

Additionally, the impact of the added drag force of the shroud on the full scale turbine post should be analyzed to ensure structural stability. If additional attachments are required, they should be designed as simply and cost effective as possible.

Before the attachment goes to market, viable materials and manufacturing methods should be investigated with the intention of enabling local production. The team hopes that the project will be carried on by future senior engineering students at SCU.

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Appendix A: Detailed Design Definition Information

A.1 Customer Needs Survey Results

Questions for Mathias Craig of blueEnergy Group

1. What is the current situation and trends in the off-grid electricity market? Do you have access to demand projections specific to small wind power?

In Nicaragua, for example, only 40% of the Atlantic Coast has access to electricity. The transmission system primarily serves the high population centers located on the Pacific Coast and central highlands of the country. The smaller, isolated communities on the Atlantic Coast make it harder to economically justify the extension of the transmission system.

Over the next 5-7 years, an increase in generating capacity of more than 100% will be required. The government is giving priority to the development of renewable energy supplies, and will require sustained levels of new investment averaging some US$ 100–120 million per year over this period.

2. In what ways have local or national governments supported or regulated your efforts in countries such as Nicaragua or Mongolia?

In Nicaragua, electric power generated from wind is not subject to specific legislation other than that contained in a specific law. At the utility scale, developers interested in developing wind farm sites require a provisional license from the MEM. Exclusivity is not presently given to any particular site. Any wind generation project greater than 1 MW requires a generation license from the Ministry of Energy and Mines (MEM) to be connected to the grid.

3. How effective is a grid-tied turbine system versus an off-grid system? Do you have recommendations for either? A preference when examining potential sites?

The economic advantage of a grid-tied system really shows for larger systems, all the more when the installation helps to lower or totally displace an already existing electric bill. We find that having a grid-tied 5 kW in Nicaragua is 5% cheaper than an isolated system in the absence of feed-in tariffs and without displacing an existing electric bill, and 31% cheaper in the case individual users are allowed to access feed-in tariffs.

4. What feedback have you gotten from stakeholders during your implementations?

While many investor or utility stakeholders had a negative view of the existing small wind sector, many more have a neutral or positive view of the future for the small wind sector. Many only suggest small wind as a complement to solar power systems or in another hybrid system.

End users deliver positive feedback when the system reliably delivers electricity and mostly negative if it is unreliable.

5. How accurate or reliable was the preliminary wind data gathered for locations in Nicaragua?

A reasonable amount of measurements and analysis of the wind potential have been done on the Pacific Coast of Nicaragua. More limited data and analysis exist regarding the central highlands and the lower wind regimes on the Atlantic Coast. There are currently several additional wind measuring projects underway in order to better evaluate the potential for wind generation in populated areas as well as rural indigenous communities, however it is not currently available.

The wind data recorded by blueEnergy and ENCO Central America was compared with the historical data from INETER52 over the last ten years and all of the data was found to exhibit the same trends of maximum winds occurring during the winter months of December through March and the minimum winds during the rainy months of June through August.

6. To what extent were the energy consumers willing to invest in the system versus an NGO?

Due to insufficient data, although the following factors are known to have a significant impact on the success of small wind rural development projects, we were unable to model: willingness to pay for service, impact of community governance on life-cycle costs, modularity and availability of micro finance.

7. What are the primary technical issues related to a grid-tied or off grid system that you would like to improve upon?

The primary technical issues pertain to a lack and/or variability of wind resource, poor reliability, maintenance requirements, design complexity, manufacturability.

8. Do you have any specific recommendations that would help us focus our research and development towards the end user?

Tying small-scale wind installations to productive uses of energy, such as irrigation or agricultural processing, is key to ensure sufficient funds can be raised to pay for the operation and maintenance of the systems

Questions for Ken Craig of Bergey Windpower:

1. What would you cite as the primary success factors of a small wind system?

Small wind power systems are dependent on sufficient local technical knowledge and ability to pay for operation and maintenance costs.

2. Why did you decide to install the system in Chile as a hybrid system versus purely a wind power system?

The system is designed to provide near grid quality electrical service on a continual basis. There is the implied understanding that this is a rural electric service and thus periods of no service will have to be tolerated for equipment failure or maintenance. The system architecture and control typology of the Tac hybrid system is extremely simple and straightforward yet the hybrid nature of the diesel system with the wind turbine enhances reliability

3. What has been the biggest challenge in maintaining the system post-implementation?

Wireless and SAESA are studying a variety of factors that may or may or not be contributing to the losses in hopes of optimizing the Tac distribution network. A few issues being considered include: Grid losses, faulty meters, improperly operating power factor compensation equipment and data collection errors on data acquisition system.

4. How were you able to assess the energy needs of the community? Did you rely on existing wind speed data or attempt to collect your own?

Wind data was collected on Isla Tac for two years prior to project implementation. An annual average wind speed of 5.4 m/s was recorded at a low point of the island. However, due to met tower shadowing effects in winter months, NREL readjusted the annual average wind speed to 6 m/s on the island.

5. Do you have any specific recommendations that would help us focus our research and development towards the end user?

Focus the expansion of the wind speed operating range at both limits rather than concentrating on accommodating only high speeds. Also, build in a buffer zone to accommodate any growth the community might experience due to the introduction of electricity.

Questions for Mike Koebbe of PowerWorks:

Could you please provide estimates for the following:

Factor by which energy production must be increased to justify cost: About 2

Required payback period: Approximately 5 years.

Weight requirement: Difficult to specify without knowing more about system and surroundings, but as lightweight as possible

Lifetime: Greater than that of the turbine (about 20 years)

Maintenance requirement: Every three years at absolute maximum.

A.2 Product Design Specifications

Characteristic/Element	Units	Design Target	Benchmark Range
Rated Wind Speed	m/s	8	4-5
Survival Wind Speed	m/s	63	54-63
Cut-in Wind Speed	m/s	2.35	2.2-4.5
Rated Power Production	kW	10	2.4-8.9
Diameter	m	7.5	3.72-7
Noise Production	dB	45	41-42.9
Cost	dollars	300	(18,000-35,000)

Figure 18: Copy of Product Design Specifications

Appendix B: Detailed Design Analysis Results

B.1 Candidate Shroud Geometries

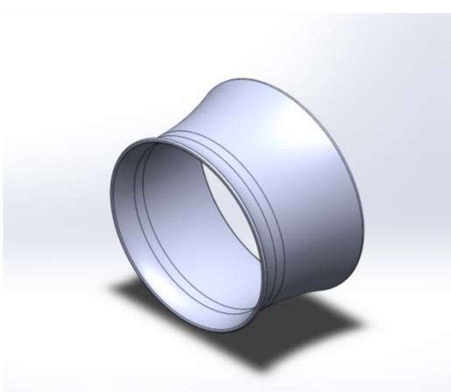


Figure 19: Shroud Geometry A

Figure 20: Shroud Geometry B

Figure 21: Shroud Geometry C

Figure 22: Shroud Geometry D

Figures 19-22: Initial Shroud Geometries Tested

B.3 Wind Tunnel Testing Raw Data

Power

	Unshrouded	Shrouded
Mass Lifted [kg]	0.0145	0.0327
Avg Lift Time [s]	3.8345	2.2493
StdDev of Lift Time	0.2848	0.1921
Power Output from Avg Lift Time [W]	0.0785	0.2501
Avg Power Output [W]	0.0787	0.2547
StdDev of Power Output	0.0046	0.0199
Wind Tunnel Velocity	53.741	
Density	1.184	
Area	0.008	
Velocity	54.078	79.063

Increase	1.462	
Cp	1.05E-04	3.36E-04

Drag

	1	2	3	5	6
Avg Delta V	-0.000153883	-0.000156	-0.000153	-0.000149	-0.000152
Avg Drag [g]	1623.932048	1642.927462	1609.685487	1570.463474	1604.057216
Avg Drag [lbs]	3.580153071	3.622030742	3.548744818	3.462275184	3.53633662
Avg Drag [N]	15.92530849	16.11158959	15.78559768	15.40096172	15.73040328
Drag Coeff	0.913623393	0.924310204	0.905608284	0.883541999	0.902441822
Average Drag Coeff	0.90590514				
Average Drag Force	15.79077215				

Density	1.1840000
Velocity	53.7410000
Inner Radius	0.0508000
Outer Radius	0.0763270
Scaled Area	0.010195005
FS Inner Radius	1.875
FS Outer Radius	2.8125

FS Area	13.80582709
Reynold's Number	346658
Average Drag Force (Scaled)	15.791
Average Drag Coefficient	0.9059
Anticipated Full Scale Drag	474

Pressure

Chord Length	CFD	Wind Tunnel
0.95	-1019.125	-601.42076
0.85	-1105.65	-622.057057
0.75	-1192.175	-713.8798661
0.65	-1394.066667	-847.9286711
0.55	-1711.225	-1136.86919
0.45	-2201.533333	-1509.564697
0.35	-2432.166667	-2012.136942
0.25	-2547.533333	-2192.812825
0.15	-2662.9	-2192.631106
0.05	-4047.1	-2192.772996

Chord Length	Shroud with Blade	Shroud Without Blade
0.95	-1099.838363	-601.42076
0.85	-1208.461458	-622.057057
0.75	-1306.241162	-713.8798661

0.65	-1581.099711	-847.9286711
0.55	-2165.965724	-1136.86919
0.45	-1811.270346	-1509.564697
0.35	-2024.205068	-2012.136942
0.25	-1855.440485	-2192.812825
0.15	-1906.899295	-2192.631106
0.05	-2192.561406	-2192.772996

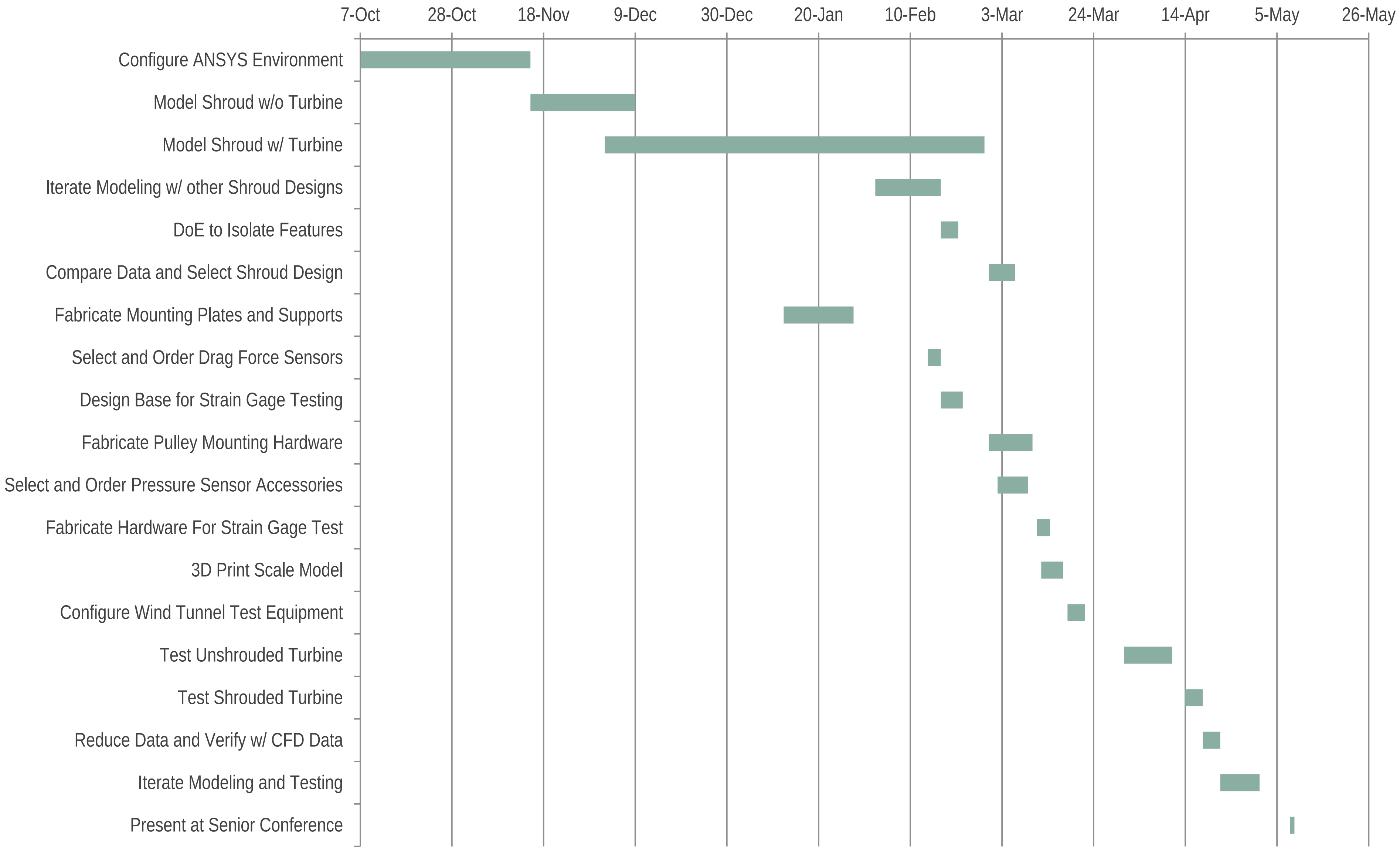
Appendix C: Project Management Data

C.1 Budget

INCOME			
Category	**Source**	**Sought**	**Committed**
Grant	Roelandts Grant	$2,000.00	$1,500.00
	Undergrad Program	$1,680.00	$1,500.00
	ASME SCVS	$700.00	$400.00
	TOTAL	**$4,380.00**	$3,400.00

EXPENSES			
Category	**Description**	**Estimated**	**Spent**
Hardware for Model	Low-Carbon Steel Rod, 1/4" Diameter	$10.00	$4.92
	Nonmarring Flat Point Socket Set Screw, Type 316 Stainless Steel, 4-40 Thread, 3/16" Long	$5.00	$4.12
	Nylon 2L-Section V-Belt Pulley, Aluminum Hub, 2" OD, 1.9" Pitch Diameter, 1/4" Bore	$30.00	$21.00
	Nylon 2L-Section V-Belt Pulley, Aluminum Hub, 6" OD, 5.9" Pitch Diameter, 1/4" Bore	$25.00	$20.29
	Miniature Ball Bearing, 1/4" Bore, 3/8" O.D., Shielded	$30.00	$50.00
	2L V-Belt	$10.00	$18.31
	Steel Ball Bearing, Plain Double Shielded for 1/4" Shaft Dia, 11/16" OD	$25.00	$30.40
	Pulley for Wire Rope, Nylon with Easy-Turn Bearings, for 1/8" Rope Diameter	$15.00	$10.00
	High-Strength 2024 Aluminum, Tube, 1/2" OD, .430" ID, .035" Thickness Wall, 3' L		$21.91
	Set Screws		$11.14
	3D Printing Filler		$14.12
	Shaft Fasteners		$52.46
Pressure Measurement	Scanivalve Equipment	$1,200.00	$453.12
Load Measurement	Subminiature Load Cells	$1,480.00	$990.00
	Strain Gages		$106.00
3D Printing Filament	1 kg of plastic filament	$40.00	
Misc.			162.15
	TOTAL	**$2,870.00**	$1,969.94

C.2 Gantt Chart



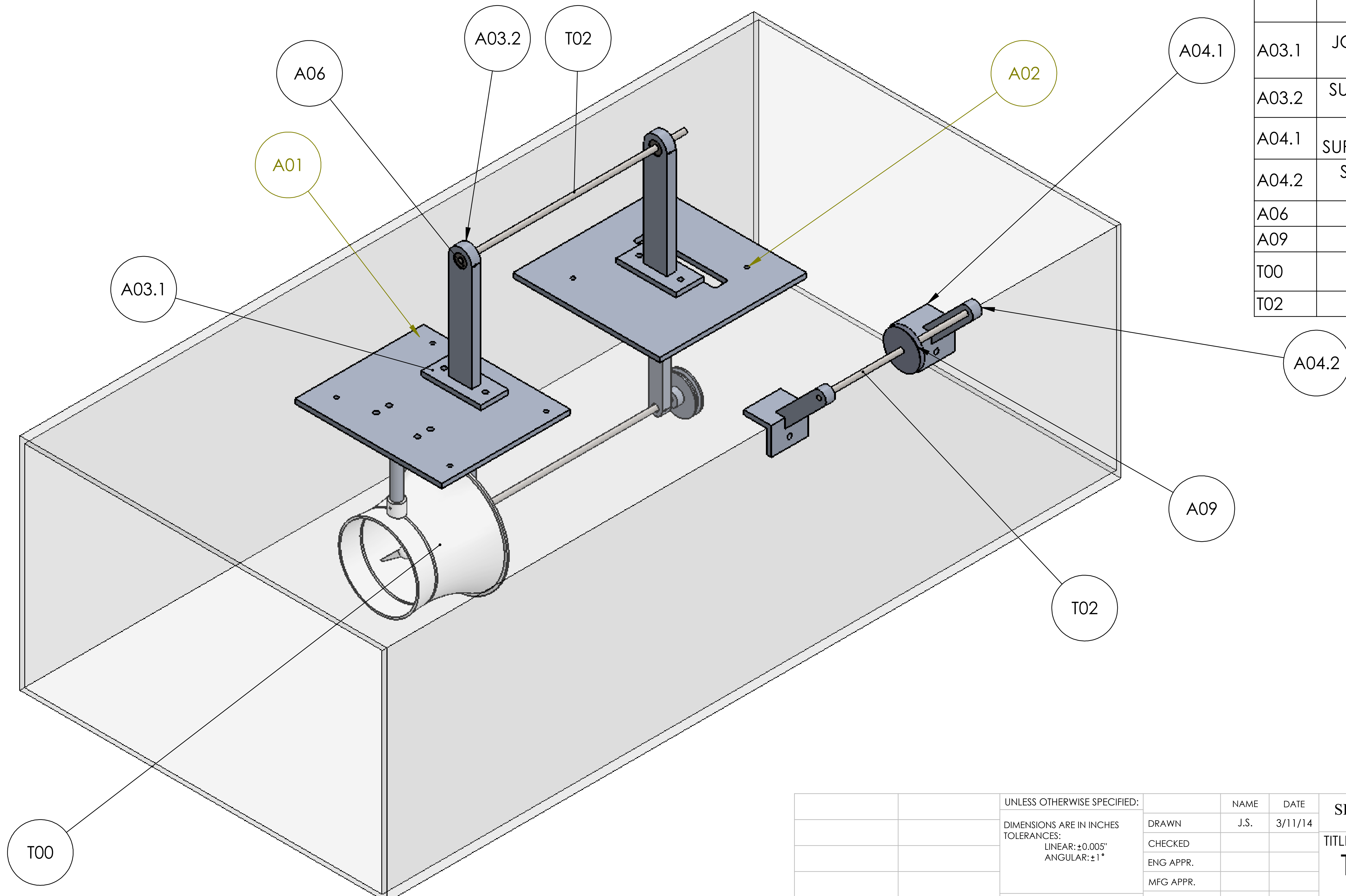
C.2 Parts List

Shrouded Small Wind Turbines													
Wednesday, March 19, 2014													
Component Description	Part #	# of items	B/M/O[1]	Vendor	Cost / part	Responsible person	Man-hours[2]	Des	Proc	Build (ea)	Assm	Order or start date	Receive or finish date
Model Vertical Support Base	T01.1	2	M	SCU		Joe & Kristen	7.5	3	0.25	2	0.25	28-Jan	4-Feb
Model Vertical Support Post	T01.2	2	M	SCU		Joe & Kristen	7.5	3	0.25	2	0.25	28-Jan	4-Feb
Low-Carbon Steel Rod, 1/4" Diameter	T02	3	B	McMaster-Carr	$4.92	Joe	2.25	0.5	0.25	0.5		21-Dec	2-Jan
Nonmarring Flat Point Socket Set Screw, Type 316 Stainless Steel, 4-40 Thread, 3/16" Long	T03	1	B	McMaster-Carr	$4.12	Joe	0.25		0.25			21-Dec	2-Jan
Miniture Ball Bearing, 1/4" Bore, 3/8" O.D., Shielded	T04	2	B	National Precision Bearings	$25.00	Joe	1.75	1.25	0.5			6-Jan	10-Jan
Shroud Base	T05.1	1	M	SCU		All	6.25	2	0.25	4		24-Feb	2-Apr
Shroud Boss	T05.2	1	M	SCU			0.75	0.5	0.25				16-Apr
Shroud Post	T05.3	1	M	McMaster-Carr	$29.46	Joe & Kristen	1.75	1	0.5		0.25	28-Feb	25-Apr
Shroud	T05.4	1	O	SCU		Joe & Mike	84	80	1	3		17-Mar	16-Apr
Blades & Hub	T06	1	O	SCU		Joe	5.5	5	0.5			14-Mar	16-Apr
Turbine Model	T00					All	20				20	18-Mar	1-May
Sub System Totals					**$63.50**		**137.5**						

Component Description	Part #	# of items	B/M/O[1]	Vendor	Cost / part	Responsible person	Man-hours[2]	Des	Proc	Build (ea)	Assm	Order or start date	Receive or finish date
Front Mounting Plate	A01	1	M	SCU		Joe & Kristen	6.5	3	0.5	3		23-Jan	3-Feb
Rear Mounting Plate	A02	1	M	SCU		Joe & Kristen	6.5	3	0.5	3		23-Jan	3-Feb
Pulley Vertical Support Base	A03.1	2	M	SCU		Joe & Kristen	6.5	2	0.5	2		24-Feb	28-Feb
Pulley Vertical Support Post	A03.2	2	M	SCU		Joe & Kristen	9.75	2	0.5	3.5	0.25	11-Mar	13-Mar
Pulley Angled Support Base	A04.1	2	M	SCU		Joe & Kristen	8.5	2	0.25	3	0.25	6-Mar	11-Mar
Pulley Angled Support Post	A04.2	2	M	SCU		Mike	10.5	2	0.5	4		6-Mar	17-Mar
2L V-Belt	A05	1	B	McMaster-Carr	$6.63	Joe	0.75	0.5	0.25	0		21-Jan	23-Jan
Steel Ball Bearing, Plain Double Shielded for 1/4" Shaft Dia, 11/16" OD	A06	2	B	McMaster-Carr	$15.20	Joe	0.75	0.5	0.25	0		21-Jan	23-Jan
Nylon 2L-Section V-Belt Pulley, Aluminum Hub, 2" OD, 1.9" Pitch Diameter, 1/4" Bore	A07	1	B	McMaster-Carr	$10.50	Joe	1.5	1	0.5	0		21-Dec	2-Jan
Nylon 2L-Section V-Belt Pulley, Aluminum Hub, 6" OD, 5.9" Pitch Diameter, 1/4" Bore	A08	1	B	McMaster-Carr	$20.29	Joe	1.5	1	0.5	0		21-Dec	2-Jan
Pulley For Wire Rope, Nylon W/easy-turn Bearings, For 1/8" Rope Diameter	A09	1	B	McMaster-Carr	$10.00	Joe	0.75	0.5	0.25	0		26-Jan	29-Jan
Wind Tunnel Aparatus	A00					All	20				20	18-Mar	1-May
Sub System Totals					**$77.82**		**73.50**						
					$141.32		**211.00**	**113.75**	**8.50**	**47.50**	**41.25**		

Appendix D: Parts and Assembly Drawings

Please continue to next page.



PART #	DESCRIPTION	QTY.
A02	CONNECTS SUPPORTS TO WIND TUNNEL	1
A03.1	JOINS MOUNTING PLATE AND SUPPORTS	2
A03.2	SUPPORTS BALL BEARING FOR AXLE ROTATION	2
A04.1	CONNECTS ANGLED SUPPORT OT WIND TUNNEL	2
A04.2	SUPPORTS PULLEY FOR LIFTING MASS	2
A06	BEARINGS	2
A09	2" DIA PULLEY	1
T00	TURBINE ASSEMBLY	1
T02	ROTATIONAL AXLE	2

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: N/A

FINISH: N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	3/11/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

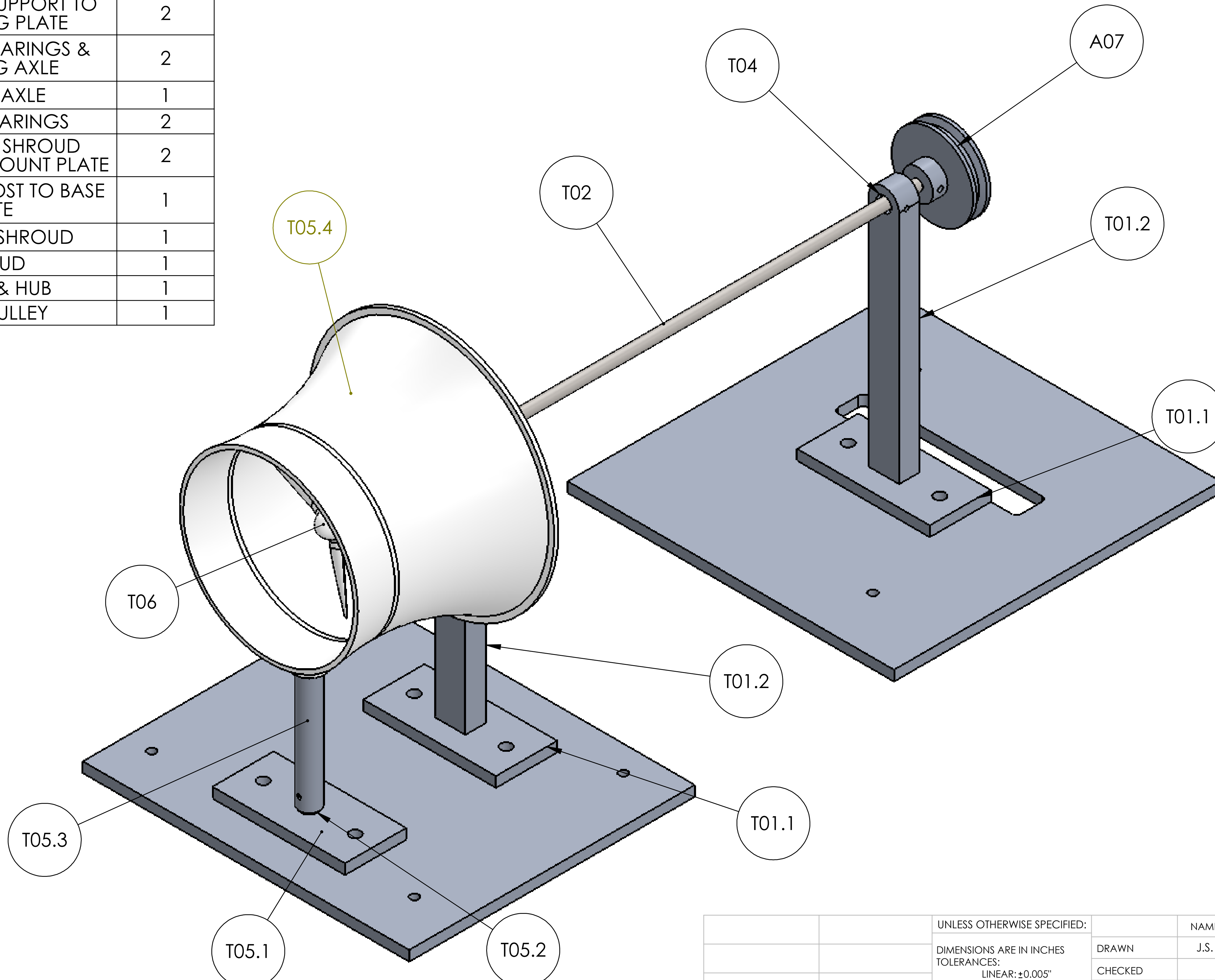
SHROUDED SMALL WIND TURBINE

TITLE:
TESTING ASSEMBLY

SIZE	DWG. NO.	REV
A	A00	3

SCALE: 1:8 WEIGHT: SHEET 1 OF 1

PART #	DESCRIPTION	QTY.
T01.1	CONNECTS SUPPORT TO MOUNTING PLATE	2
T01.2	SUPPORTS BEARINGS & ROTATING AXLE	2
T02	MODEL AXLE	1
T04	MODEL BEARINGS	2
T05.1	CONNECTS SHROUD SUPPORT TO MOUNT PLATE	2
T05.2	CONNECTS POST TO BASE PLATE	1
T05.3	SUPPORTS SHROUD	1
T05.4	SHROUD	1
T06	BLADES & HUB	1
A07	2" DIA PULLEY	1



NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL N/A

FINISH N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	3/19/14
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

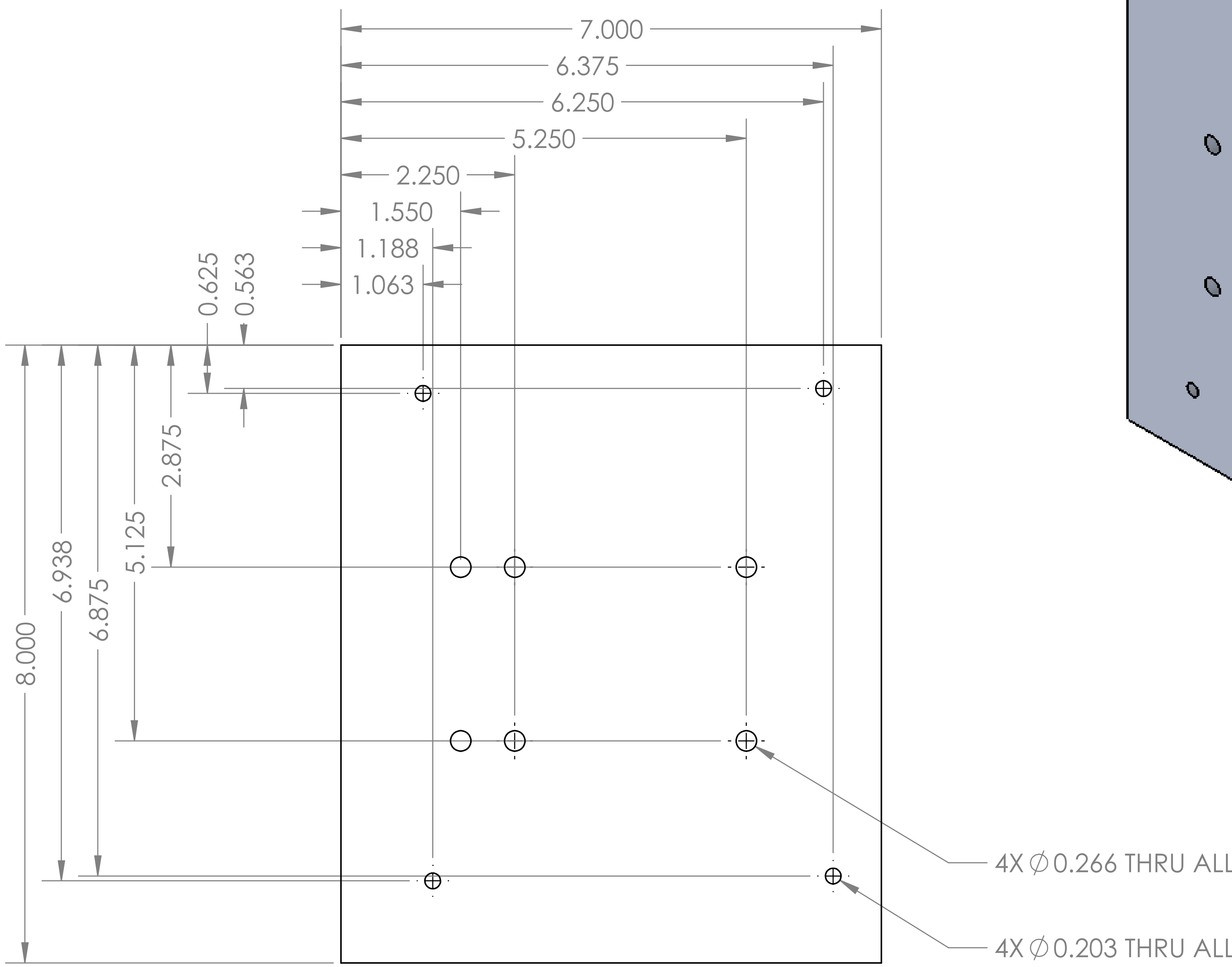
SHROUDED SMALL WIND TURBINE

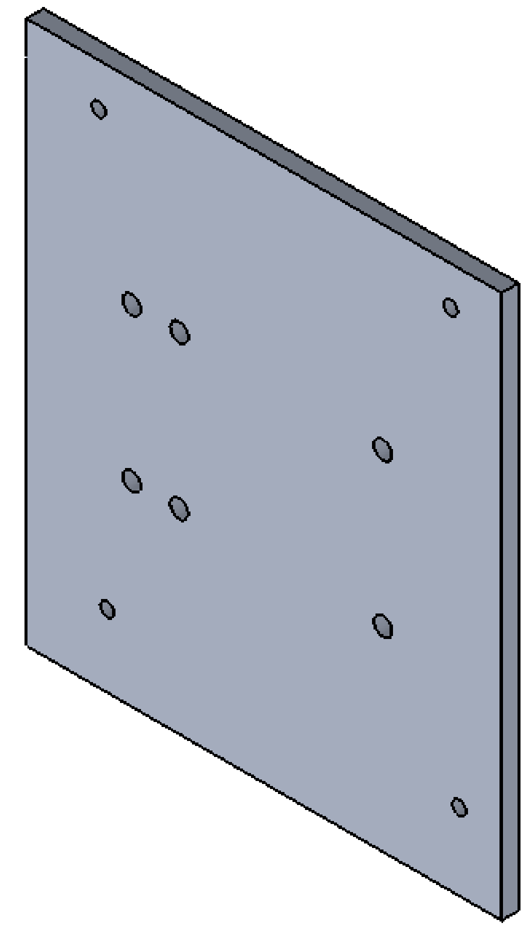
TITLE:

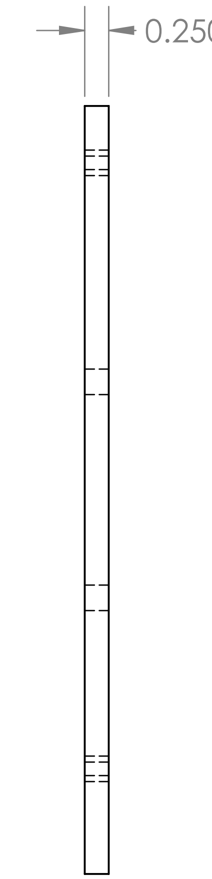
TURBINE ASSEMBLY

SIZE A | DWG. NO. T00 | REV 3

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1







PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	1/23/14
CHECKED		
ENG APPR.		
MFG APPR.	K.F.	2/3/14
Q.A.		

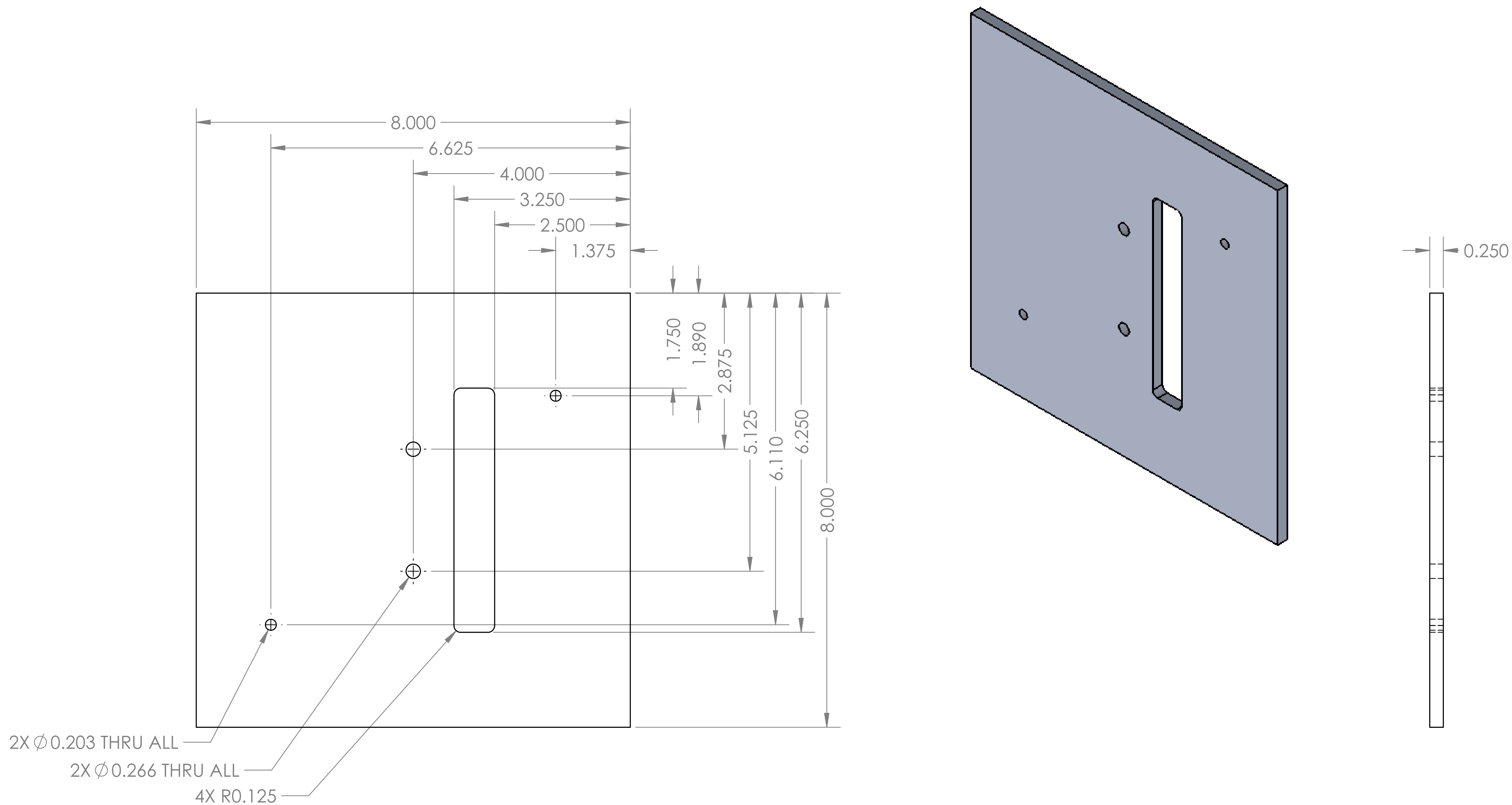
COMMENTS:

SHROUDED SMALL WIND TURBINE

TITLE: FRONT MOUNTING PLATE

SIZE	DWG. NO.	REV
A	A01	3

SCALE: 1:4 WEIGHT: SHEET 1 OF 1



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TOLERANCES:
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ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	1/23/14
CHECKED		
ENG APPR.		
MFG APPR.	K.F.	2/3/14
Q.A.		

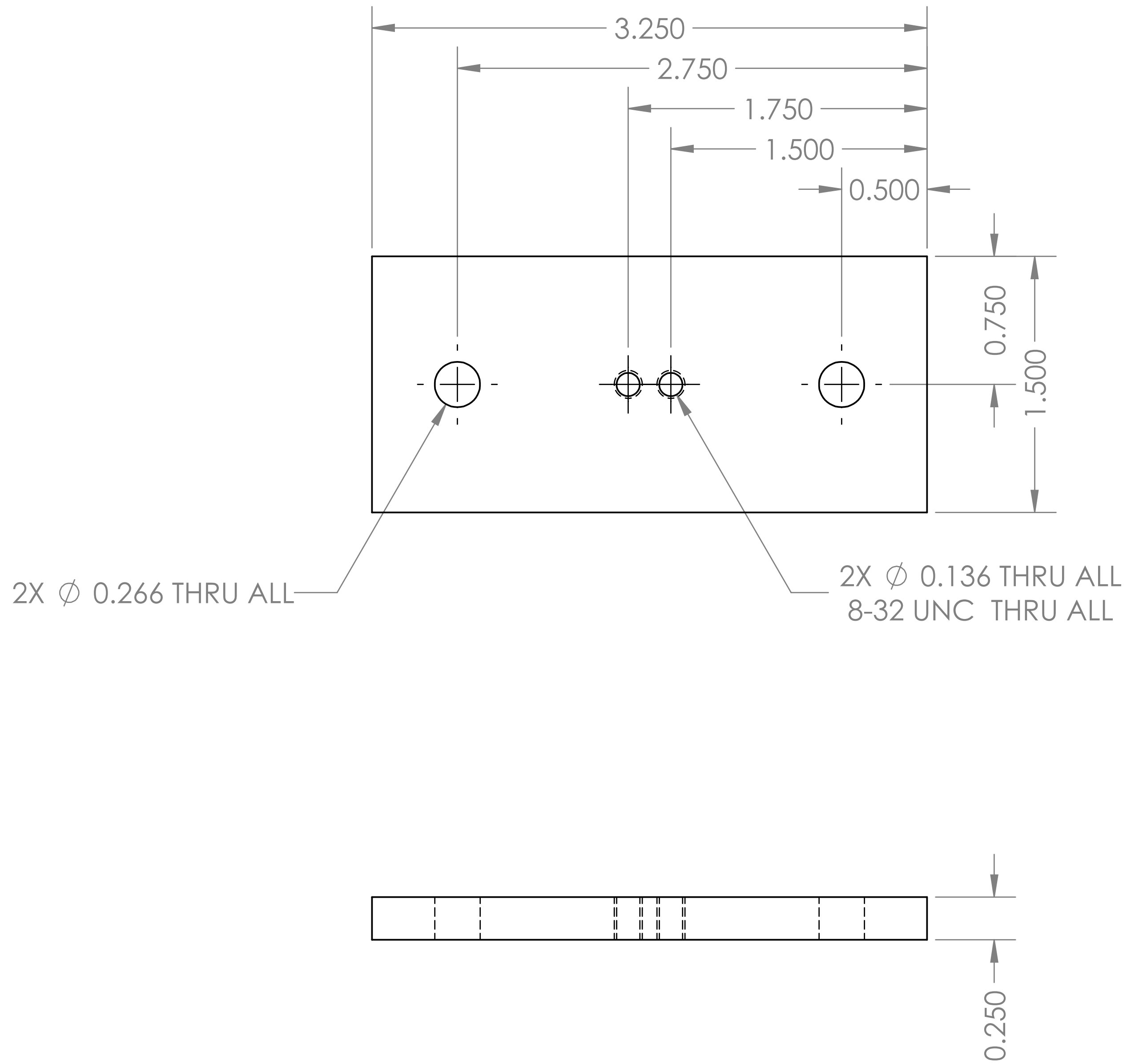
COMMENTS:

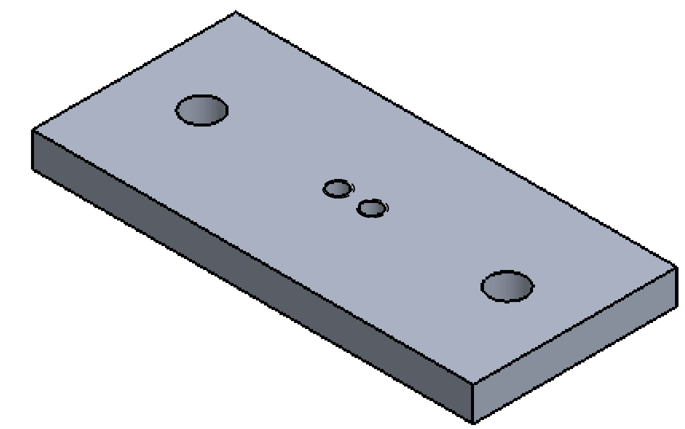
SHROUDED SMALL WIND TURBINE

TITLE: REAR MOUNTING PLATE

SIZE	DWG. NO.	REV
A	A02	3

SCALE: 1:4 WEIGHT: SHEET 1 OF 1





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APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	2/24/14
CHECKED		
ENG APPR.		
MFG APPR.	K.F.	2/28/14
Q.A.		

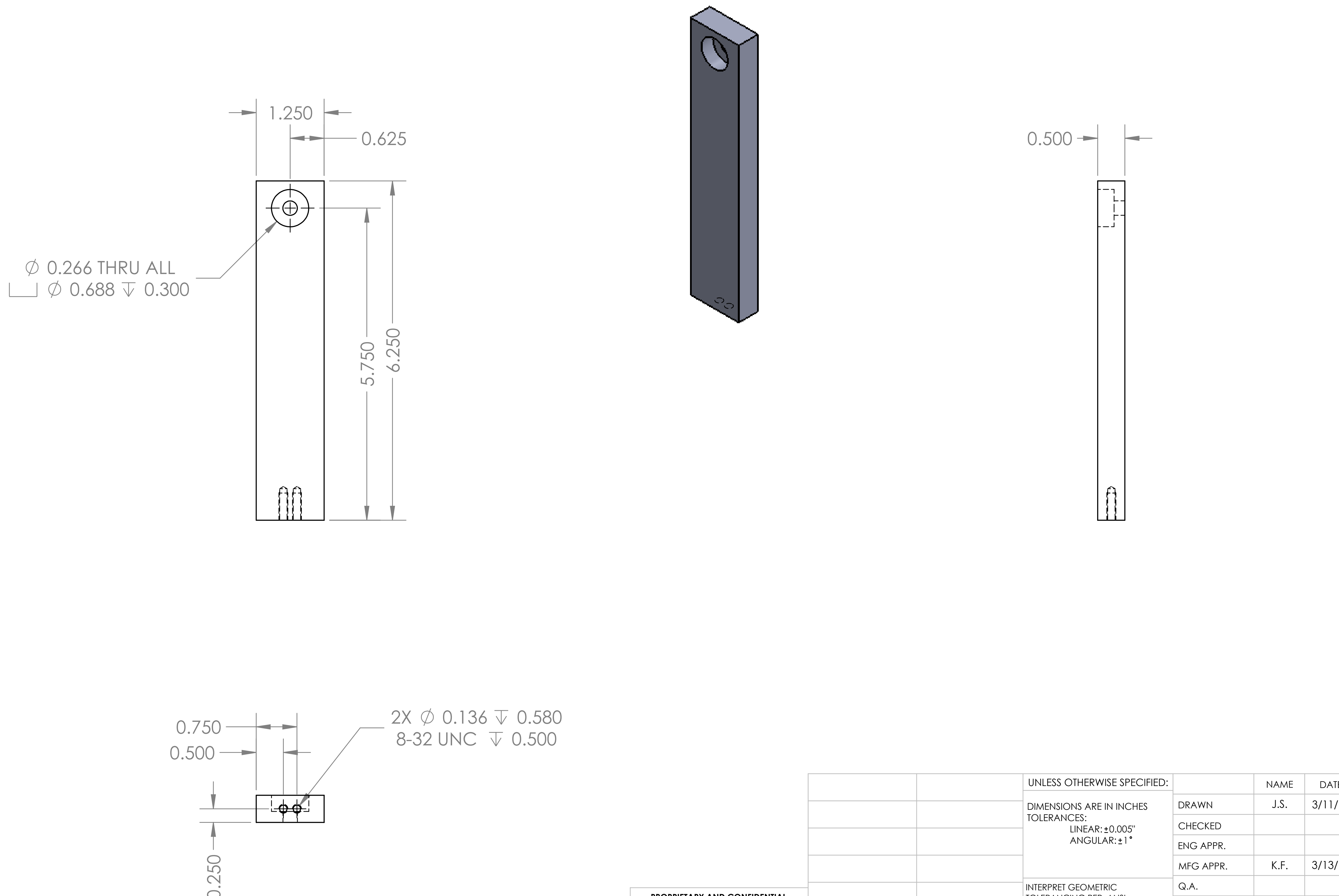
COMMENTS:

SHROUDED SMALL WIND TURBINE

TITLE:
PULLEY VERTICAL SUPPORT BASE

SIZE	DWG. NO.	REV
A	A03.1	3

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

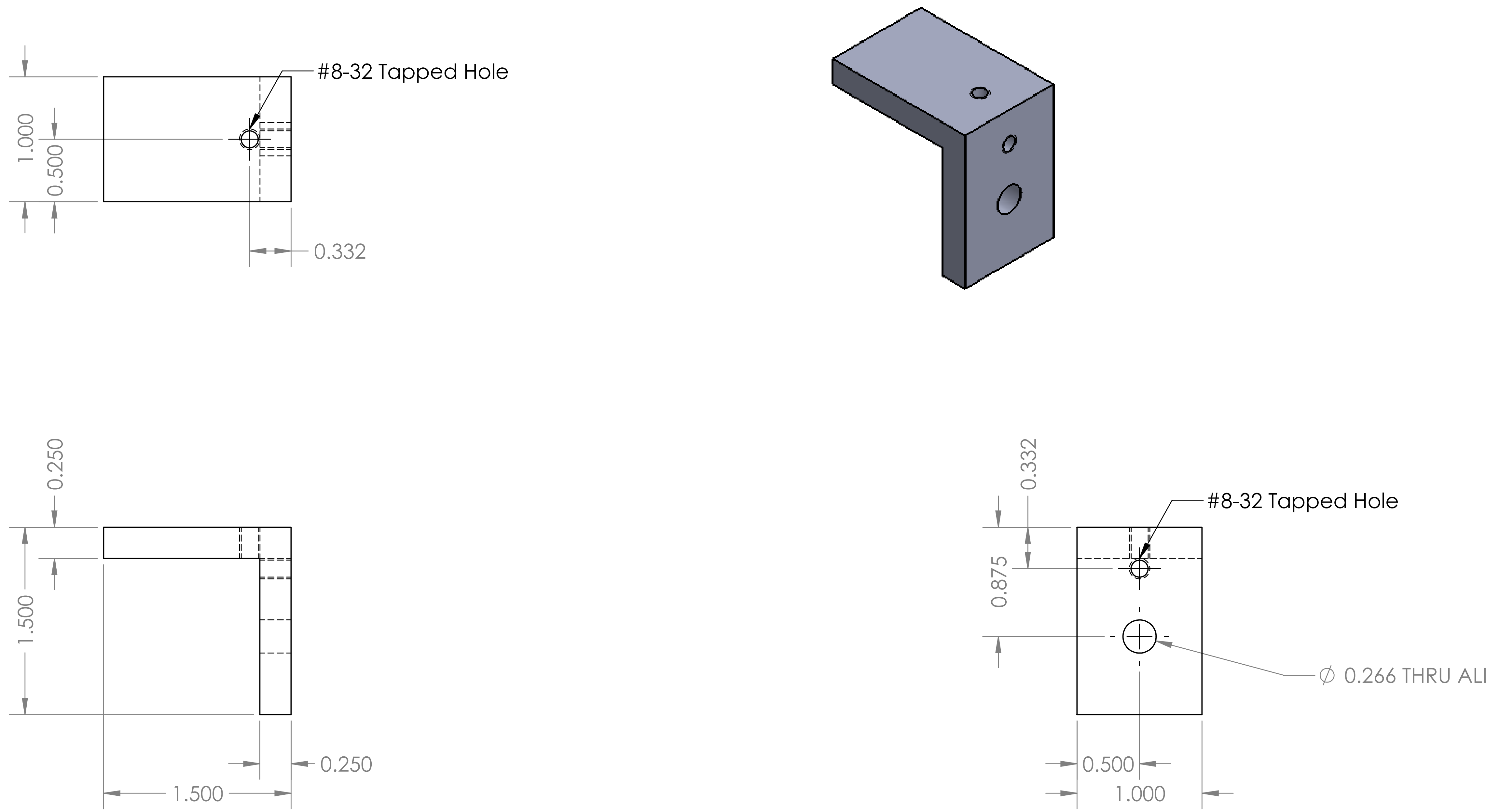
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	3/11/14
CHECKED		
ENG APPR.		
MFG APPR.	K.F.	3/13/14
Q.A.		
COMMENTS:		

SHROUDED SMALL WIND TURBINE

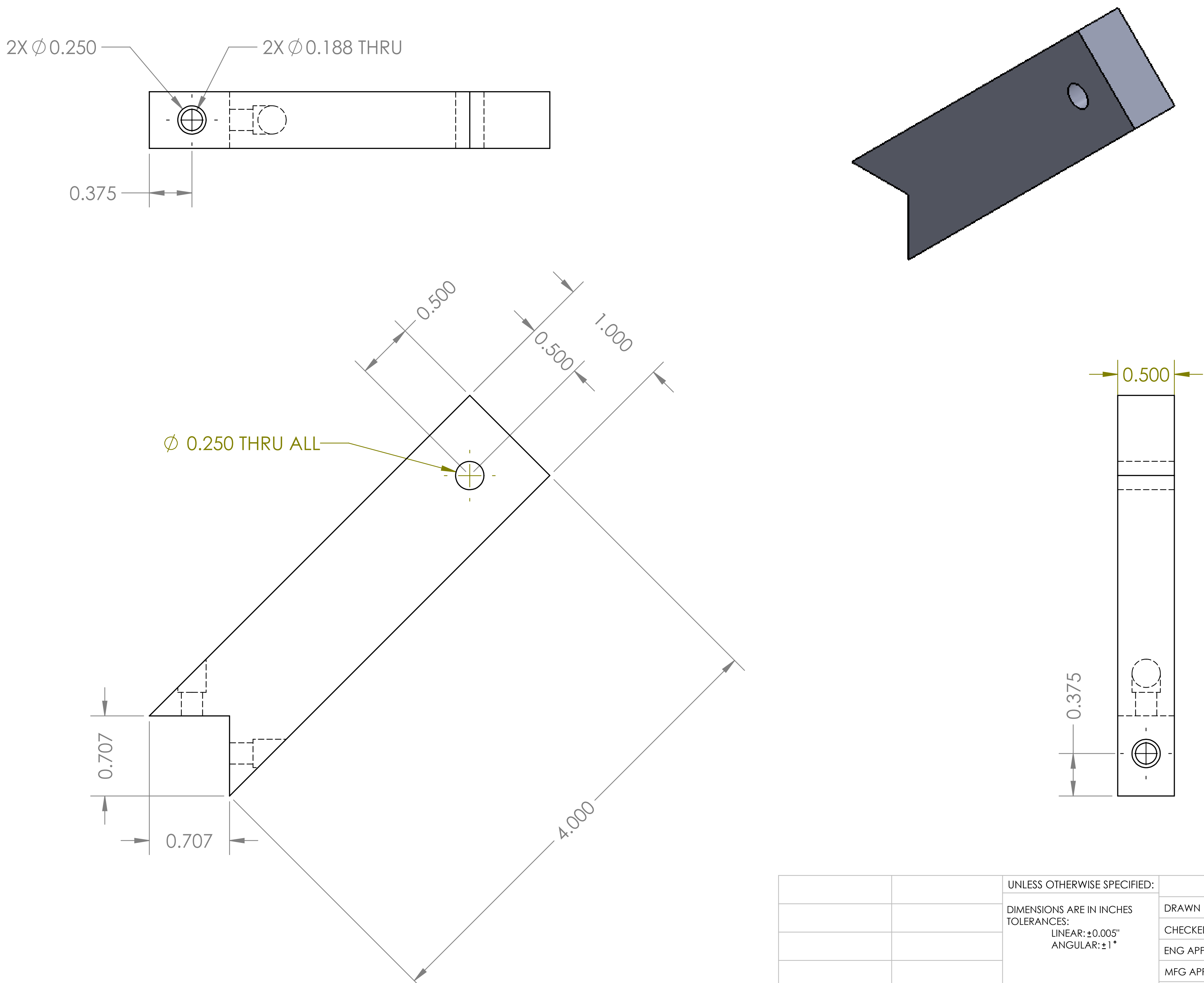
TITLE: PULLEY VERTICAL SUPPORT POST

SIZE	DWG. NO.	REV
A	A03.2	3
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	SHROUDED SMALL WIND TURBINE
DIMENSIONS ARE IN INCHES TOLERANCES: LINEAR: ±0.005" ANGULAR: ±1°	DRAWN	J.S.	2/23/14	TITLE:
	CHECKED			PULLEY ANGLED SUPPORT BASE
	ENG APPR.			
	MFG APPR.	J.S.	3/11/14	
INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.			
MATERIAL ALUMINUM	COMMENTS:			SIZE A · DWG. NO. A04.1 · REV 3
FINISH MACHINED				
DO NOT SCALE DRAWING				SCALE: 1:2 · WEIGHT: · SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	2/23/14
CHECKED		
ENG APPR.		
MFG APPR.	M.H.	3/17/14
Q.A.		

COMMENTS: COUNTER BORES FOR SCREW HEADS ONLY NEED TO BE DEEP ENOUGH SO THAT ENTIRE DIAMETER IS FLAT.

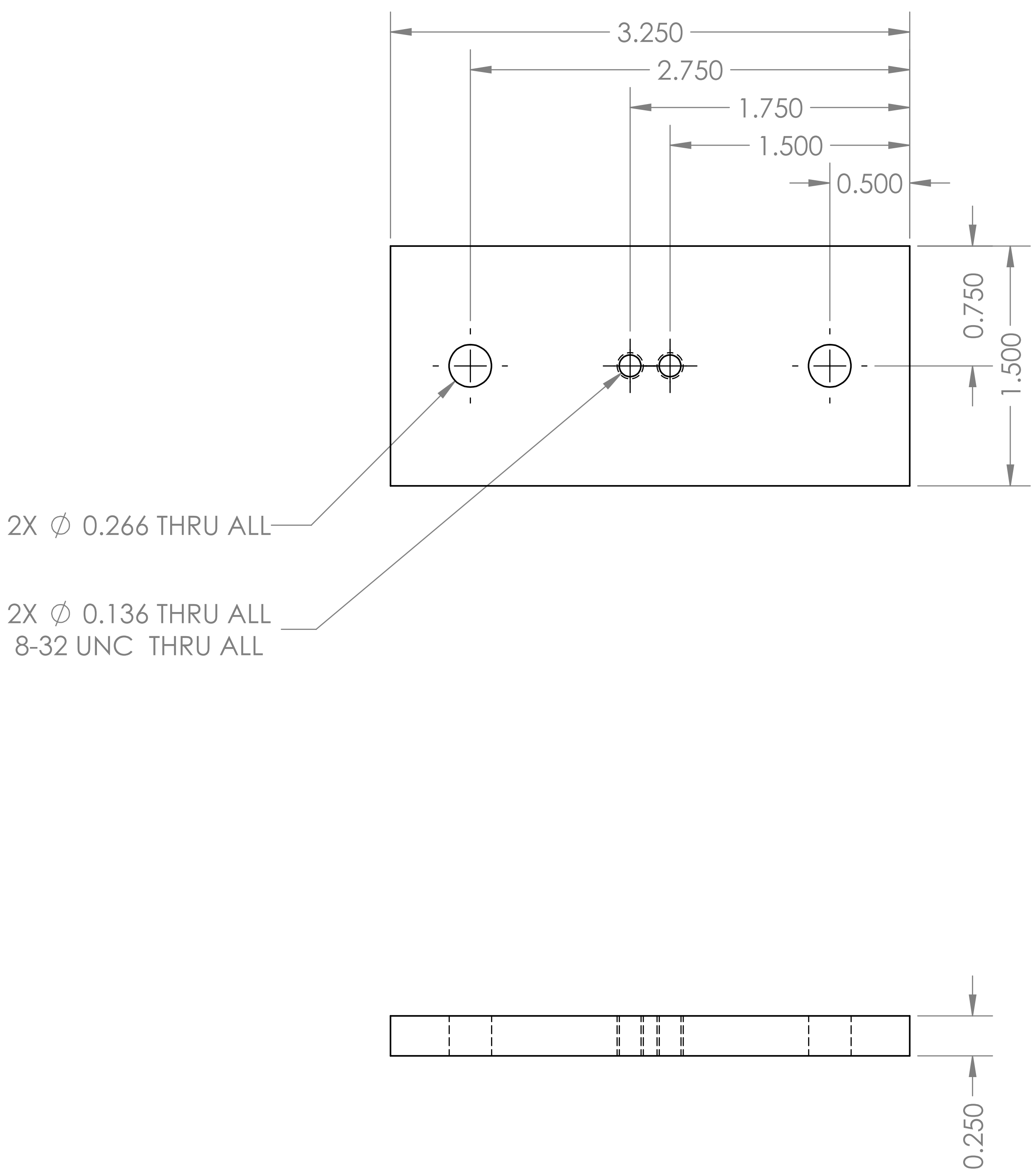
SHROUDED SMALL WIND TURBINE

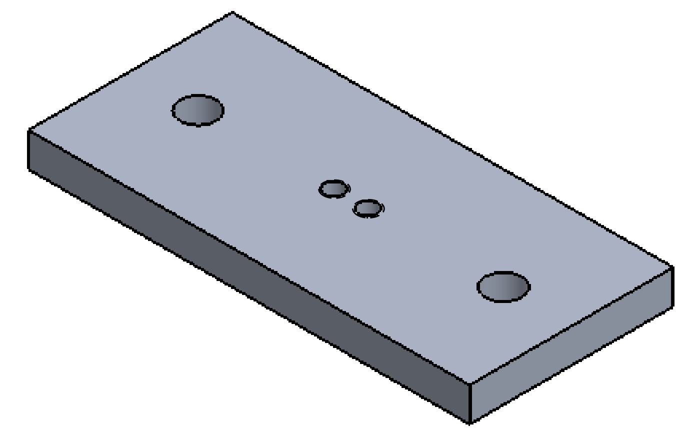
TITLE:

PULLEY ANGLED SUPPORT POST

SIZE	DWG. NO.	REV
A	A04.2	3

SCALE: 1:2 WEIGHT: SHEET 1 OF 1





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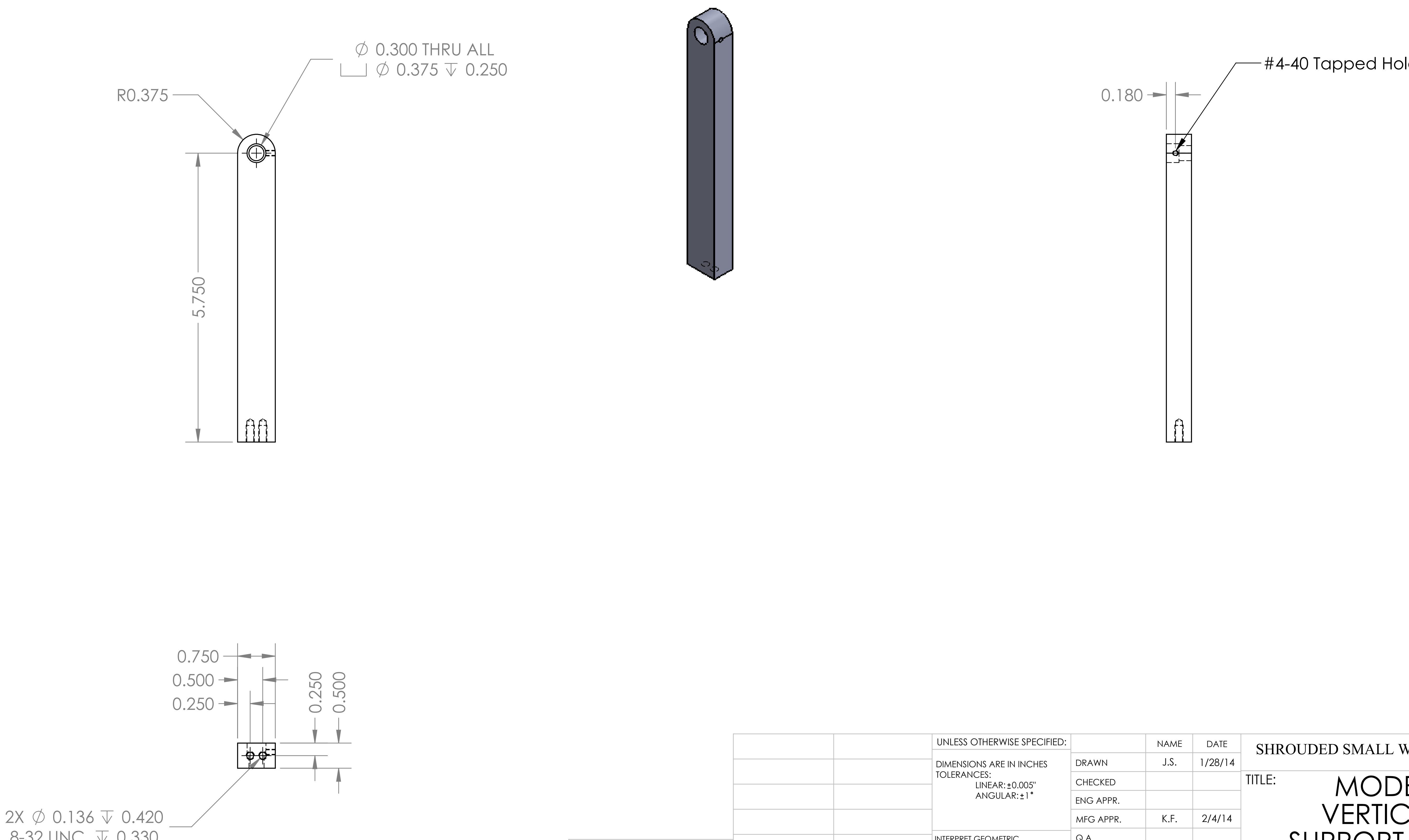
	DIMENSIONS ARE IN INCHES TOLERANCES: LINEAR: ±0.005" ANGULAR: ±1°	DRAWN	J.S.	1/28/14	TITLE:	
		CHECKED			MODEL VERTICAL SUPPORT BASE	
		ENG APPR.				
		MFG APPR.	K.F.	2/4/14		
	INTERPRET GEOMETRIC TOLERANCING PER: ANSI	Q.A.				
	MATERIAL ALUMINUM	COMMENTS:			SIZE A	DWG. NO. T01.1 · REV 3
NEXT ASSY · USED ON	FINISH MACHINED					
APPLICATION	DO NOT SCALE DRAWING				SCALE: 1:2 · WEIGHT:	SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

DO NOT SCALE DRAWING

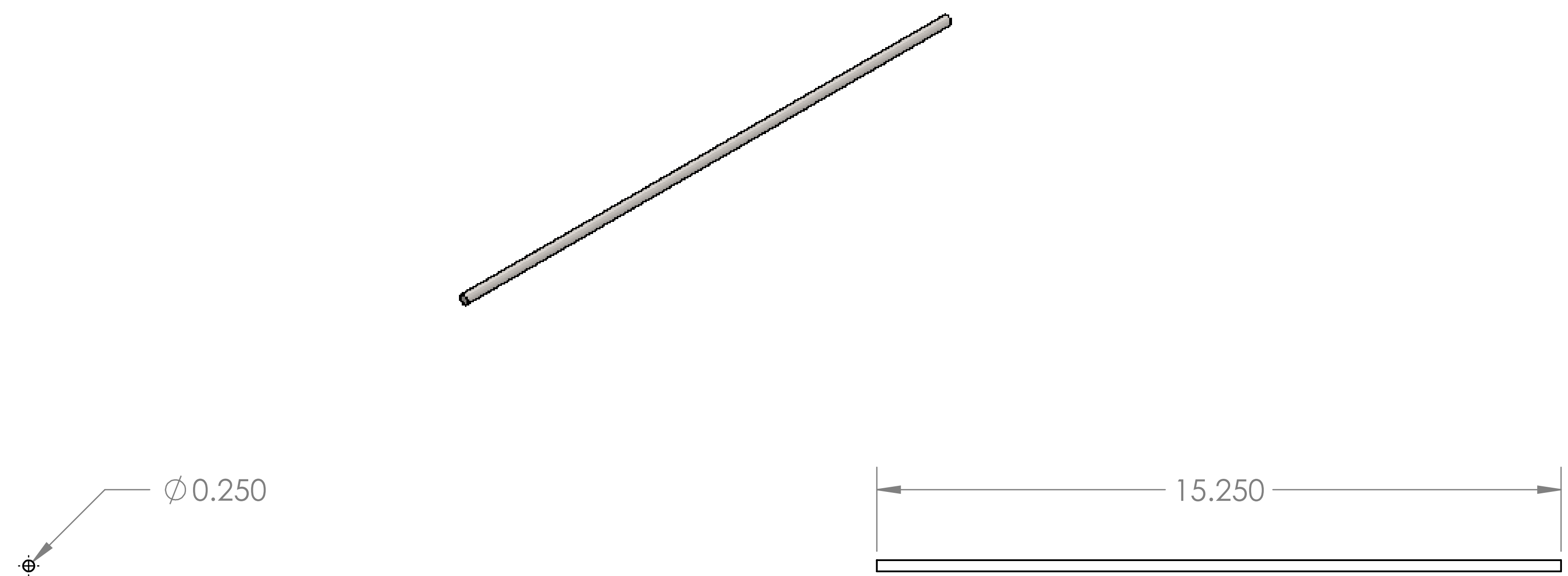
	NAME	DATE
DRAWN	J.S.	1/28/14
CHECKED		
ENG APPR.		
MFG APPR.	K.F.	2/4/14
Q.A.		
COMMENTS:		

SHROUDED SMALL WIND TURBINE

TITLE: MODEL VERTICAL SUPPORT POST

SIZE: A | DWG. NO.: T01.2 | REV: 3

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



SHROUDED SMALL WIND TURBINE

TITLE:

MODEL AXLE

	NAME	DATE
DRAWN	J.S.	2/23/14
CHECKED		
ENG APPR.		
MFG APPR.	J.S.	4/16/14
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: LOW CARBON STEEL

FINISH: AS PURCHASED

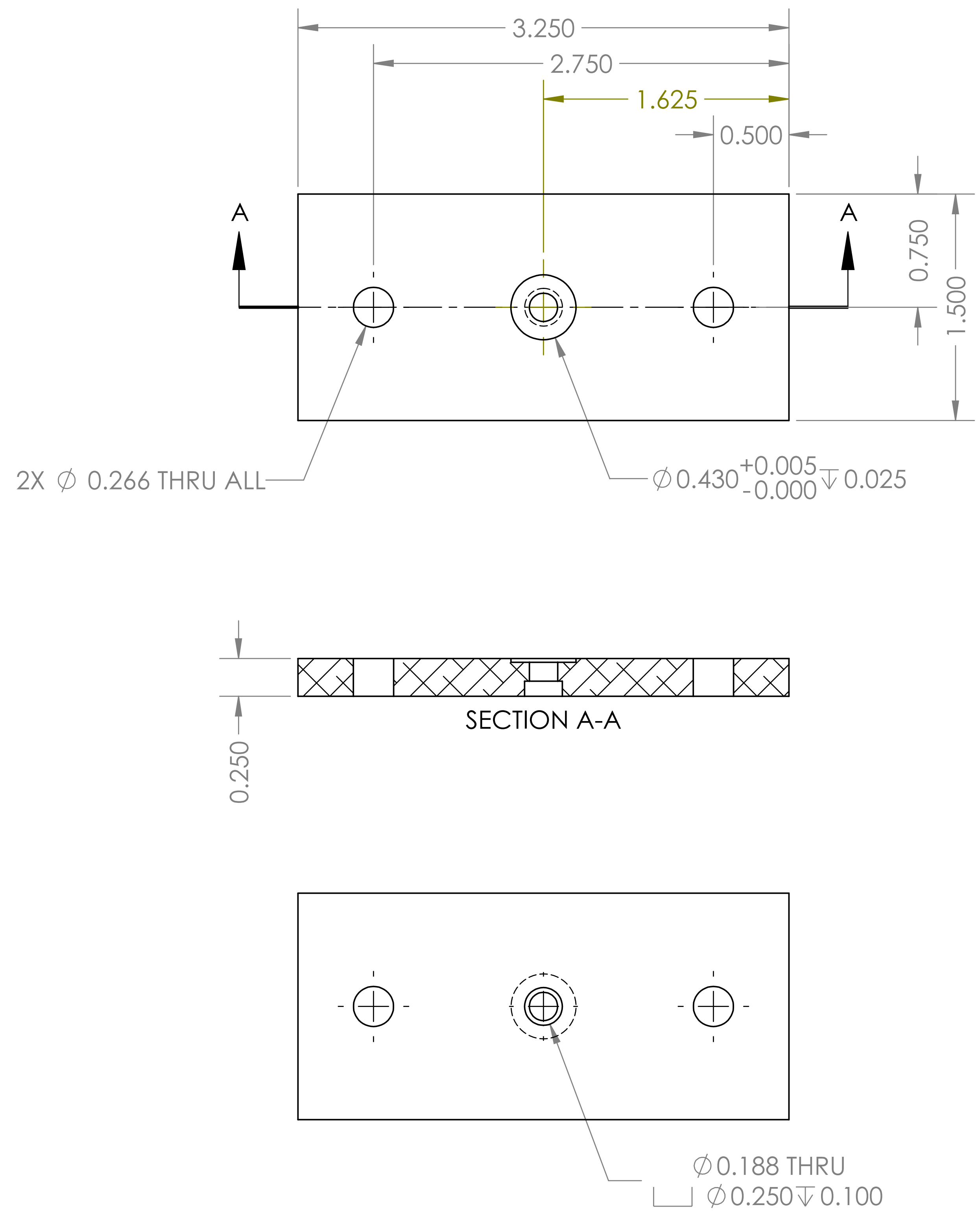
DO NOT SCALE DRAWING

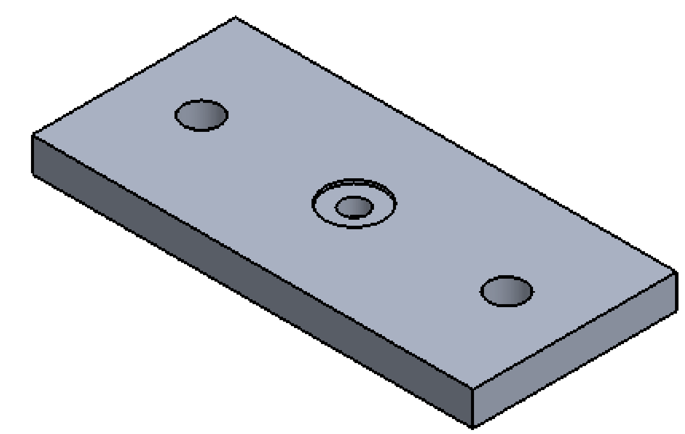
NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

SIZE A | DWG. NO. T02 | REV 3

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1





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NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: MACHINED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	2/23/14
CHECKED		
ENG APPR.		
MFG APPR.	K.F.	4/2/14
Q.A.		

COMMENTS:

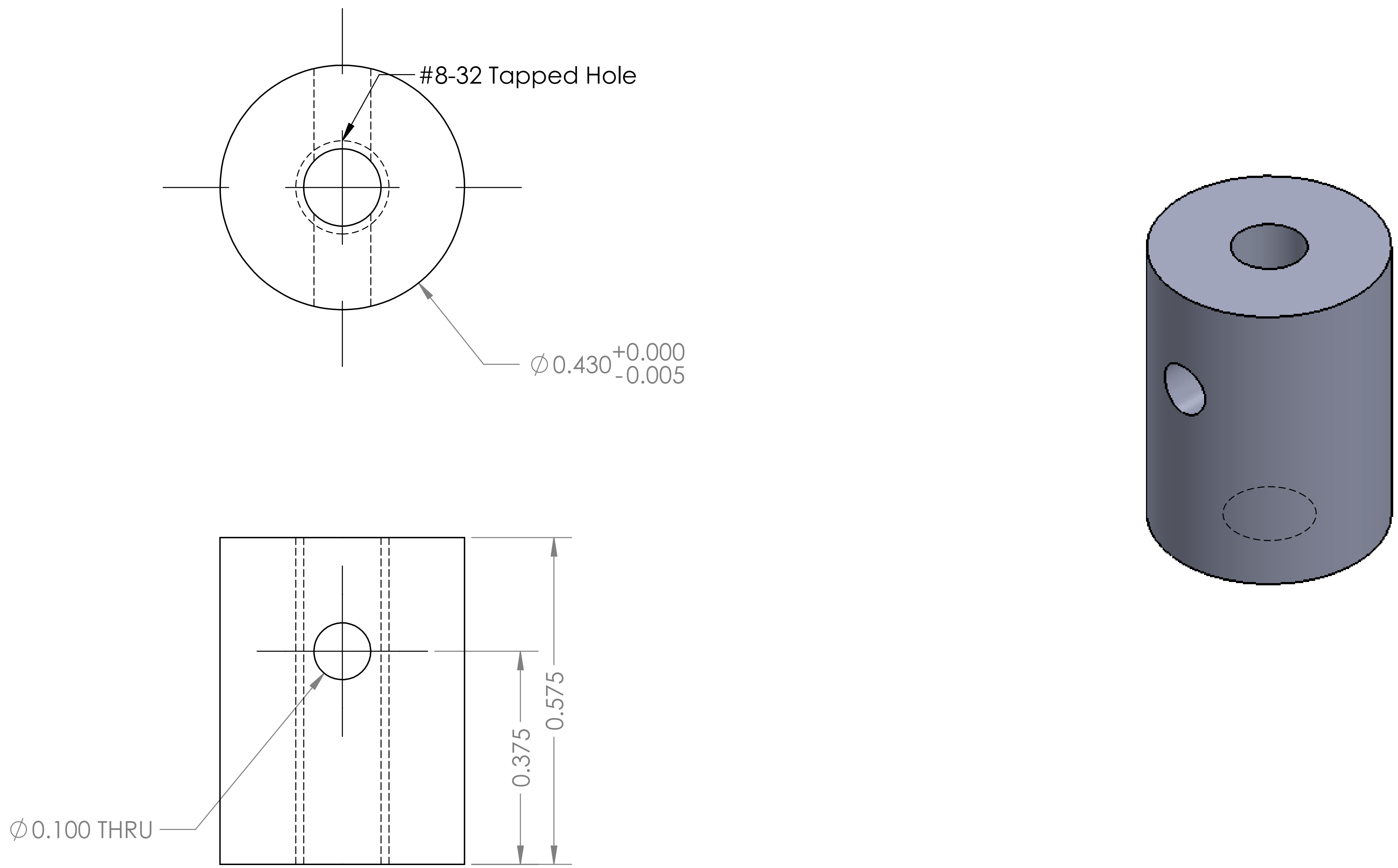
SHROUDED SMALL WIND TURBINE

TITLE:

SHROUD BASE

SIZE	DWG. NO.	REV
A	T05.1	3

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		
DIMENSIONS ARE IN INCHES TOLERANCES: LINEAR: ±0.005" ANGULAR: ±1°		
INTERPRET GEOMETRIC TOLERANCING PER: ANSI		
MATERIAL	ALUMINUM	
FINISH	MACHINED	
NEXT ASSY	USED ON	
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	2/23/14
CHECKED		
ENG APPR.		
MFG APPR.	J.S.	4/16/14
Q.A.		
COMMENTS:		

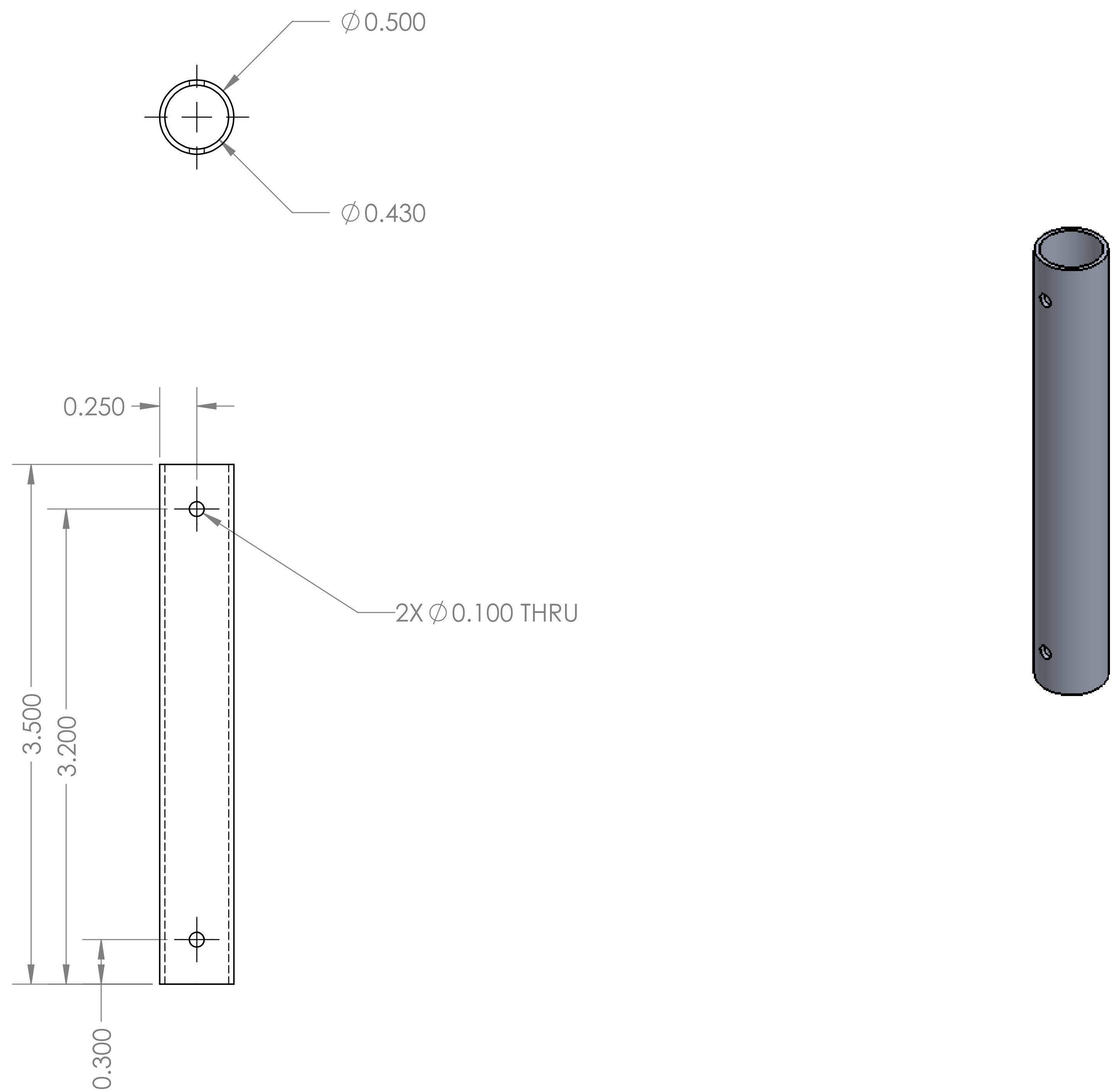
PROPRIETARY AND CONFIDENTIAL

SHROUDED SMALL WIND TURBINE

TITLE:

SHROUD BOSS

SIZE	DWG. NO.	REV
A	T05.2	3
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ALUMINUM

FINISH: AS PURCHASED

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	2/23/14
CHECKED		
ENG APPR.		
MFG APPR.	M.H.	4/25/14
Q.A.		

COMMENTS:

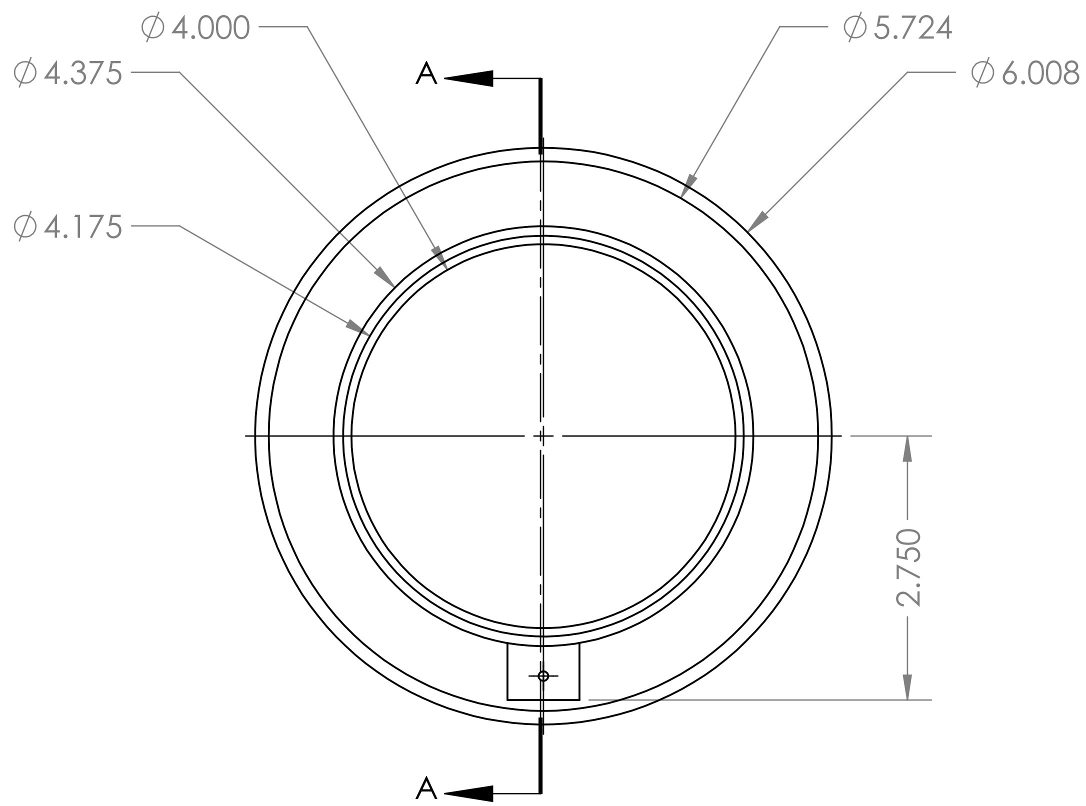
SHROUDED SMALL WIND TURBINE

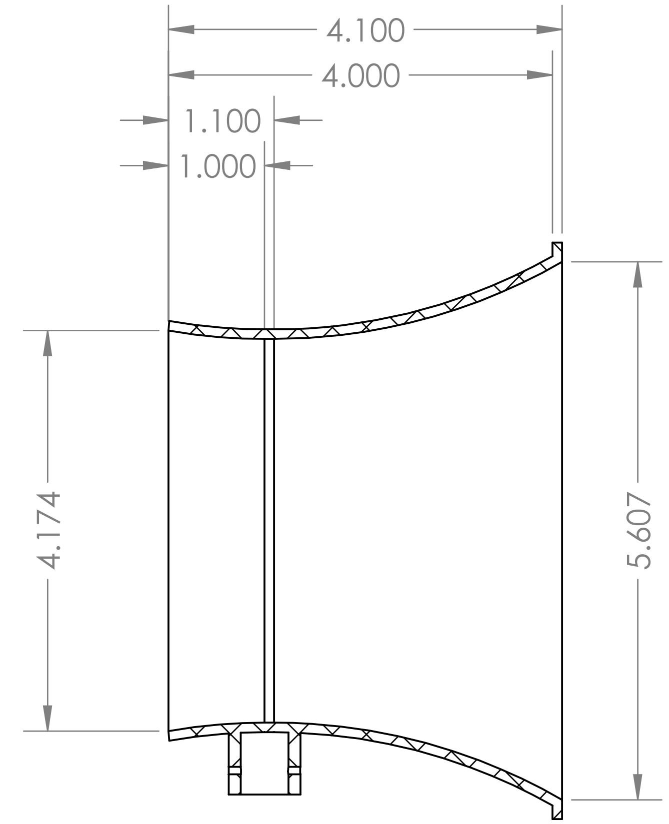
TITLE:

SHROUD POST

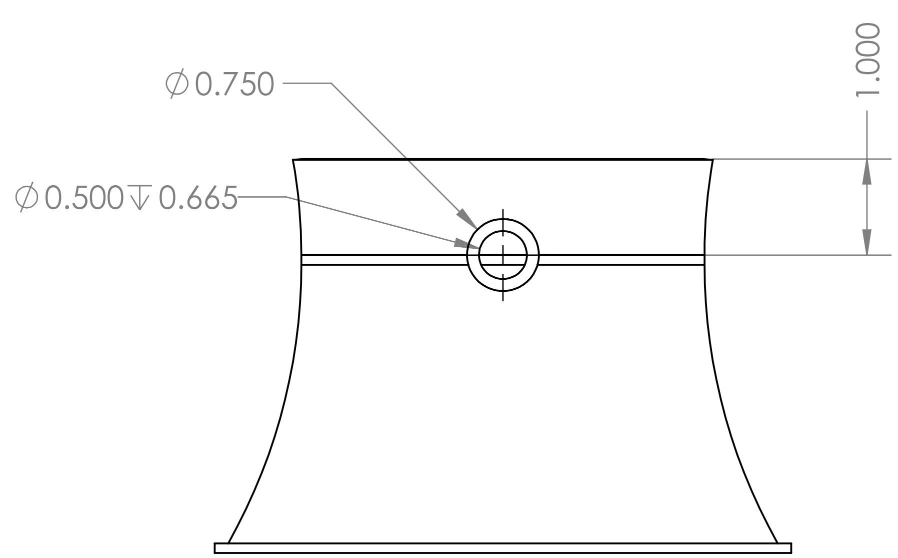
SIZE	DWG. NO.	REV
A	T05.3	3

SCALE: 1:2 WEIGHT: SHEET 1 OF 1





SECTION A-A



INNER CURVATURE DETAIL DIMENSIONS FOR SECTION A-A	
X POSITION (FROM FRONT) [IN]	RADIUS [IN]
0	2.087
0.2	2.056
0.4	2.0315
0.6	2.024
0.8	2.0035
1.0	2.000
1.1	2.000
1.2	2.001
1.4	2.0075
1.6	2.021
1.8	2.041
2.0	2.068
2.2	2.1015
2.4	2.1425
2.6	2.1905
2.8	2.246
3.0	2.309
3.2	2.3795
3.4	2.4585
3.6	2.5455
3.8	2.642
4.0	2.7475
4.1	2.8035

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
LINEAR: ±0.005"
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER: ANSI

MATERIAL: ABS

FINISH: 3D PRINTED (EXTRUDED)

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	J.S.	5/16/14
CHECKED		
ENG APPR.		
MFG APPR.	D.M.	4/16/14
Q.A.		

COMMENTS:

SHROUDED SMALL WIND TURBINE

TITLE:

SHROUD

SIZE	DWG. NO.	REV
A	T05.4	4
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1