Final Project Report: Heliostat-Concentrator Solar Cooker

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Nomenclature

Heat flux	The time rate of heat transfer per unit area
Heliostat	A device including a reflective surface that turns so as to keep reflecting sunlight toward a target
Insolation	The cumulative solar energy per unit area over a defined period of time
Irradiation	The instantaneous incident (solar) radiative power per unit area
Lath	A thin flat strip of wood
Paraboloid	The solid generated by revolving a parabola about its axis
Off-axis paraboloid	The section of a paraboloid defined by a plane not parallel to its axis
Scheffler dish	A flexible off-axis paraboloid solar concentrator invented by Wolfgang Scheffler
Solar azimuth angle	The angle between a projection of the vector from an observer on Earth to the sun on a horizontal reference plane and due north
Solar elevation angle	The angle between a horizontal reference plane and the vector from an observer on Earth to the sun
Solar zenith angle	The angle between the vertical and the vector from an observer on Earth to the sun; the complement of the elevation angle

EXECUTIVE SUMMARY

This document is the full report for the senior project of Cal Poly Mechanical Engineering students Ian Davison and Devin Mast. The report encompasses the full project process, including background research, identification of need, design requirements, design development, proposed design, design realization, changes to proposed design, and design verification. We were tasked with the design and manufacture of a "dual mirror" solar cooker to verify a concept for a new type of off-axis parabolic solar cooker conceived by Dr. Pete Schwartz, the sponsor of the senior project and a physics professor at Cal Poly. Previously, off-axis parabolic solar cookers have used a deformable concentrator to adjust for seasonal change in solar position. The core innovation of the dual mirror concept was to replace the deformable concentrator with a rigid dish and use a tracking heliostat to adjust for seasonal variation, redirect the light, and provide a constant light source on the dish. The motivation for this modification is to simplify construction and lower costs, as deformable dishes must maintain precise geometry throughout deformation and are therefore difficult to manufacture. This means traditional off-axis parabolic solar cookers are often beyond the financial reach of the intended users: economically disadvantaged communities in developing countries. The scope of the project initially encompassed the creation of both the concentrator and the heliostat but was redefined at the beginning of fall quarter to solely encompass the tracking heliostat, as proof of concept could be accomplished using a previously built concentrator. The heliostat was completed and testing was performed fall quarter.

1. Introduction

This report was compiled by Team Helios of the California Polytechnic State University (Cal Poly) in San Luis Obispo, California. It represents the cumulative efforts of team members Ian Davison and Devin Mast, senior Mechanical Engineering students, on the behalf of their sponsor Dr. Pete Schwartz. Team Helios was under the advisement of Professor Eileen Rossman of the Cal Poly Mechanical Engineering Department.

The team was tasked with developing a solar cooker. The cooker will better meet the needs of members of developing communities in Yemen[1] by offering power comparable to current state-of-the-art products while being more affordable, reliable, easy to use, and serviceable on site. It should outperform the previous Scheffler heliostat built by Cal Poly students and be competitive with other solar cookers on the market. For the purposes of this project, we have focused our efforts on the design and construction of the heliostat frame, tracking system, and concentrating dish[2] of a solar cooking system. Future projects may investigate integration into living structures, cooktop design, and insulation of cookware. In the long term, this project will facilitate the development of a solar cooking system that will improve the quality of life in developing communities worldwide.

1.1 Solar Cooking Background

In developing countries there is a need for a low-cost means of cooking food. Many regions burn fuels to create the heat needed to boil water and bake, but there are several problems associated with fuel-burning cooking. In fuel-scarce regions, cooking consumes valuable organic resources, which degrades the local environment and can sometimes lead to aggravated competition for these resources [1]. Some regions are so scarce in fuel that it is too time-consuming and/or dangerous to collect [1]. Cooking with fire also leads to soot-contaminated air, food, and water, which is harmful to health [1]. People in developing communities with such limited resources cannot afford alternate fuels like natural gas. These factors contribute to the need for an alternative source of energy for cooking.

With the help of various organizations, communities in India, Egypt, Ecuador, Nepal, and many other countries have turned to solar energy as an alternative because it has several advantages over fuel-fed fires. Irradiation at the Earth's surface is roughly 1,000 W/m^2, or 1 kW/m^2. By focusing this radiation to a more concentrated area, temperatures suitable for cooking can be reached. Since solar cookers require only sunlight, there is no need to gather or burn fuels. The result is better air quality, less time spent foraging for fuel, and less damage to the local environment [1]. A solar cooker is a one-time investment that produces free, clean heat as long as there is sunlight.

Some communities are not turning to solar cooking, however. Some of the impediments to the transition include the need for a different cooking space. This can either be a separate outdoor space, or integrated into an existing home, but either way switching to solar cooking requires the construction of new or different infrastructure. Solar cookers also consumer a fair amount of space, since the power output is directly correlated to the area of sunlight collected by the dish. It is difficult to implement a solar cooker in communities with tight space constraints. Another issue is the reliability of a solar cooker, which is

[1] The project was originally associated with an interested NGO in Yemen, but that changed in May 2015. See Section 5.2.1 Target Users.
[2] The focus of the project with regard to the concentrating dish shifted in fall of 2015. Refer to Section 5.2.2 Concentrator.

only effective when the sun is strong. One work-around involves thermal energy storage systems, but that comes at an added cost with additional losses.

Currently there are a number of solar cookers on the market that have been implemented in developing communities. The simplest of these is a heat-trap box style cooker; an example is shown in Figure 1.

Figure 1. A woman in Totolgalpa uses a solar box cooker to produce baked goods for sale. [2]

Solar box cookers are inexpensive and easy to manufacture. They “cook at moderate to high temperatures and often accommodate multiple pots. Worldwide, they are the most widespread” [3, 4]. They do not cook as fast as a fire.

Curved concentrator cookers are expensive and require trained skilled workers and specialty equipment to produce. Additionally, they need to be adjusted regularly so they face the sun properly throughout the day and year. These costs are offset by their cooking power, because they concentrate sunlight from a larger area more accurately, resulting in higher heat and faster cooking times. They are especially suited to large community cooking operations [4].

There are two main types of curved (parabolic) mirrors: on-axis and off-axis. Examples of each of these are shown in Figure 2, next page. The more common design is the on-axis parabolic mirror, which is a rigid mirror in the shape of the bottom of a paraboloid. These concentrators either have control systems that use two axes to account for daily rotation and seasonal change or are manually pointed at the sun at the time of use [5]. The second type of mirror is called a Scheffler Reflector, which is an off-axis parabolic mirror. This design requires daily rotation and seasonal deformation of the dish to concentrate sunlight on a fixed focus throughout the year [6, 8]. Figure 3 on the next page is a schematic showing how the geometry of an off-axis parabolic mirror focuses sunlight.

Figure 2. An Indian woman and her family outside their home with a parabolic concentrator (A) [3]. A Scheffler reflector at the Barli Development Institute in Indore (B) [3].

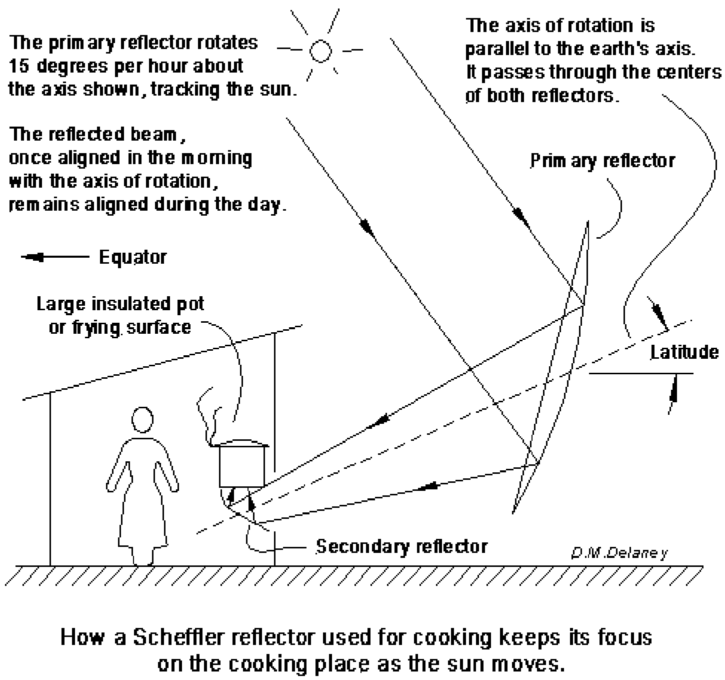

Figure 3. Diagram and explanation of parabolic concentration for solar cooking purposes [7]

There is also a hybrid of these two types, called a panel cooker, which combines the principle of concentrating sunlight using the geometry of a paraboloid with the simple, planar construction of a box cooker. They are inexpensive and fairly easy to make, which has made them popular. Figure 4, next page, shows a common panel cooker.

Currently, there are a number of ways that researchers test solar concentrators. This variation in testing methods is a result of differing objectives of solar cookers. Some focus on being cheap as possible or on minimizing user input, while other try to maximize power supplied to cooking surface. One example of testing protocol is the WBT (Water Boiling Test): “a laboratory test that evaluates stove performance

Figure 4. Panel cookers made from corrugated plastic with a reflective coating being used in India. [2]

while [boiling or simmering water] in a controlled environment to investigate the heat transfer and combustion efficiency of the stove." [10]. A similar test is the CCT (Controlled Cooking Test). This method attempts to evaluate the performance of designs in real life settings in comparison to traditional methods of consumable fuel stoves. We plan to perform multiple tests incorporating these techniques when we have completed our project.

1.2 Objectives

Ultimately we aimed to optimize the concentration of sunlight at a single stationary "point" for the purpose of cooking. The end users will be members of communities in rural areas of developing nations, so an additional objective is to maximize user-friendliness and minimize cost. Further, primary purposes of choosing solar power to begin with include low operating cost and sustainability, so the solution should also be designed and built with this sustainable manufacture and materials in mind. Before the product is implemented in developing communities overseas, we wish to verify the design here in San Luis Obispo, CA, so the product is tailored to this location. Finally, from the project management perspective, it is our objective to deliver a finished, working solar concentrator that accomplishes these objectives in December 2015.

To link these objectives to engineering specifications, we employed a Quality Function Deployment (QFD) diagram. The QFD diagram is a tool that systematically incorporates the needs of each customer and engineering requirements to meet these needs. It also facilitates comparisons with existing competitive designs, and provides a graphical comparison of how well these other products meet the customer needs. Building a QFD diagram is ultimately a systematic method to make sure there are engineering specifications that can be measured to determine that a product meets customer needs.

Using this tool, we created specific metrics by which to assess the success of our design in meeting customer requirements. Our QFD provides a comparison between box cookers, panel cookers, Scheffler Reflectors, and others. Our goal was to create a solar cooker that is competitive with others on the market.

1.2.1 Optimize Concentration at a Stationary Point

A main factor in concentration efficiency is the geometry of the concentrator dish. We implemented a paraboloid mirror, which relies on precise geometry to accurately redirect light to its focal point. Box and panel type concentrators, in contrast, use planar surfaces angled in such a way as to reflect light onto a

focal area. Our objective was to design the optimal concentrator dish geometry to focus nearly all of the incident radiation. This is important to the end user, because it affects how quickly the user can cook.

Adaptability to the instantaneous position of the sun is also important to optimal concentration. As the sun travels across the sky, the incident radiation changes direction, and the solar concentrator must account for this. For some concentrator designs requiring lower precision it would be sufficient for the user to reorient the cooker by hand, as needed. For cookers requiring greater precision, like parabolic reflectors, a more precise positioning system is needed. The sun's relative position also changes depending on the season and latitude, which a cooker's frame geometry must be able to account for. This is important to the user because it is difficult to adjust the cooker and cook simultaneously.

1.2.2 User-Friendliness

For a solar cooker to be successful, it must be more user-friendly than open fire. This means minimizing the number and magnitude of user inputs, such as repositioning the cooker or making tuning adjustments. By extension, this means the cooker should be freestanding--no one should have to hold it while in operation.

A solar cooker is a significant investment for low-income communities, so it needs to be made to last. Therefore it was our objective to design a solar cooker that is weather resistant and requires simple, low maintenance.

1.2.3 Cost and Sustainability

When delivering engineered products to developing communities, the greatest potential for change exists when the products can be made locally. Cost becomes prohibitive to the buyer when the device must be assembled in another country and imported. For these reasons, our objective was to design a device that could be made of materials that are locally available to the end user. A local trained craftsman should be able to build the device without special equipment or facilities.

Solar cookers function by redirecting light using reflective surfaces, so it was our objective to identify and employ a material with a high reflectivity-to-cost ratio. We also sought to use relatively low-cost materials for the frame construction.

1.3 Requirements

From the objectives discussed above, we devised a set of engineering requirements to test how well a design meets each one. Table 1, next page, summarizes these requirements. The predicted risk for each is indicated as high (H), medium (M), or low (L). The compliance, or method used to verify the specification is met, is indicated as some combination of analysis (A), test (T), inspection (I), or similarity to existing designs (S).

Table 1. Solar cooker formal engineering requirements

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Daily setup time	10 minutes	Max.	L	T, S
2	Maximum user input force	30 N	Max.	L	T, S
3	Number of user controls	5 controls	Max.	L	I
4	Purchase price	$200	Max.	M	I, S
5	Static heat spot, relative to cooker	True	± 5 cm	L	T
6	Product life	5 years	Min.	M	I
7	Functional latitude range	34.6°	± 1°	L	T
8	Wind speed while operable	10 m/s	Min.	L	T
9	Wind speed before failure	30 m/s	Min.	M	A
10	Risk of minor injury, severe injury	1%, 0.1%	Max.	L	I
11	Power to cooking surface	40 kW/m^2	± 10 kW/m^2	L	A, T
12	Works with ordinary cookware	True	None	L	I
13	Annual maintenance	10 hours	Max.	L	A
14	Daily maintenance	5 minutes	Max.	L	T
15	Materials sourceable within range of target location[3]	200 km range	Max.	M	T

1.3.1 User Parameters

The user parameters were chosen to ensure the product is easy to use. We expect that someone using our product would not want to spend more than 10 minutes tuning or managing it in any way on a daily basis. When the user does need to alter the output of the device, any adult should be capable of doing so, thus the 30 N (6.7 lb_f) maximum input force. Also important to user friendliness is the complexity of operating the product. Since the number of possible user inputs affects the ease of operation, we limited them to 5.

1.3.2 Investment Considerations

Because this is a significant investment for low-income communities, we are striving to keep the cost down. A typical Scheffler reflector costs over $600, while we estimate the last Cal Poly prototype to have

[3] Following the change of scope of our project in May 2015 (see section 5.2.1 Target Users), this sourceable range requirement applies only to the long term product(s) and not our delivered prototype, which is the focus of this senior project.

cost around $200. Our requirement is to exceed the value of the last Cal Poly prototype by building a better reflector for less[4]. We also require that the product last for at least 5 years because a long life is needed to justify the price of expensive equipment.

1.3.3 Performance

To make sure customers are satisfied with the product and do not need to change their cooking habits drastically, we require that our product develop a stationary heating zone that can be used with normal cookware, so the experience is similar to cooking over a fire. To the same end, we require that our product work with ordinary pots and pans. To ensure that the device will be efficacious, it is required that it supply 40 kW/m^2 to the cooking surface at our latitude in San Luis Obispo, CA of 34.6° N. The heat flux requirement was derived by assuming a cooking power of ~2 kW (typical for a modern electric stove and $2m^2$ Scheffler dishes) through the area of a 20 cm-diameter circle (about the diameter of a medium sized pan) and then requiring only about 60% of that to account for losses.

The cooker should be able to perform satisfactorily under ordinary wind conditions. For this, we specified that the cooker should be operable in winds of up to 10 m/s (22 mph). The designers agreed this is the wind speed above which we would be uncomfortable cooking outdoors.

1.3.4 Safety

The geometry of the cooker will affect how well it meets our customers' needs. For example, it should be stable enough that strong winds will not cause failure or user injury. For this case, we specified that it should withstand a 30 m/s (67 mph) wind in worst-case conditions, which should allow the dish to withstand storms without extensive damage. It should also be free of sharp edges, pinch points, and unguarded moving parts. Additionally, users should be thermally protected from high-heat components. This is of high importance, because the concentrated sunlight can quickly burn the user or set fire to the surroundings if improperly used.

1.3.5 Maintenance and Sustainability

We also chose to set maintenance requirements for the product. It should not require more than 10 hours of maintenance annually, so that it demands less than 1 hour of attention per 36 days of use. We also specified that it is unreasonable for a user to perform more than 5 minutes of daily maintenance on the product. Maintenance may involve cleaning, lubricating, painting, or servicing the device, but these activities should not take up much time.

We specified that all raw materials for the product must be sourced from within 200 km of the target site[5]. This was to address the issues of environmental sustainability, economic sustainability, and dissemination sustainability. Keeping material sourcing close to the manufacturing site reduces pollution and energy wasted by shipping, while also reducing costs. Importantly, it ensures the product can be produced locally. "If the product can't be produced locally, then it isn't *their* technology. In order for the technology to become locally owned, produced, and have locals be accountable for it, [it must be] locally produced" [9].

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[4] See Section 5.2.2 Concentrator for project changes affecting this requirement.

[5] Following the change of scope of our project in May 2015 (see section 5.2.1 Target Users), this sourceable range requirement applies only to the final product(s) and not our delivered prototype.

1.4 Year-Long Plan

Here we break down the stages of the development of our product by the winter, spring, and fall academic terms.

1.4.1 Winter

At this point in the design process, our main focus was research. After partnering with Dr. Schwartz and establishing ourselves as a team, we began to investigate current solutions to the main problem: cook food in a sustainable fashion. We concentrated this research on solar concentrators and their use in solar cooking. Once we had a grasp of the subject matter and had met with Dr. Schwartz, we began creating the QFD. Here we outlined the project requirements as discussed previously.

Following completion of the QFD, we began ideation. We continued our research into different methods of solar cooking to develop as many solutions as possible for the problem. Towards the end of winter quarter, we entered the design selection process, which is documented in section 3.2 Top Concepts.

1.4.2 Spring

Starting at the beginning of spring quarter, we began in-depth design work in preparation for construction of our product. This included testing of materials and organizing a set of technical drawings. Throughout spring quarter we worked towards the implementation and construction of a full scale product.

During this time, we completed the analysis of our design. Halfway through spring quarter, we expanded on our Preliminary Design Report to reflect the new information we learned through research, experimentation, and construction. This was presented to our sponsor and advisor in the form of a Critical Design Report (CDR). This report included a full description of our design, complete technical drawings, safety and failure mode considerations, and supporting analysis.

After this report we continued with the construction of our device. At the end of spring quarter we reported our progress to Dr. Schwartz in the form of a project update report.

1.4.3 Fall

In fall, we completed construction, analysis, and testing. The testing included design verification to determine whether the product accurately met the engineering specifications and the customer requirements. Modifications were made to the design to optimize its performance and overall usability. The results of the analysis were compiled over the course of fall quarter and used to create this Final Project Report. This report is an extension of the Critical Design Report and includes everything we learned previously. It includes the full design of the product, technical drawings for manufacturing, testing results, and additional analysis.

2. Background

This section includes details on existing solar cooking products and relevant solar cooking standards. The purpose of this section is to establish the baselines and norms of the contemporary solar cooking industry.

2.1 Existing Products

There are numerous solar cooker designs that are used throughout the world. The category that is most similar to our product is also the least prevalent: the off-axis parabolic concentrator.

The most well-known product similar to our device is the Scheffler Reflector. This device, created by the German engineer Wolfgang Scheffler, is an off-axis parabolic dish. It tracks the sun's daily movement with rotation of the concentrator and the sun's seasonal movement by changing the shape of the concentrator.

The next closest type of solar cooker is the on-axis parabolic cooker. This has many more variations, including the Balcony Cooker, the SolSource, the Sun Chef, the Solar Flame, the Cookup 200, and more. These dishes all use the same geometric principles with small variations in material use and support systems. The dual mirror concept is different than all of these due to the introduction of the tracking heliostat. Occasionally parabolic dishes will add a plane mirror after the concentrator to change the orientation of the focusing light, however no designs that we found used a plane mirror before a concentrator to provide a constant light source.

2.2 Applicable Standards

While the solar cooking community is relatively small, there are a number of standards worldwide. For instance, Nepal has a set of standards specifying design requirements that must be met. However, no such specifications exist in America and no design specifications are accepted worldwide by the solar cooking community. There are substantially more standards when it comes to the performance testing of solar cookers. This is partially due to the fickle nature of testing, which is dependent on the weather, an ever changing factor. Performance tests include: the Water Boiling Test Version 4.2.3; the ASAE s580.1; the IS 13429 1-3; the Controlled Cooking Test; and the Kitchen Performance Test. We used these tests as the basis for our performance testing.

3. Design Development
This section details the design process of our product. In our design process it was important to thoroughly investigate all possible solution avenues, and so this section details the concept generation and selection methods used to assure the best choices.

3.1 Concept Generation

To create a wealth of ideas, we conducted research on existing designs, searched patented products, and employed some creative thinking processes. Most of our initial concepts were generated by brainstorming as a team, seeking combinations and simplifications of ways to concentrate light. Much of our later ideas were inspired by the research we were doing in parallel and conversations with Dr. Schwartz. We came across numerous innovative ways of concentrating light, including Fresnel lenses, glass spheres, adapted umbrellas and satellite dishes, old television lenses, collapsible and portable designs, various implementations of parabolas, and many more. While thinking creatively about potential solutions, we guided ourselves with the primary function of the product, which was to cook food by focusing sunlight. To help aid our understanding of this requirement, we experimented with some crude small scale models, seen in Figure 5. These models helped us better intuit ways of concentrating sunlight to create a “hot spot.”

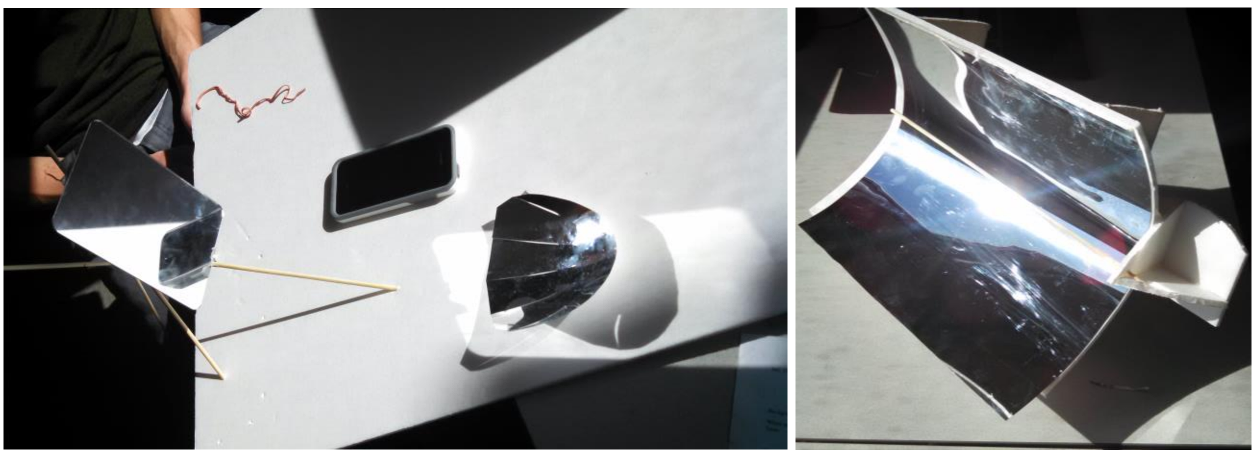

Figure 5. Small scale models used to facilitate understanding of how to concentrate sunlight. Models were built with wooden skewers, scrap Mylar, and foam core.

3.2 Top Concepts

From the various concepts generated, the following were our top six.

This first of our ideas was inspired by one of the more prevalent existing solar cookers, the on-axis paraboloid concentrator. This idea uses the geometric property of a parabola that rays incident to the concave side of a parabola are reflected to a single point, known as the focus. This property is illustrated in Figure 6A below. Figure 6B is a hand sketch of our concept.

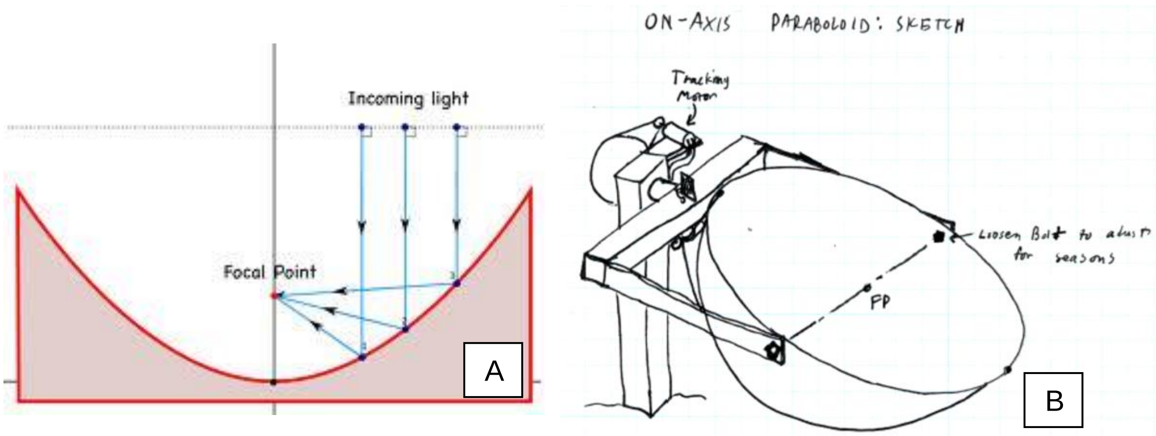

Figure 6. Focusing reflective geometric property of a parabola (A) and hand sketch of our conceptual design (B).

Our concept features dual-axis tracking to compensate for the daily and annual changes in the sun's position in the sky. The daily tracking axis could be adapted with a motor, as shown. The seasonal tracking axis would require manual adjustment on a regular basis. This concept features relatively simple construction and an efficient geometry. That is to say that the form is relatively tolerant of geometric imperfections, and that the ratio of reflective surface area to the area of concentrated light is relatively high, compared to an off-axis paraboloid section, discussed later on. Some issues with this design are that it can be difficult for the user to reach the food at the center of a large dish, and the device cannot be used to cook inside.

Our next idea was to make a concentrating lens from water and a transparent vinyl sheet. We could improve on the design by Dan Rojas, shown in Figure 7A, next page. Figure 7B is our sketch of the design—which we termed the "floating puddle"—with our modifications to improve performance.

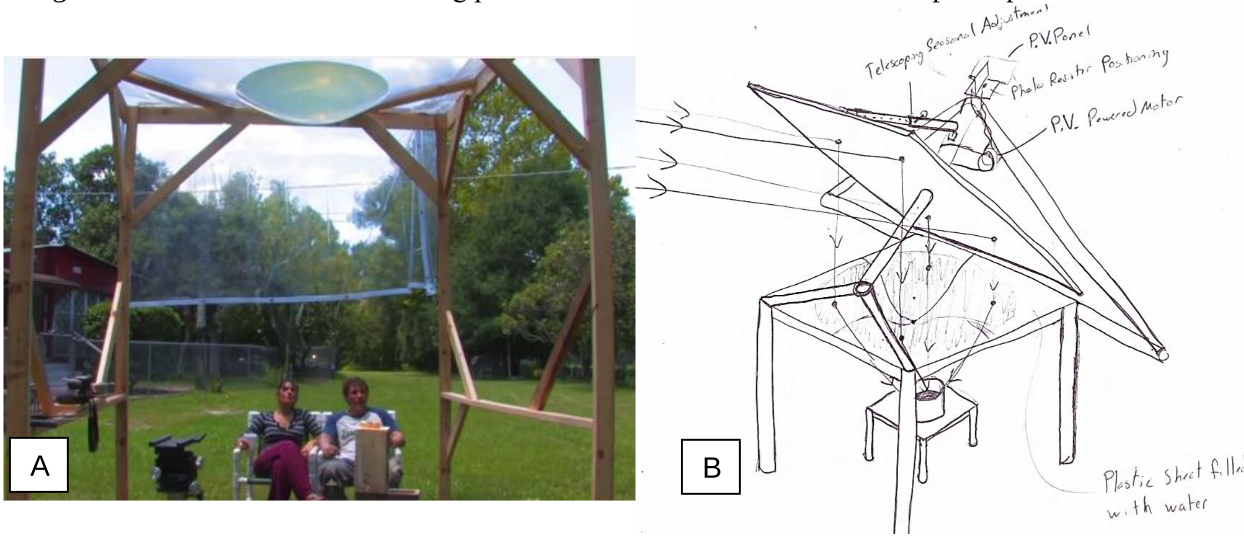

Figure 7. "Floating Puddle" concept based on Rojas' design (A) [11], and our sketch of a modified design that compensates for the daily motion of the sun (B).

A planar tracking mirror was introduced because the existing design only worked when the sun was directly overhead. This design is very inexpensive and the materials would be easy to source. However, the device has to be quite large to concentrate enough sunlight, the "puddle' would evaporate and cease to

focus if disturbed by wind, and there are considerable inefficiencies associated with the transmission of radiation through the water and the plastic.

Another concept we considered was the existing Scheffler design. This is the state of the art in solar cookers. It uses a dish in the shape of an off-axis paraboloid section, which deforms to compensate for the seasonal variations of the sun. It rotates about a fixed axis to track the sun during the day, using a clockwork mechanism driven by a weight. Figure 8 is a conceptual diagram of the design.

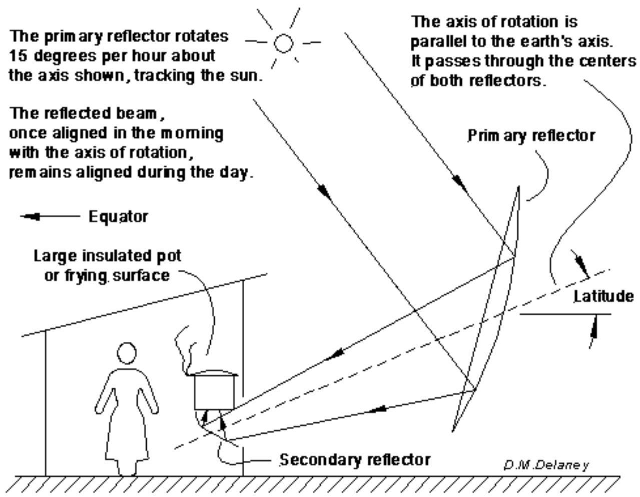

Figure 8. Conceptual diagram of a Scheffler dish, which
has a focal point that remains fixed relative to the ground.

The Scheffler is an efficient and reliable design. It also directs the heat away from itself, creating an unobstructed heat zone that can be easily used for cooking. However, the construction is complicated and requires trained craftsmen to execute it properly. Both the dish and the tracking mechanism have very tight tolerances, which are challenging to meet in a developing community.

We also generated the concept of using a rigid glass or plastic lens to focus light. A Fresnel lens is an efficient way to focus incoming light with great accuracy. The lens must be on the line between the focal point and the sun, so to heat a pot from below, we mounted the mirror lower than the food and used a mirror to track the sun and direct it at the lens throughout the day. Our concept sketch is seen in Figure 9.

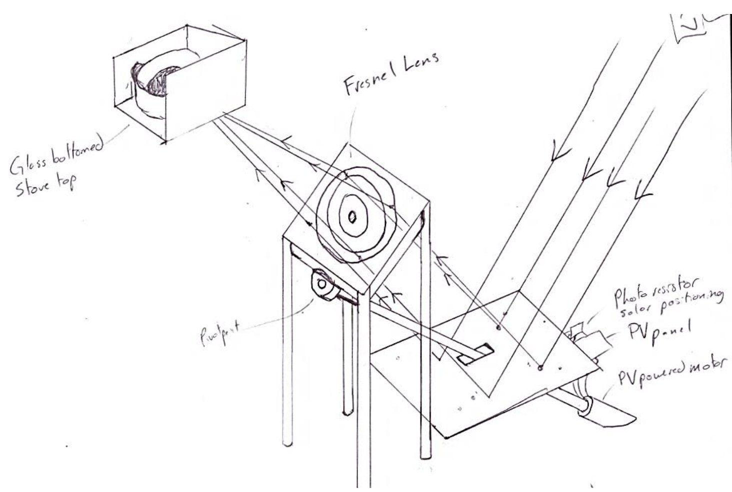

Figure 9. Sketch of Fresnel lens concentrator concept showing
relative positions and tracking device.

The lens concept’s strength was that lenses can be purchased ready-made with high quality geometry due to their history of use in other applications. However, the cost of a large, accurate lens is high, and sourcing one in a developing community would be challenging. Additionally, a Fresnel lens’ surface ridges make it difficult to clean out any dust or grit that would settle on its surface. This opaque layer would significantly reduce the lens’ efficiency.

Another idea that came forward as a top concept used two reflectors. The first is a plane mirror that tracks the sun throughout the day and keeps it directed at the same area, as seen in some of the preceding concepts. The second reflector is an off-axis paraboloid section that concentrates the light from the plane mirror to the cooking point. As far as we could determine, no existing designs are similar to this configuration, shown in Figure 10.

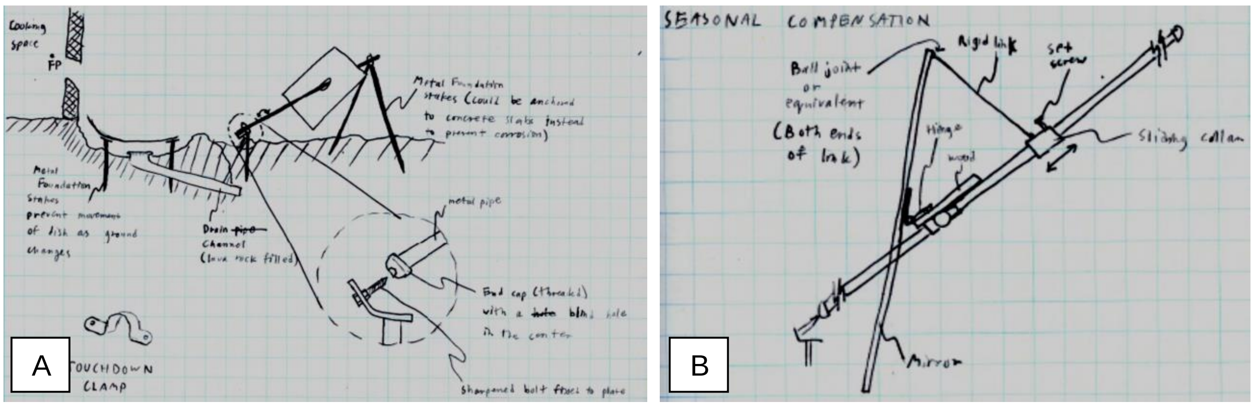

Figure 10. Concept sketches for a dual-mirror system layout (A) and a potential seasonal compensation system design (B).

This design allowed for the concentrating reflector to be sheltered as it is kept on the ground near a wall. Like the Scheffler, it would also create an easy-access unobstructed heat zone, but its advantage over the Scheffler is that it doesn’t require a deformable dish. Although the concentrator dish is not deformable, it does still need to be a precise paraboloid section. Another drawback is that there is some loss in efficiency at both reflective surfaces, instead of just at one.

The final of our top six concepts employed a heat transfer fluid, heated by a parabolic trough. A tracking system rotates the trough to follow the sun during the day, which continually heats a heated fluid, such as sunflower seed oil. The heating process causes convective circulation, leading to a constant supply of hot oil at the top of the reservoir, where food can be cooked. See Figure 11.

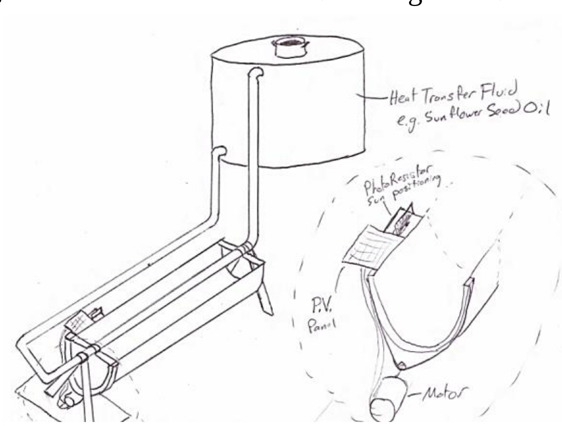

Figure 11. Parabolic trough concept, where a high-temperature fluid carries heat to the cooking interface.

This approach is different in that the concentrated sunlight is not directly cooking any food. The benefits include the simpler geometry of a parabolic trough and the ease of routing the heat to any desired location. The fluid reservoir could also be used for space heating or for cooking after dark, due to the thermal energy stored by the fluid. However, the cost of the fluid would be high, as would the expenses of the piping and fluid maintenance. There are also the issues of a lower efficiency due to conduction and the issue of a long start-up time to get the fluid up to cooking temperatures.

3.3 Selection Process

To choose the best design, we coupled our engineering judgment and experience with two forms of comparative matrices.

The first, called a Pugh matrix, compared each idea to a datum, or baseline, idea by scoring either +, 0, or - as an indication of meeting each customer requirement better, the same, or worse than the datum. The results often do not reflect how much better or how much worse, because the symbols omit information about the magnitude of each rating. For example, a minus could be an extreme issue, but the Pugh matrix doesn't reflect this. The benefit of the Pugh matrices, then, is that they led us as designers to examine why certain ideas scored well or poorly when we did not expect it.

The second form of matrix was a weighted decision matrix, which assigned numerical weights to each customer requirement to reflect their relative importance to the success of the product. Each product is then assigned a numerical rating for how well it meets each criterion. The weighted ratings are then summed and can be compared to give insight into how well each design measures up to the others. Refer to Appendix C: Decision Matrices for the weighted decision matrices, logbooks for Pugh matrices, and Appendix B: Quality Function Deployment for customer requirements.

We used these decision tools to compare what we believed to be the best choice of concept with a detailed consideration of how well each concept would perform. It was based on the combination of our judgment and the results from these tools that we selected our concept.

3.4 Selection

Through our selection process, it became clear that one design stood out from the rest: the Dual Mirror. This design provides a balance of performance, usability, and cost that made it stand out from our other ideas.

Our main tool to choose our design was our decision matrix (see Appendix C: Decision Matrices). This tool clearly displays the attributes and shortcomings of each design. Through analysis of the decision matrix and in depth discussion of its results, we came to the conclusion that the Dual Mirror was better suited to our requirements than each of the other designs.

The Dual Mirror design scored higher than any other design, scoring a whole 9 points better than the second best design, the lens. These two designs scored similarly on many of the categories, with the dual mirror taking the lead in a few key sections. On a daily basis, a user of the dual mirror would input less time than as user of the lens due to the geometry of the lens. The design would utilize a Fresnel lens, which approximates a regular lens in a single plane through the use of concentric ridges. These ridges would fill easily with debris and quickly decrease the performance of the mirror, requiring daily input to ensure optimum performance. This lens is also a specialty item, which increases the cost of the product considerably. While the lens design could be slightly more compact, the benefits of the dual mirror easily outweigh this consideration.

The third best design was the Scheffler at 10 points less than the Dual Mirror. Basic analysis showed that this design would actually perform better than the dual mirror; however, it has other shortcomings that make it less than ideal. Firstly, the deformable nature of the concentrator increases cost, complicates construction, and worsens the user interface. Despite the slight inefficiency caused by a second mirror, the Dual Mirror has comparable power output, as shown by our calculations. We came to the conclusion that the Scheffler method is better suited for communities that are constructing large scale systems like that of Abu Road, Rajastan [8].

The next best idea was the Heat Transfer Fluid. This idea was very promising at first; the ability to route heat to any desirable location through piping was very appealing in regards to our purpose of building a solar kitchen. However, we found that it had shortcomings the Dual Mirror did not. Firstly, the heat transfer fluid itself would be expensive: water cannot be used due to the danger of steam creation in the pipes at the concentrator and all alternatives (e.g. sunflower seed oil) are relatively expensive and unavailable in third world countries. Secondly, due to scarcity of support and resources, any issues caused by plumbing could cause the device to stop functioning. Despite the construction advantages of having a parabolic trough as opposed to an off axis paraboloid, we decided the Heat Transfer Fluid was not the design we wanted.

The other three design concepts scored even lower than these previously presented. They ran into problems with reliability (Floating Puddle), inability to cook inside (On Axis Paraboloid), product life (Cal Poly's), among other issues. We determined that the Dual Mirror would better meet our customer's and sponsor's requirements than each of these other designs.

4. Proposed Design

This section investigates the chosen concept by providing a complete description of the geometry, materials, manufacturing processes, and testing plans. The design presented in this section was proposed at the time of the CDR. Changes have been made following the CDR throughout the end of spring quarter and the entirety of fall quarter, and are documented in Section 5.2 Design Changes since the Critical Design Report.

4.1 Design Details

Our design is subdivided into two parts: the heliostat (also referred to in this report as the reflector or primary reflector) and the concentrator. The heliostat redirects sunlight such that the concentrator receives optimal irradiation. In this section we offer the details of these two main parts of the design.

4.1.1 Reflector

The reflector, as seen in Figure 12, consists of a plane mirror with 3 main geometric concerns: latitude, daily tracking, and seasonal tracking.

Figure 12. A 3D rendering of the primary reflector

The rotation of the plane mirror is driven by a small motor to follow the daily movement of the sun. This small motor is controlled by a relatively small, analog circuit and powered by a 12V battery. The circuit consists of two photoresistors, regular resistors, an op-amp comparator, a DC relay, a breadboard, and a rechargeable battery. The two photoresistors are used to detect the position of the sun: when one of the photo-resistors does not receive sunlight, the circuit will rotate the mirror to directly face the sun. This results in discrete movements of the mirror with a time delay. This is advantageous over a directly connected motor that continuously turns the mirror, as the continuous motion quickly drains the battery. Our motor will rotate the mirror via of a string drive. This provides a large moment arm in a cost effective method. The rotational axis is secured on one side by a pin joint, and on the other side by a concentric half-pipe. The bottom end of the rotational pipe is fixed with an endcap, with a small bowl bored in the center, which mates with a bolt milled to a point, providing a low-cost, low-friction bearing. At the high end, the rotating pipe is cupped by a half-pipe, supporting the vertical load, while a bolt protruding out the top resists axial load.

The rotational axis must be specifically angled relative to level ground to compensate for latitude differences. This is executed properly by making the angle of the axis of rotation with respect to horizontal equal to the local latitude, thus producing an axis parallel to the Earth’s. By angling the reflector towards the equator (due South, for our Northern Hemisphere location), light can then be

reflected onto a concentrator on the equator-side of the reflector. In order to ensure the incoming light provides a constant irradiation at an unchanging angle, the reflector must direct the light so it is parallel to the rotational axis (and Earth's axis). Thus, the rotational axis must be in line with the axis of the paraboloid as seen in Figure 13. This is accomplished by support the pin joint and the concentric pipe by

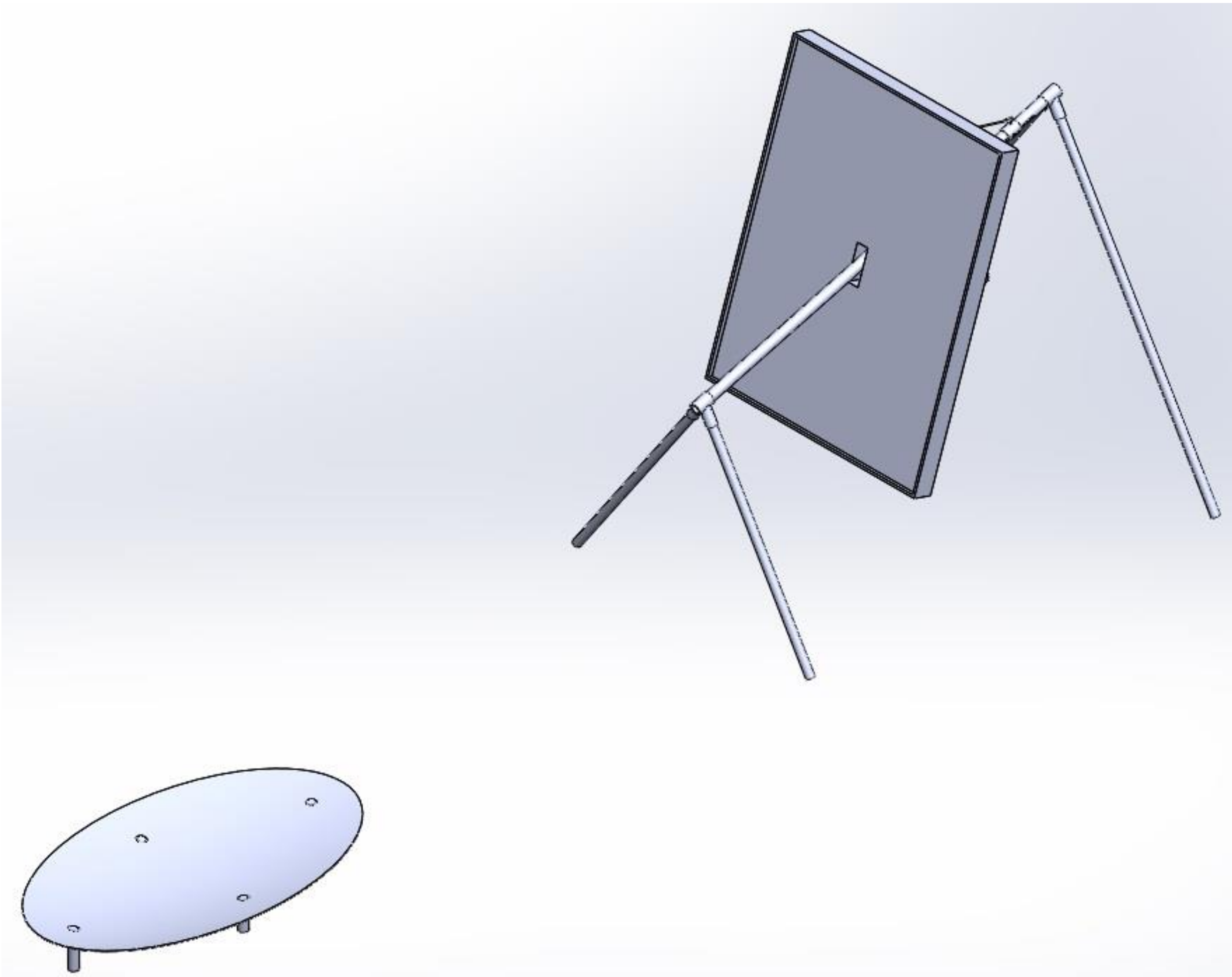

Figure 13. A 3D layout of the overall system

angled steel plates clamped to steel pipes that serve as the legs of the frame.

Additionally, the heliostat must adjust to compensate for the seasonal change of the Sun's path through the sky. To account for this change, the angle of our reflector with respect to the rotational axis must vary between 33° and 57°. This is true for any latitude, because the seasonal variation is directly related to the angle of inclination of the Earth's rotational axis. Initially, we thought to accomplish this through a rigid rod attaching the back of the reflector frame to a small pipe, concentric to the rotational pipe, which could be fixed in place by a pin fitting into a hole in the small pipe and a set of holes in the rotational pipe. To increase the rigidity of the frame, we have opted for two rigid rods, and to increase resolution of the seasonal adjustment, we opted for a pair of set screws instead of the quick-release pin (See Figure 14). This is beneficial, as the change in angle of the mirror is not discretized throughout the year, but instead varies continuously.

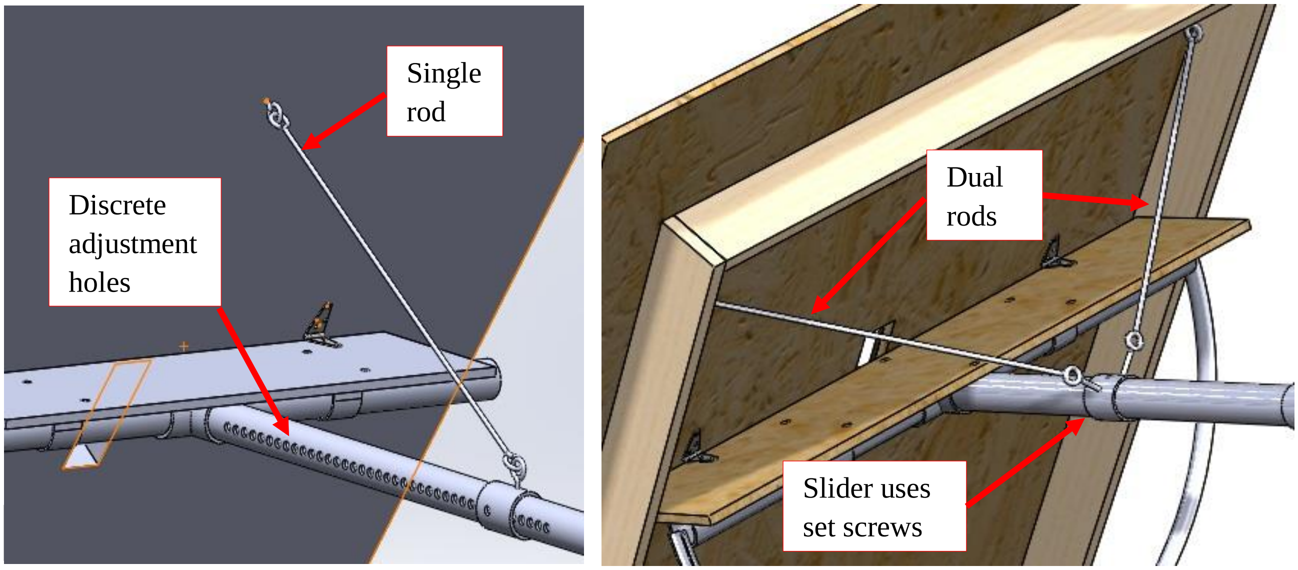

Figure 14. Conceptual (A) and revised (B) design of seasonal adjustment for the primary reflector

4.1.2 Concentrator

The design of the concentrator was not finalized to the same extent as the heliostat at the time the CDR was authored. A number of different manufacturing techniques have been explored at Cal Poly previously, none of which we were comfortable with settling on before understanding firsthand the challenges of manufacturing a paraboloid surface. To improve our understanding and better inform our design choices, we opted to build a small scale prototype.

The construction technique we chose for the prototype involved building a mold for the paraboloid surface, then laying up and gluing together a lattice of wood lath in this mold. Finally, reflective Mylar strips were affixed to the finished lattice.

The mold was created by revolving a parabolic pattern about its axis, sweeping out a parabolic profile in a shallow hole in the earth at the Student Experimental Farm. We chose to make the mold this way because it is close to the first principles of a paraboloid, literally revolving a parabolic path in space. The parabolic profile was created by marking and connecting points on a piece of thin plywood, whose locations were calculated and mapped in Cartesian coordinates. The points were connected and then this profile was cut out. The cutout was next affixed to an axle and supported so that it would sweep out a shallow hole in the ground when revolved.

Next, the hole was dug such that there remained roughly 1cm between the solid earth and the wood pattern throughout the range of its sweep. Then a thin layer of a cement-like mixture of water, sand, and clay was spread in the shallow hole. By sweeping back and forth with the pattern, it could be seen where the mixture needed to be lower of higher. The pattern was swept back and forth and the mixture redistributed until it was only just in contact with the pattern throughout its range. The mold was then allowed to cure. Figure 15 shows the parabolic pattern and mold after sweeping out a uniform surface.

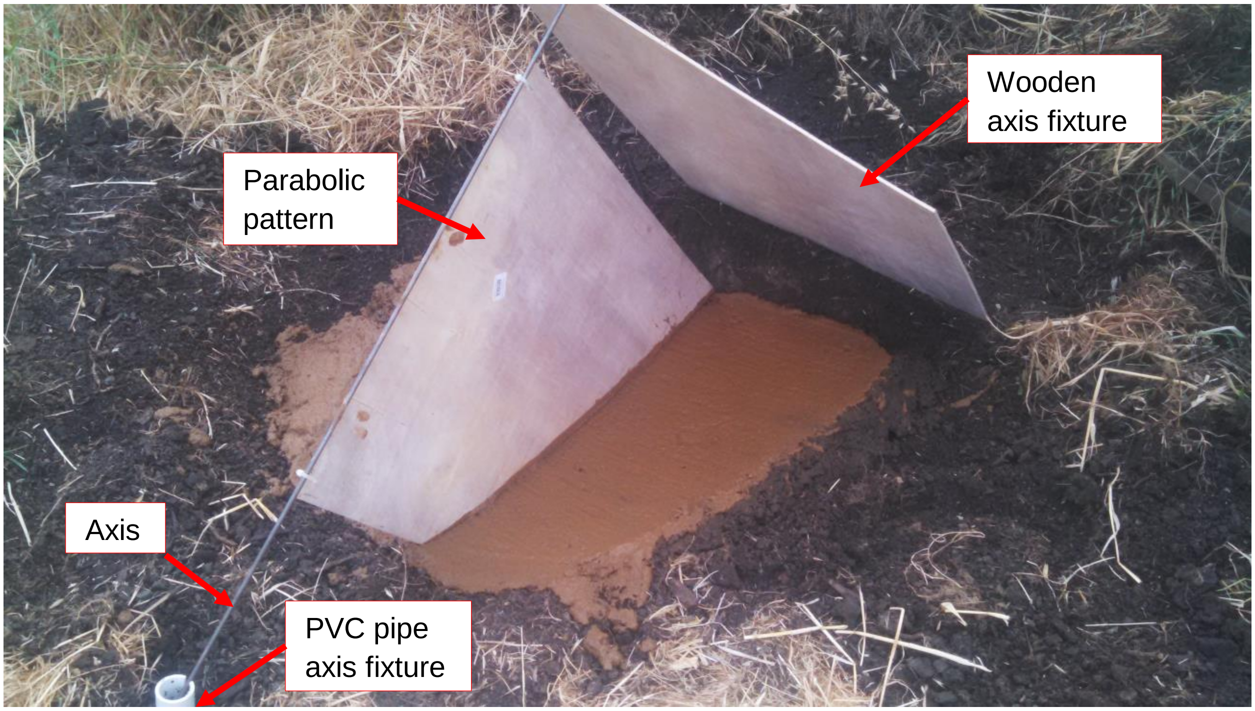

Figure 15. Parabolic profile sweep setup with finished mold surface. When revolved about the axis, the pattern lightly contacts the light brown concrete-like mixture evenly.

Once cured, narrow wooden lath was placed in the mold in two orthogonal layers. The top layer was chosen to run concentric to the parabolic axis to aid with adhering the reflective material later. A dab of glue was placed at each point where the slats crossed, then the assembly was pressed in place by burying it in dirt. The wood and the pressing dirt were separated by a layer of heavy plastic. The glue was allowed to cure for two days. Figure 16 shows the results.

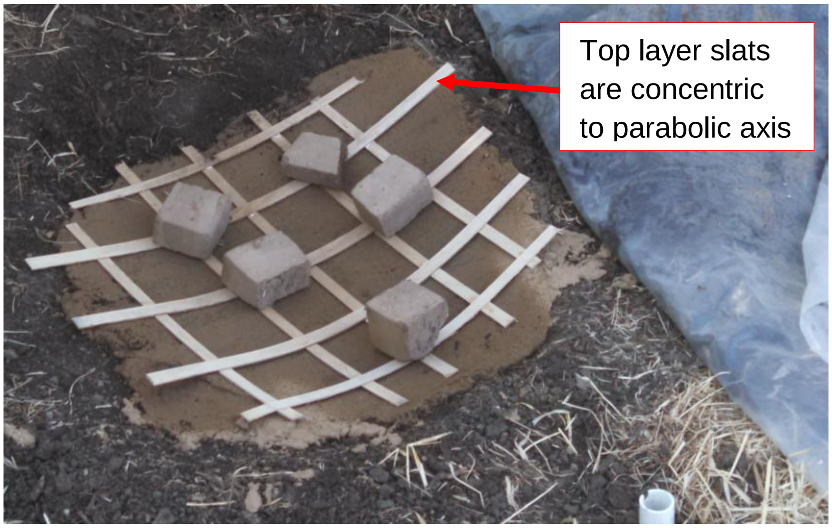

Figure 16. Wooden lath frame, weighted down by bricks after pressing dirt and plastic were removed. The bricks were necessary because the elasticity of the wood caused the frame to separate slightly from the mold.

Once cured, the wooden frame was removed. Sheets of Mylar were cut to span the distance between the slats of the top layer, and then affixed using a single staple in the center, followed by tape. Figure 17 shows the finished prototype.

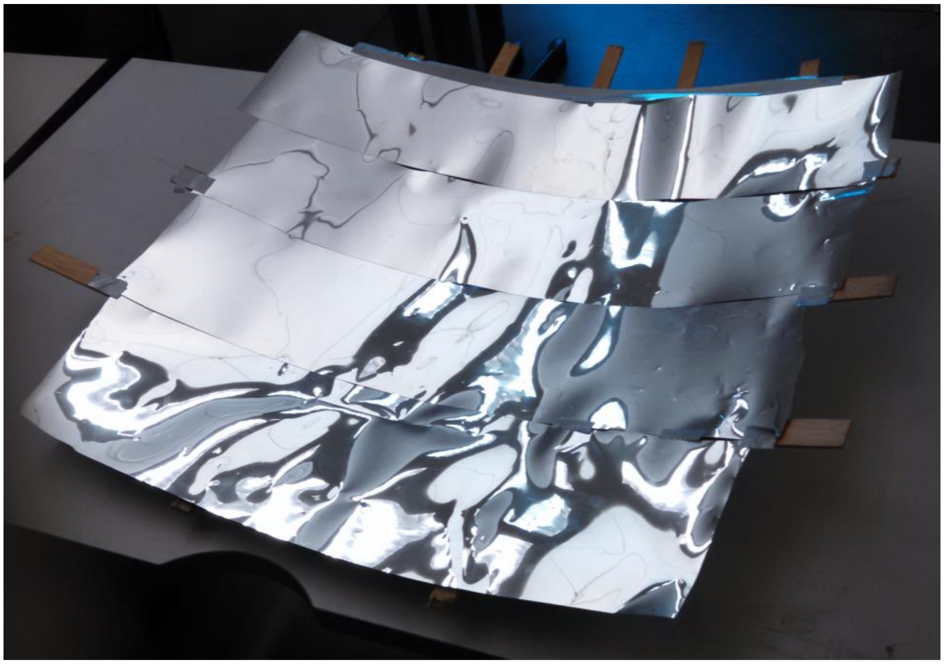

Figure 17. Completed prototype with Mylar strips adhered to wooden frame.

In building the concentrator this way, we learned that the wood lath frame was too springy; once the frame was removed from the mold, it sprung back slightly towards its original planar shape. We also learned about the criticality of imperfections in the reflective surface. It was important not to over-constrain the reflective material, because it would introduce unwanted distortions. The Mylar used was wrinkled and had dents and smudges, seen in Figure 17 as the distorted reflections in the surface of the reflector. These imperfections significantly scattered the light received, producing a very crude focal point. We believe these are the primary sources of imperfection in our construction technique. The method was a success in that it produced an effective concentrator, with which we were able to burn large holes in a piece of black foam core board.

With these results, we could make a well-informed and structured decision about the best—or hybrid of—known concentrator construction methods. Section 5.2.2 Concentrator details our ultimate decision on construction of the concentrator.

4.2 Material Selection and Production

We selected materials to best meet our design requirements. For the frame, the main considerations were strength, durability, ease of manufacture, and cost. For the mirrors, there was the added consideration of reflectivity. Additionally, we considered each material's availability and manufacturability in developing countries. While we designed the product to be calibrated and used in San Luis Obispo, where we had access to extensive fabrication technologies, we kept the design simple and manufacturable regardless of location.

4.2.1 Reflector

The majority of the reflector used off-the-shelf parts. The mirrors themselves are 1'x4' bedroom mirrors mounted onto a 4'x5' plywood sheet. The mirrors are low cost and have adequate reflectivity, while the plywood is low cost and sufficiently strong. The frame itself consists primarily of 1.5" schedule 40 steel pipe with off-the-shelf brackets and mounts. The steel is a common building material and easy to work with, since it is weldable. It is also robust and durable.

4.2.2 Concentrator

The concentrator requires attention to detail in its manufacture and material selection. To achieve an acceptable efficiency, the geometry of the dish must be very precise. We investigated the use of a cob mold to shape wooden strips into the correct shape. This mold could be easily created with readily available materials at low cost using a plywood parabolic profile swept through a wet mixture which is then cured (see Section 4.1.2 Concentrator). The choice of reflective material depends on reflectivity and durability. The efficiency of our product is quickly compromised by surface imperfections like dents, scratches, and contaminants. We recommend reflective aluminum in our final design, as it is more resistant to deformation that Mylar and has a comparable reflectivity. We weigh resistance to deformation heavily because accidental bends or even the slightest of curvature anomalies can have significant effects on the concentration of the light, and Mylar is more susceptible to more sudden changes in curvature.

4.3 Analysis Results

As a tool in our design process, we have analyzed critical design features to learn more about the system and to lend confidence to our decisions. Notably among these are the correlations between

- Concentrator size and cooking power,
- Reflector deflection and concentration,
- Heliostat construction and out-of-plane deflection,
- Reflector construction and torque requirements, and
- Reflector weight and deflection.

This section summarizes the results from these investigations. Refer to Appendix D: Detailed Analysis for complete calculations.

4.3.1 Concentrator Size and Cooking Power

The measure of cooking power we are using is an area density, kW/m^2, which captures the combination of two properties: the total power delivered and the area it is distributed to. The total power delivered is proportional to the irradiation area of the concentrator, and the area of distribution is related to the geometric accuracy of the concentrator.

To calculate the size of the concentrator needed for our cooking power requirement, we considered the reflective efficiencies and construction inaccuracies as power losses, then back-solved for the irradiation area required, knowing the average insolation for our location. We found that we will require a roughly 1.13 m^2 irradiation area.

4.3.2 Reflector Deflection and Efficiency

For a perfect system, the heliostat reflector is perfectly planar, and so if incident rays are parallel, then all reflected rays are parallel. The geometric principle of the paraboloid concentrator we are employing is that rays parallel to the paraboloid's axis and incident to the concave face of a paraboloid are reflected to

the focal point. When incident rays are not parallel, they are not reflected to converge at the parabola's focus; instead they may not focus at all or will focus at some other point. For our system, it was important to understand how deflection of the primary reflector would affect concentration at the focus.

We modeled the system with a reflector of circular curvature and an ideal concentrator. We adjusted the offset at the peripheral ends from the ideal reflector to the actual curved reflector surface, and observed the change in focal width at the theoretical focal point. Figure 18 below shows the ray tracing model developed in Solidworks, used to explore this relationship between deflection and concentration.

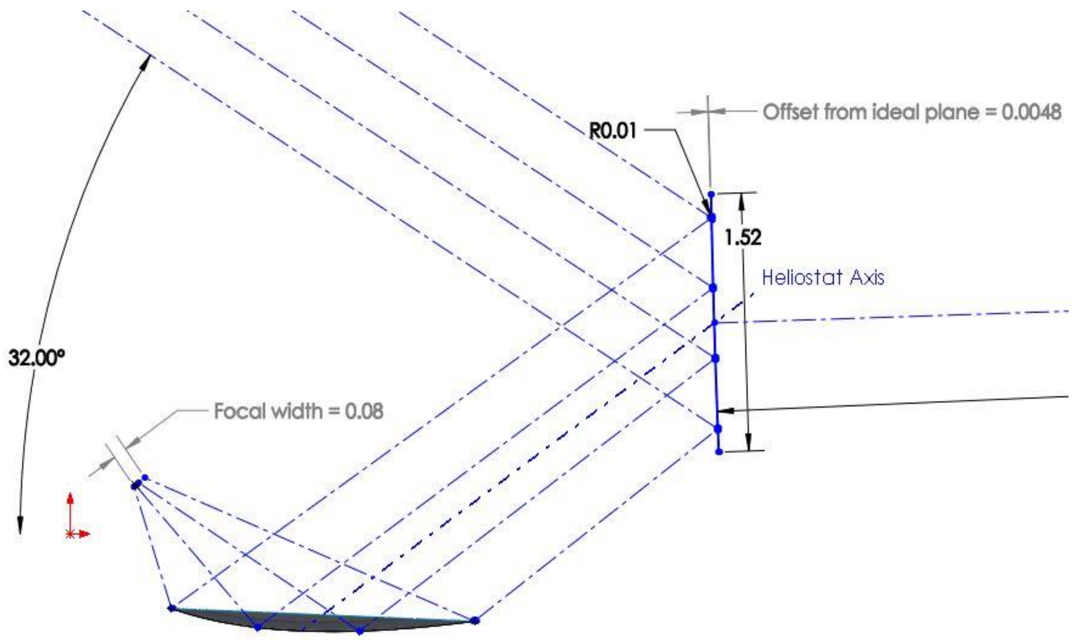

Figure 18. Solidworks ray tracing sketch, assuming ideal concentrator and circular reflector. Dimensions in meters.

4.3.3 Heliostat Construction and Out-Of-Plane Deflection

With an understanding of how tolerant the system is of reflector deformation, we needed to verify that the construction of our reflector would not permit excessive deformation. We modeled the reflector surface as a beam in bending under its own weight, treating the components as homogenous materials. We assumed the plywood was perfectly bonded to the beams behind it. The analysis took advantage of the symmetry in the system, and considered only a 2D model of the reflector. This meant that weight densities were collapsed to a single plane and considered in units of weight per length. Worst-case material properties and reflector orientation were used to yield a conservative analysis.

The results from the beam theory analysis indicated a peripheral deflection of about 3 mm, which is allowable based on the results of our ray tracing. As seen in Figure 18, a deflection of 4.8 mm yields a focal width of 8 cm, which is small enough to achieve our desired concentration.

4.3.4 Reflector Construction and Torque Requirements

In order to design the tracking motor and drive train system, we needed to know how much torque would be required to turn the daily tracking axle. We considered torques due to friction in the bearings and the torque required to accelerate the reflector at 0.5 rpm/s. we found that 2.26 N-m (20.0 in-lb_f) of torque is needed to move the reflector as desired.

4.3.5 Reflector Weight and Deflection

To be sure the part used for the daily tracking axis was sturdy enough, we checked the deflection it would undergo due to its weight and the weight of the reflector. The axle was modeled as a simply supported beam in bending subject to a distributed load and a point load. The model assumed the beam was horizontal, and thus yielded a conservative estimate. The weight of the reflector was taken from the Solidworks model of the reflector assembly, which accounts for component volumes and densities. We found that the beam would deflect by less roughly 1 mm (.04 in). This is an acceptable deflection because it will not impair the operation of the reflector.

4.4 Cost Analysis

This section presents the costs the project is expected to incur. Project costs primarily consist of the material costs of constructing the prototype, outlined in Table 2.

Table 2. Actual costs for heliostat system prototype

Subsystem	Projected Cost
Heliostat Frame	$ 102.31
Heliostat Reflector	$ 70.81
Tracking Circuit	$ 38.44
TOTAL	$ 221.51

The majority of the cost of the heliostat frame is hardware, priced according to McMaster-Carr and Home Depot. The reflector will be the second most expensive part of the prototype, where nearly half the cost is the glass mirrors sourced from Home Depot. The tracking circuit cost includes circuit elements and the motor mount. The total cost is only 11% over our $200 budget.

Refer to Appendix D: Vendors and Pricing for detailed a detailed cost breakdown.

4.5 Schematics

A full set of drawings for the construction of the Reflector is available in Appendix J: Technical Drawings.

4.6 Safety Considerations

To safeguard against potential failures that may result in damage to the product or users, we completed a Failure Modes and Effects Analysis (FMEA). In this analysis, we carefully considered all the modes of failure possible for each subsystem and component. Possible causes or mechanisms for each potential failure mode were then explored, and all of these combinations were scored based on their severity and likelihood of occurrence. The criticality of each potential failure mode and effect was quantified as the product of the severity and occurrence scores; thus, a high severity and a high likelihood compound to

denote a critical item that needs attention. For items with criticality above 20 (out of 100 possible), we have proposed solutions that were incorporated into the design.

The items with the highest criticality are failures that significantly compromise the cooking power of the product. The items of greatest criticality involved the imperfections, degradation, or wear on the reflective surfaces. To address these, we proposed methods of refining construction and maintenance schedule. Refer to Appendix I: Potential Failure Modes and Effects Analysis for complete details.

Based on the results of the FMEA, we did not identify any major safety concerns with our concentrator. The FMEA was continued until the conclusion of our project to be sure that all possible safety hazards have been identified and addressed.

4.7 Maintenance and Repair

Maintenance and repair are guaranteed issues concerning products like our dual mirror system, which will receive use almost every day and be exposed to the elements.

In order to maintain adequate power to the cooking surface, both the reflector and mirror will have to be cleaned regularly. The actual frequency of this process was determined in the fall as explained in the Design Verification Plan in Appendix E: Design Verification Plan. Additional maintenance will likely be require as well.

The string in the string drive motor system will likely wear over time and fail. This part is cheaply and easily replaceable with little to no tools required. The pivot points of the reflector will need regular application of grease in order to ensure the reflector can rotate properly without overly stressing the motor.

5. Product Realization

At the time of the CDR, little actual construction had taken place. Since then, the design was altered, the product was created, and much knowledge was gained. This section outlines the manufacturing process, changes to the project since the CDR, and recommendations for the future.

5.1 Fall Construction

The week before class began fall quarter, we picked up where we left off at the end of spring quarter. This began with the rapid construction of a 1/5th scale prototype to ensure that our design was feasible. This was shortly followed by the manufacturing of all necessary parts and the design and creation of the tracking circuit. The manufacturing of the parts included cutting components to size, welding components together, and drilling holes for assembly. The tracking circuit required consultation from an EE student and an EE professor, multiple iterations of the design, and creation of a computer model. These two tasks were completed at the end of week 5. A temporary stand was designed and built to hold the product until its planned in-ground installation after the Senior Expo, and the components were assembled into their subassemblies. Finally, the pieces were brought together. At this point, a number of small issues presented themselves. The following weeks were spent redesigning these small subsystems (e.g. the tensioner system). The date of testing had to be pushed back during this time. Finally, we attempted to combine the concentrator and heliostat and begin testing. This proved harder than expected as the concentrator had not retained the ideal geometry and was difficult to secure. This setback pushed testing back further. Finally, the product was finished and testing was started.

5.2 Design Changes since the Critical Design Report

There are a number of changes to the design since May. There are two main changes regarding the scope of the project, and a number of small design tweaks to improve manufacturability/ease of use.

5.2.1 Target Users

In late May of 2015, it was confirmed that Dr. Schwartz's contact in Yemen was not interested in our work. Since we were no longer designing for a particular community, we lifted our requirement for our proof-of-concept prototype that our design be made with materials sourceable within a reasonable range of the target community, since we could not know in which community our cooker would be implemented. However, we still wanted to make sure the parts of our prototype could easily be replaced with equally functional components that would be attainable at similar cost in potential target communities. Our prototype reflects this intent.

5.2.2 Concentrator

Over summer, Dr. Schwartz suggested that we could begin testing earlier if we used an existing concentrator instead of waiting until that portion of the manufacturing was complete. This idea was retained until the beginning of fall quarter, during which time it became apparent that we were going to run into time constraints due to manufacturing. As the creation of a new concentrator is not necessary for design verification of the dual mirror concept, we decided to narrow the scope of our project to only include the heliostat. Our final product reflects this change, with the heliostat and associated tracking systems newly fabricated and the concentrator borrowed from a previous project.

5.2.3 Seasonal Adjustment

At the time of the CDR, our seasonal adjustment consisted of two rigid rods with eyehooks on either end that connected the upper mirror assembly to the rotating axis via a concentric pipe fixed with set screws. Shortly following the CDR, we realized a much simpler method of accomplishing the necessary degrees of freedom. To execute it, we created metal support rods as shown in Figure 19 whose pins on either end were parallel. This avoids the out-of-plane complications that encumbered the previous design.

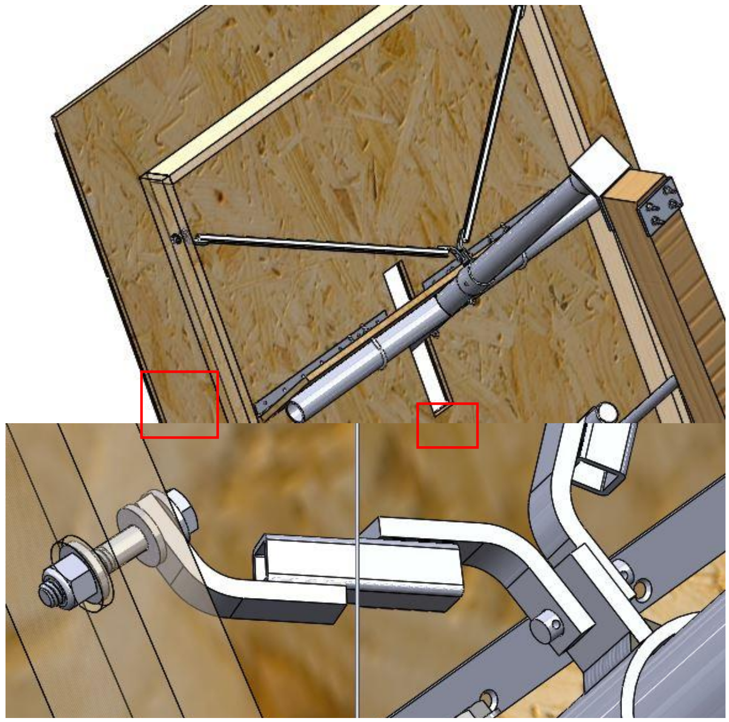

Figure 19. Close up of the new seasonal adjustment support rod design.

5.2.4 String Guide/tensioner

We also made a number of changes to the daily tracking. The first change was made both for ease of manufacture and cost reasons. We eliminated the semicircular string guide and added a pulley and large deformation spring to supply the motor adequate tension. We found that the semicircular guide would be hard to manufacture, especially in a developing country, and a similar result could be obtained by eliminating the string guide, adding a larger displacement string, and adding a pulley to direct the string around the hinge board as seen in Figure 20.

Figure 20. String tensionr system. Used to eliminate slack in the daily tracking system as the geometry of the string drive changes with the rotation of the heliostat.

5.2.5 Tracking Circuit and Power Source

Over the summer between spring and fall quarter, we began work on creating the tracking circuit by talking to undergraduate electrical engineering student Nick Hayes. With his advice, we were able to figure out the necessary components to create the circuit seen below in Figure 21.

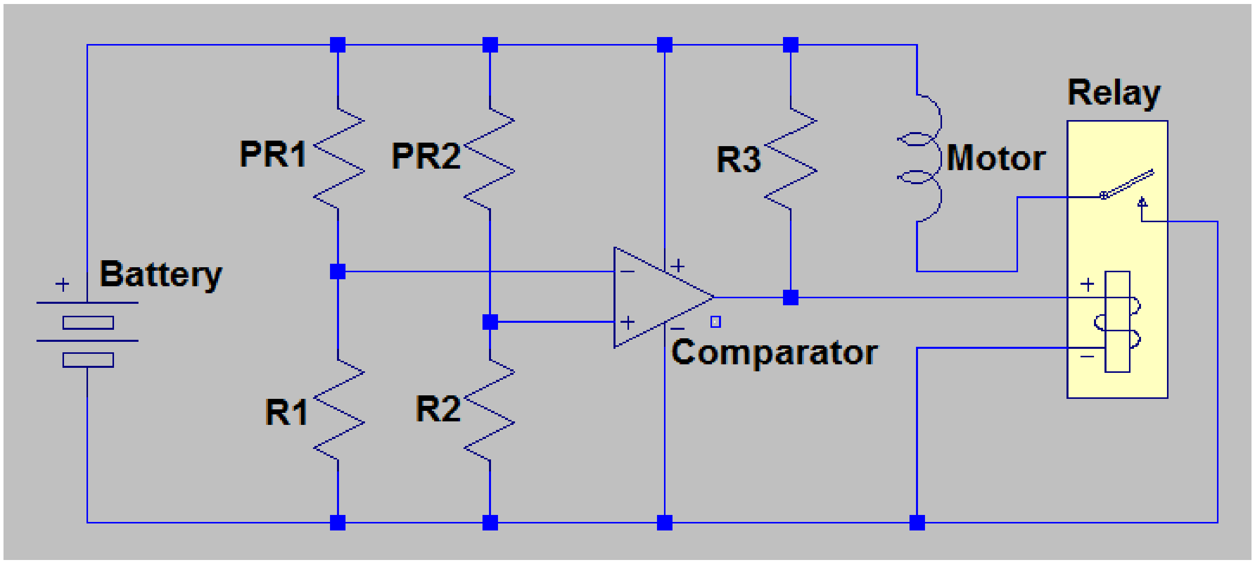

Figure 21. Tracking circuit: used to detect movement of the sun and actuate the motor to orient the heliostat.

This circuit consists of only IC's and discrete circuit elements (exact specifications can be found below in Table 3) to detect changing sunlight and actuate the motor. It is currently powered by a 12V power source, but ideally this could be replaced by a rechargeable battery and charging solar panel. Two photo resistors are placed on either side of the Photocomparator Divider (Drawing P001) on the Photocomparator Base (P002). The divider projects perpendicular to the heliostat surface; when the sun position moves, it casts a shadow on the east side of the Photocomparator base and the east photoresistor. This changes the resistance of said photoresistor. The comparator receives two input voltages dependent on the resistance of the two photoresistors and, when the west photoresistor detects sunlight and the east does not, triggers the relay which actuates the motor. When cloud cover casts shadow on the heliostat, the resistance of both photoresistors will change and the voltage difference will not be sufficient to trigger the comparator. This allows the heliostat to track the sun's movement without being confused by cloud cover.

Table 3. Tracking Circuit Component Specifications

Circuit Component	Specifications
Motor	Amico a12032000ux0190
Relay	TE OUAZ-SS-112D
Comparator	LM 311
R1	1000Ω
R2	2200Ω
R3	150Ω
PR1	80Ω in direct sunlight, 600Ω in shade
PR2	80Ω in direct sunlight, 600Ω in shade

5.2.6 Top and Bottom Support

In order to increase the safety and sturdiness of our design, we made two small changes to the top and bottom supports. We welded a bolt onto the top of the rotating pipe parallel to the pipe's axis. This bolt fits through a hole in the top bracket and a nut secures the top side of the assembly to the frame.

Secondly, we added a 2-inch section of semicircular pipe on the bottom support, which acts as a backup support in the unlikely case that the pipe falls off of the pivot bolt.

5.2.7 Temporary Stand

Due to the fact that it was most convenient to build and test our product near the student shops and that we must present our project at Senior Expo, we created a temporary stand for the device. The stand holds the 4”x4”wooden post and secures the lower legs. This allows the device to be free-standing until it is permanently mounted in the ground at the Student Experimental Farm. The lower two feet of each leg will be sunk into a foundation to secure the device and ensure a long lifetime despite occasional strong winds. Since this temporary stand is not something that someone would need to recreate our system, the technical drawings for it are not included in this report.

5.3 Recommendations for Future Design Development

In the event that another group wishes to improve on our design, we recommend the following design changes to improve the product.

5.3.1 Insulation Possibilities

Over the summer, we realized that our definition of the scope of our project was somewhat limiting. By defining the project as ending at the hot spot, we neglected any changes that could be made at the hotspot. As such, we designed our product to provide 1200 watts to the hot spot—60% of the power of a conventional stovetop. However, with creative use of insulation and reflective material, we may have been able to cook at a much lower power (decreasing the size and cost of the complicated heliostat and concentrator) by surrounding the sides and top of the pot with sheep’s wool or similar insulation and leaving the bottom open for the concentrated light. This does not negate the usefulness of our project, as the concept has still been verified and insulation testing could be performed even with the larger scale device by blocking a portion of the incoming light to adjust the input power. It is a potential area to investigate and improve upon the current design.

5.3.2 Reflective Surface Coverings

We recommend that the reflective surfaces be covered with a light cloth to prevent animal intrusion and potential damage to the surfaces.

5.3.3 Frame Alterations

There are two potential major changes to the frame: switch the configuration of the legs and lighten the overall weight.

The current frame is built as a tripod of sorts, with two short legs in the front and one main support in the back. We found that the two legs in front caused not two shadows on the concentrator, but four, decreasing the efficiency more than expected. This is due to the sunlight casting a shadow from the legs on the reflector and the redirected light casting a shadow of the legs on the concentrator. If the orientation of the supports were to be flipped, with a central support in front and two support in the back, the efficiency could be increased. We chose the current configuration for its structural stability however, so this would have to be taken into account.

The second change would be to lighten the overall weight of the heliostat. The frame and heliostat are together quite heavy: more than one person could safely move. Especially with the consideration of

insulation at the hotspot, it is likely that the frame could be streamlined to produce a more convenient and manageable design.

One further alteration would be to include a means of locking the rotation of the daily tracking axis. This would prevent inadvertent rotation due to wind, which could crash the mirror assembly into the tracking motor bracket. We managed by bracing the mirror assembly with wood and spacer blocks temporarily.

5.3.4 Concentrator

We believe that the majority of our performance issues stem from inefficient concentration of the light by the concentrator. We decided to eliminate the concentrator from our project scope because we knew that previous projects at Cal Poly had created solar concentrators and that we could borrow one of these concentrators to verify that our heliostat was properly working. However, at the time of this decision we were not aware the magnitude to which the concentrator had deformed. If we had known, we may have opted for a different course of action, but regardless we already were working overtime finishing the heliostat. We recommend that a concentrator be constructed for this device and the old concentrator be recycled. From the preliminary prototyping that we were able to complete, we found that a concentrator could be constructed by sweeping a mold in the ground and laying mylar in this mold. We leave this as a possibility for future development.

5.3.5 Tracking System

During our testing, we found that at the extremes of the heliostat rotation, the string began to slip on the pulley. We recommend that the pulleys on the tensioner system and motor be switch to knurled aluminum and the string be swapped for a coated cord.

The seasonal adjustment took a lot of trial and error to dial in properly. We recommend marking out on the rotating pipe where the adjustment slider ought to be set to for evenly spaced times throughout the year. Also, we recommend that the setscrews should be relocated on the slider pipe so as to eliminate slop and unintentional pivoting. Currently they form an axis about which the slider pivots, introducing a small angular range that the mirror assembly can freely rotate through. This range should be limited to improve reliability and durability. Further, we recommend that a lever be permanently attached to each set screw for ease of adjustment.

In the current design, the motor and tracking circuitry are directly exposed to the atmosphere. We recommend that all electronic components be carefully protected from water intrusion to prevent a short circuit.

6. Design Verification

Following construction of the device, verification of the design was necessary to determine whether or not the dual mirror concept met our requirements. Prior to construction, a full testing plan was created to guide our testing efforts. This section lists the intended and completed tests.

6.1 Testing Procedures

We created six testing procedures to determine whether we adequately met our requirements. These can be found in Appendix F: Testing Procedures. These tests are matched with specifications as shown in Table 4.

Table 4. Test names and associated specification numbers

Test Name	Spec #
Daily Setup Time	1
Maximum Input Force	2
Static Heat Spot	5
Static Heat Spot with Wind	5
Performance	11
Regular Maintenance	14

Not all tests were completed according to the original specifications after we realized that we over-specified them; in using the product and performing some tests we learned enough by simple observation that we could confidently say the other requirements were met without subjecting them to rigorous tests. The requirements specified for testing in Table 1 are iterated below in Table 5 with the revised requirements and compliance verification types.

Table 5. Revised specifications for testing formal requirements

Spec. #	Parameter Description	Requirement or Target	Tolerance	Compliance
1	Daily setup time	10 minutes	Max.	Observed
2	Maximum user input force	30 N	Max.	Observed
5	Static heat spot, relative to cooker	True	± 5 cm	Tested
7	Daily tracking axis inclination	34.6°	± 1°	Inspected
8	Wind speed while operable	10 m/s	Min.	Not Tested
11	Power to cooking surface	40 kW/m^2	± 10 kW/m^2	Tested
14	Daily maintenance	5 minutes	Max.	Observed

6.2.1 Daily Setup Time

Daily setup included removing the chocking, manually rotating the mirror assembly to the start position, removing coverings, seasonal adjustment as needed, and switching on the electronics. We did not rigorously time these tasks, as could have been done with a stopwatch. Nevertheless, never in our experience setting up the device did these tasks require more than 10 minutes.

Results: Setup requires less than 10 minutes.

6.2.2 Maximum Input Force

User inputs included manually rotating the mirror assembly, removing coverings, switching on electronics, and performing seasonal adjustment as needed.

Results: In our experience using the machine, we never needed to exert a force in excess of 30 N.

6.2.3 Static Heat Spot

This test was designed to verify that the heliostat did its job properly. If the heat spot was not static, it would indicate either a problem with the daily tracking or seasonal adjustment. We could discern which system was at fault because if the automated daily tracking functioned but the heat spot migrated, we would know the seasonal adjustment was out of calibration.

Before this test, we verified that the tracking circuit triggered the motor as desired. As soon as the circuit was completed, it was tested to ensure it would trigger when the correct photoresistor fell into shadow.

Results: The tracking circuit properly engages the motor and rotates the heliostat to properly reflect light onto the concentrator whenever the east side photoresistor falls into shadow. This successfully kept the entire concentrator supplied with light correcting for the azimuth angle. The seasonal adjustment easily corrected for the elevation of the sun for the current season, although we had to run the system for a few hours to get it dialed in properly.

6.2.4 Static Heat Spot, with Wind

In the end, we were unable to follow the testing procedure originally created to test for a static heat spot in windy conditions. This was partially due to manufacturing setbacks, but mostly due to the weather not cooperating during the days that we were able to test.

Nevertheless, we were able to obtain some preliminary results. Following its completion, we left the device outside in the courtyard of Bonderson Projects Center. During a month-long period, the week of October 19th was especially windy and reported outdoor wind speeds (maximum of 23 mph, or 10.3 m/s) exceeded the testing wind speed. While the wind speed at the heliostat was not necessarily as high as the reported maximums and we did not verify cooking ability in these conditions, it does demonstrate that the device is able to withstand high winds without structural failure.

Results: The heliostat can withstand higher windspeeds than its predecessors. The exact magnitude is unknown.

6.2.5 Performance

This test was based off of a performance testing standard published by ASABE (American Society of Agricultural and Biological Engineers). The device was used to raise the temperature of water and the power supplied to the hotspot was calculated from the energy absorbed by the water. A thermocouple data logger system was used to record the temperature of the water; this can be found below in Figure 22.

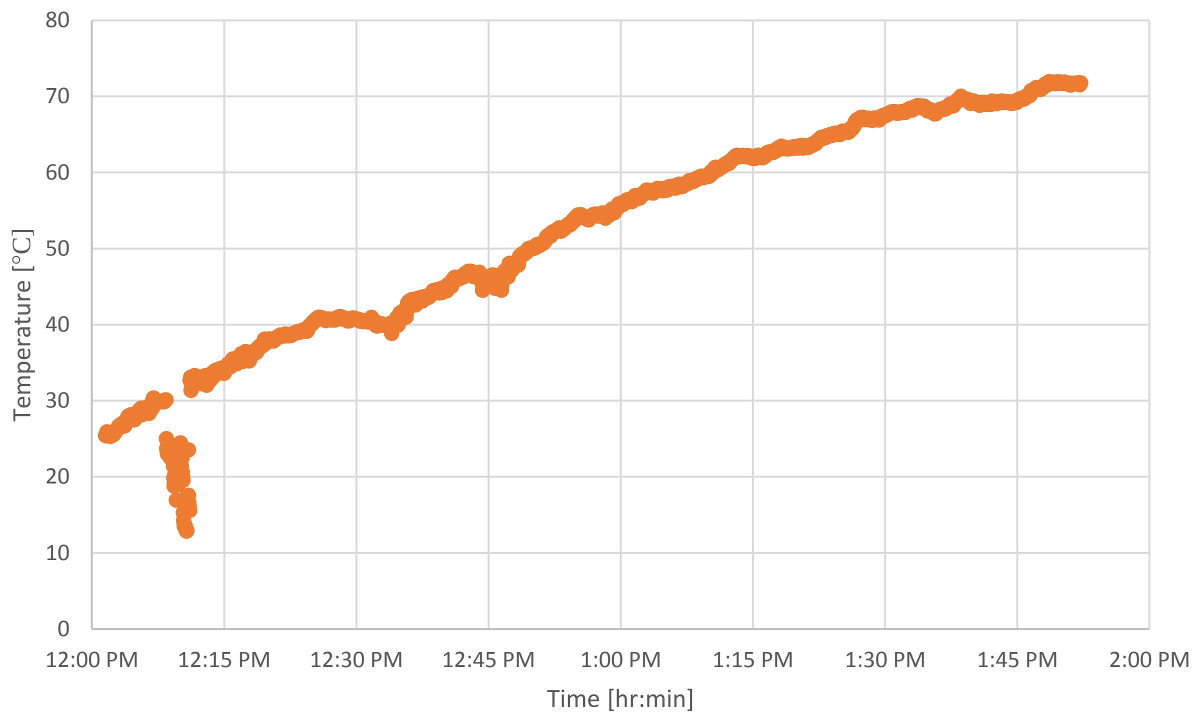

Figure 22. Plot of temperature as a function of time demonstrating how the solar cooker heated up 2 kilograms of water.

We found the power supplied by the device at a water temperature 50 °C above ambient to be 35 Watts. This is considerably lower than the required power of 1200 watts. We can account for some of this difference when we take into account potential inefficiencies: the legs shadows, the washers, not perfectly planar mirrors, inefficient reflectivity of the mirrors, and seasonal change of irradiation (the value of 1200 watts was calculated using summer values for irradiation and current irradiation values may be as low as half of the summer values). However, all these together does not result in the performance obtained. The light profile at the hot spot produced by the concentrator is roughly 40 cm in diameter, but is unevenly distributed and partially scattered. While more testing is necessary to determine the exact cause of this low performance, we believe that the main cause is the concentrator.

In addition to finding the average power delivered by the concentrator, we also found the power with multiple time steps to give us a sense of the instantaneous heat transfer balance to the pot. This can be seen below in Figure 23.

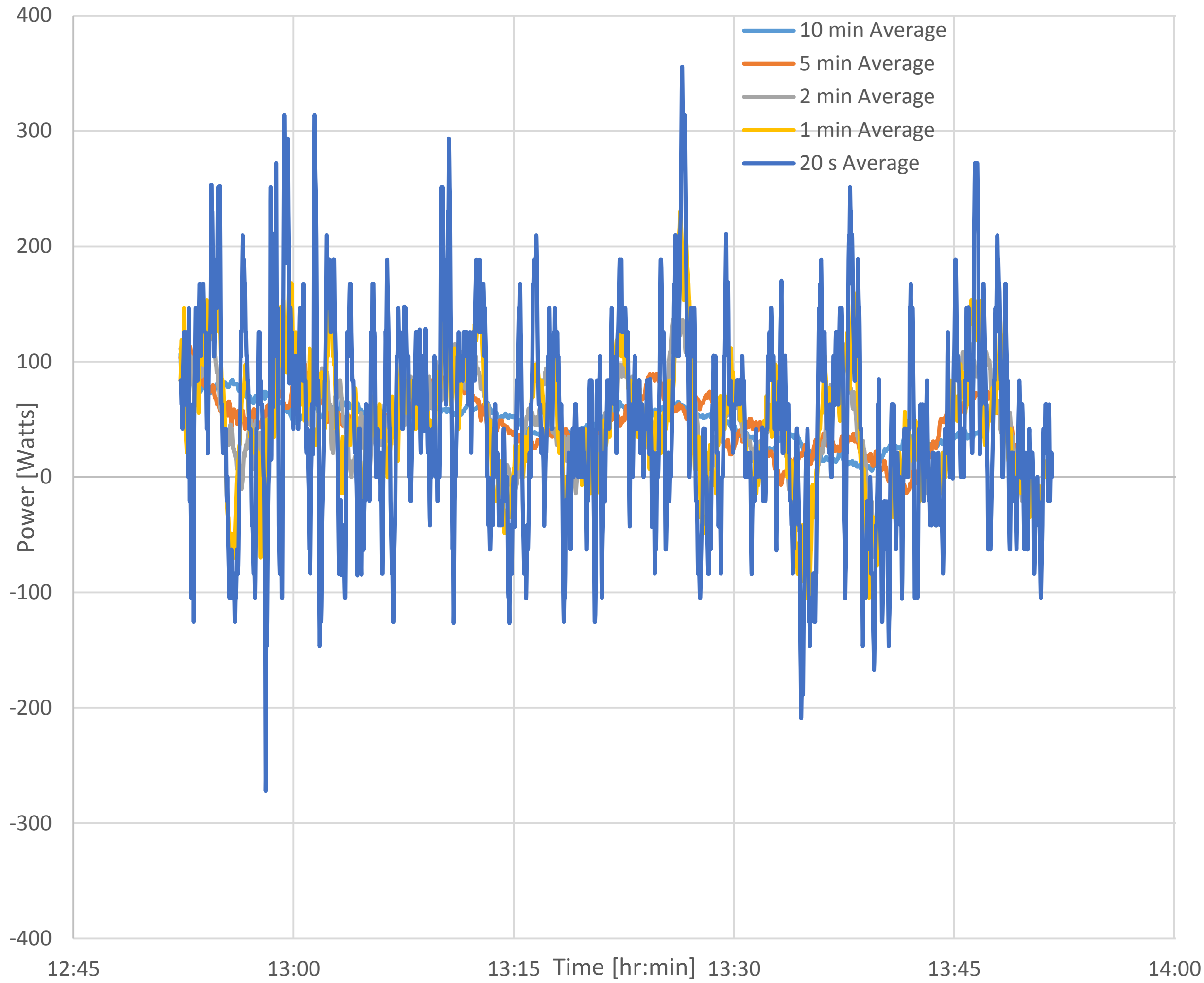

Figure 23. Instantaneous power absorbed at the hot spot with varying time steps.

Results: The device performs much worse than expected. This failure has a number of potential causes; the primary cause we suspect is at fault is the concentrator's improper geometry. We suggest the device be tested with a more accurately shaped concentrator to thoroughly investigate the root cause of failure.

6.2.6 Maintenance

As previously stated, the device was left outside for the month prior to Senior Expo. During this time it was exposed to three periods of rain, a wide variation in wind and sun, a cold snap, and a significant amount of dust and grime created from the nearby machine shop. From our estimation, this has had negligible effects on the power output and no effects on the structural integrity or user interaction with the device.

7. Conclusion

This project was pitched to the mechanical engineering students by Dr. Pete Schwartz, a professor in the Physics department. For some time, he has been involved in the field of solar cookers. These devices attempt to solve a problem of two interconnected societal trends: the need to support the growing population and the push to become sustainable and self-supporting. These two trends combine in many ways, including a lack of sustainable, appropriate cooking technologies in developing countries. One solution to this need is the solar cooker. Dr. Schwartz pitched the project to design and build a Dual-Mirror Solar Cooker; while other solar cookers exist and use similar technologies, no other cookers use this specific geometric design (the dual mirror has only been attempted once before, by a previous senior project group at Cal Poly). This project was an attempt to verify the design concept, produce a working model for testing purposes, and design a product for this concept that was reliable, cost effective, and simply constructed.

This project began with research and analysis of the concept and how it compared to other designs on the market. We determined that the dual mirror was a worthy approach to fulfilling the need, continued with the design of the dual mirror system, created small and full scale prototypes, and tested this device for our design verifications.

Throughout the course of the past year, we encountered many issues and setbacks and the device and project changed accordingly. The largest change from our initial goal was the elimination of the concentrator from the scope of the project. While this change was necessary in order for us to complete the project and not necessarily vital to the verification of the concept, it did negatively impact the outcome of the project. Upon completion of the heliostat, we tested the performance of the solar cooker and found that it failed to meet our design specifications. A number of potential causes other than the improper geometry of the concentrator can be found in Section 6.2.5. Following our testing, we have a number of recommendations (these are fully elaborated in Section 5.3 Recommendations for Future Design Development) for further investigation of this design: insulation at the hotspot should be investigated to allow for a smaller scale device; a cover should be designed for the heliostat and concentrator; the support structure should be investigated to eliminate shadows; most importantly a concentrator with proper geometry should be constructed.

Appendix A: References

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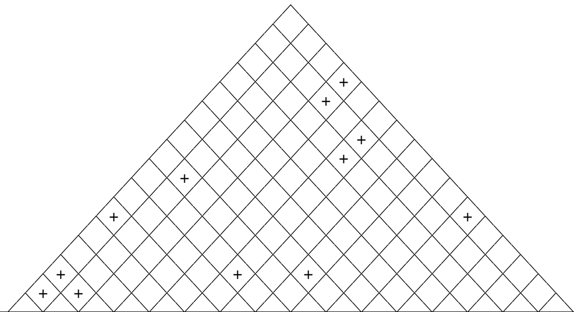
Appendix B: Quality Function Deployment

QFD: House of Quality
Project: Solar Collector
Revision: 3
Date: February 1, 2015

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

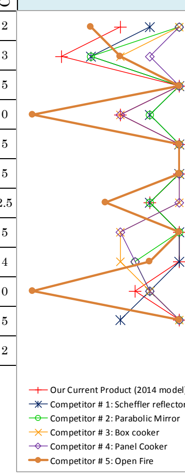
Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Weight Chart	Relative Weight	Dr. Schwartz	Women who cook with the product	Communities who purchase the pro		Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	1: Daily user input [minutes]	2: Maximum user input force [N]	3: Operation actions [# user controls]	4: Purchase price [USD]	5: Fixed heat spot, relative to cooker [Y/N]	6: Product life [years]	7: Functional lattitude range [degrees]	8: Windspeed while operable [m/s]	9: Windspeed before failure [m/s]	10: Risk of injury [custom weighted index]	11: Maximum power to cooking surface [kW/m^2]	12: Works with ordinary pots/pans [Y/N]	13: Annual maintenance [hours]	14: Daily maintenance [minutes]	15: Materials sourceable in range of target location [km]	16: Size (length x width x height) [m]	Our Current Product (2014 model)	Competitor # 1: Scheffler reflector	Competitor # 2: Parabolic Mirror	Competitor # 3: Box cooker	Competitor # 4: Panel Cooker	Competitor # 5: Open Fire	Row #
								Direction of Improvement	▼	▼	▼	▼	◇	▲	▲	▲	▲	▼	◇	▲	◇	▼	▼	▼							
1		7%	3	3	2		9	Easy to use	●	●	●		▽					▽		○					3	4	5	5	5	2	1
2		9%	3	3	5		9	Low cost				●									▽		○	○	1	2	2	3	4	3	2
3		8%	4	4	2		9	Stationary cooking spot					●												5	5	5	5	5	5	3
4		10%	4	4	4		9	Long lasting						●			○				○	○			3	4	4	3	3	0	4
5		9%	3	4	3		9	Specific to user latitude							●										5	5	5	5	5	5	5
6		7%	3	3	2		9	Freestanding stability								●	●	○							5	5	5	5	5	5	6
7		13%	5	5	5		9	Safe to use	▽				▽			○	○	●							4	4	4	5	5	2.5	7
8		10%	4	4	4		9	Cooks quickly											●						5	5	5	3	3	5	8
9		4%	2	2	1		3	Easy access to pot/pan					▽					○		▽					5	5	3.5	3	3.5	4	9
10		7%	3	2	3		9	Low maintenance													●	●			3.5	4	4	4	4	0	10
11		10%	3	4	4		9	Manageable size																●	5	3	5	5	5	5	11
12		5%	4	1	1		9	Sustainable manufacture						○									●		3	2	2	5	5	2	12

WHO: Customers

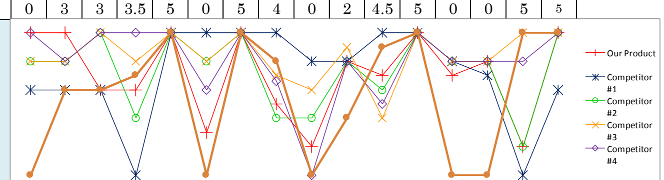
NOW: Current Product Assesment - Customer Requirements



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	10 minutes	30 N	5 controls	$200	Yes	5 years	± 50°	10 m/s	30 m/s	1%, 0.1%	100 kW/m2	Yes	10 hours	5 minutes	200 km	1.5mx1.5mx1.5m
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	3	9	9	9	9
Technical Importance Rating	75	62	62	84	98	109	78	101	133	158	94	25	103	94	74	115
Relative Weight	5%	4%	4%	6%	7%	7%	5%	7%	9%	11%	6%	2%	7%	6%	5%	8%
Weight Chart																

Current Product Assesment - Engineering Specifications

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Our Product: 2014 model	5	5	3	3	5	1.5	5	2.5	1	4	3.5	5	3.5	4	1	5
Competitor #1: Scheffler reflector	3	3	3	0	5	5	5	5	4	4	5	5	4	3.5	0	3
Competitor #2: Parabolic mirror	4	4	5	2	5	4	5	2	2	4	3	5	4	4	1	5
Competitor #3: Box cooker	4	4	5	4	5	4	5	3.5	3	4.5	2	5	4	4	5	5
Competitor #4: Panel cooker	5	4	5	5	5	3	5	3.3	0	4	2.5	5	4	4	4	5
Competitor #5: Open fire	0	3	3	3.5	5	0	5	4	0	2	4.5	5	0	0	5	5



Column # 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

Appendix C: Decision Matrices

Table 6. System style decision matrix.

Engineering Requirement	Direct Weight	Relative Weight	Cal Poly's		Scheffler		Dual Mirror		On Axis Paraboloid		Heat Transfer Fluid		Lens		Floating Puddle	
			UW	W	UW	W	UW	W	UW	W	UW	W	UW	W	UW	W
Daily user input [minutes]	4	9.2%	4.5	18	3.5	14	5	20	2	8	4	16	4	16	4	16
Maximum user input force [N]	1.5	3.4%	5	7.5	2	3	5	7.5	4	6	5	7.5	5	7.5	4	6
Operation actions [# user controls]	1	2.3%	3	3	3	3	3	3	1	1	2.5	2.5	3	3	3	3
Purchase price [USD]	3	6.9%	3	9	1	3	3	9	4	12	3	9	1	3	4	12
Fixed heat spot, relative to cooker [Y/N]	4	9.2%	4	16	4.5	18	4.5	18	2.5	10	5	20	4.5	18	3	12
Product life [years]	3	6.9%	2	6	4	12	3.5	10.5	4	12	3	9	3	9	2	6
Functional latitude range [degrees]	3	6.9%	3	9	3	9	3	9	3	9	3	9	3	9	3	9
Wind speed while operable [m/s]	2	4.6%	2	4	4	8	4	8	3	6	4	8	3	6	2.5	5
Wind speed before failure [m/s]	2	4.6%	1.5	3	3.5	7	3.5	7	4.5	9	4	8	3.5	7	2	4
Risk of injury [custom weighted index]	5	11.5%	4	20	4	20	4	20	3.5	17.5	4	20	4	20	4.5	22.5
Maximum power to cooking surface [kW/m^2]	4	9.2%	4.5	18	4.5	18	4	16	4.5	18	3.5	14	4	16	3	12
Works with ordinary pots/pans [Y/N]	2	4.6%	5	10	5	10	5	10	5	10	3.5	7	5	10	5	10
Annual maintenance [hours]	2	4.6%	4	8	4	8	4	8	4.5	9	2	4	4	8	3.5	7
Daily maintenance [minutes]	2	4.6%	4.5	9	4.5	9	4.5	9	5	10	4.5	9	4.5	9	3.5	7
Materials sourceable in range of target location [km]	2	4.6%	3	6	3	6	3	6	3	6	3	6	3	6	3	6
Size (length x width x height) [m]	3	6.9%	4	12	4	12	3	9	4.5	13.5	3.5	10.5	4.5	13.5	3	9
Total:	43.5	100%	57	158.5	57.5	160	62	170	58	157	57.5	159.5	59	161	53	146.5

Table 7. Daily tracking mechanism decision matrix.

Engineering Requirement	Direct Weight	Relative Weight	Clockwork		Manual		Electric	
			UW	W	UW	W	UW	W
Daily user input [minutes]	5	21.3%	3.5	17.5	1	5	4.5	22.5
Maximum user input force [N]	3	12.8%	2	6	4	12	5	15
Operation actions [# user controls]	5	21.3%	1.5	7.5	4	20	3	15
Purchase price [USD]	4	17.0%	4	16	5	20	3	12
Product life [years]	1	4.3%	2.5	2.5	3	3	4	4
Annual maintenance [hours]	3	12.8%	4	12	4	12	4	12
Materials sourceable in range of target location [km]	2.5	10.6%	5	12.5	5	12.5	3	7.5
Total:	23.5	100%	22.5	74	26	84.5	26.5	88

Table 8. Seasonal adjustment decision matrix.

Engineering Requirement	Direct Weight	Relative Weight	Turnbuckle		Electric		Wooden Blocks		Telescoping		Perforated Disk	
			UW	W	UW	W	UW	W	UW	W	UW	W
Daily user input [minutes]	3.5	14.0%	4	14	5	17.5	5	17.5	4	14	4	14
Maximum user input force [N]	4	16.0%	4	16	5	20	2	8	4	16	3.5	14
Operation actions [# user controls]	4.5	18.0%	4	18	4	18	2	9	3	13.5	3	13.5
Purchase price [USD]	2	8.0%	3	6	1	2	5	10	4	8	2.5	5
Product life [years]	3	12.0%	5	15	2.5	7.5	4	12	4	12	3.5	10.5
Annual maintenance [hours]	2	8.0%	5	10	2	4	5	10	5	10	5	10
Materials sourceable in range of target location [km]	1	4.0%	3	3	2	2	5	5	4.5	4.5	3	3
Adjustability	5	20.0%	5	25	5	25	2	10	4	20	3	15
Total:	25	100%	33	107	26.5	96	30	81.5	32.5	98	27.5	85

Appendix D: Vendors and Pricing

Heliostat Costs

NET PROJECT COST: $ 221.51

Part Description	Qty.	Unit Cost	Net Cost	Source
Reflector				
1/2-in OSB, 48"x96"	1	$ 9.15	$ 9.15	Home Depot
1"x3" 10 ft length	2	5.12	$ 10.24	Home Depot
49" x 13" Framed Door Mirror	5	$ 5.98	$ 29.90	Home Depot
1/4 - 20 Zinc-Plated Steel Hex Nut (10 pack)	1	$ 1.18	$ 1.18	Home Depot
1/4-20 x 1.5 Hex cap bolt	2	$ 0.90	$ 1.80	Home Depot
1/4-20 Nylock lock nut	2	$ -	$ -	Scrap
Steel pipe mounting clamp	2	$ 2.57	$ 5.14	Home Depot
1/16 in thick neoprene sheet	1	$ 4.57	$ 4.57	Home Depot
Fender washers (6 pack)	2	$ 1.18	$ 2.36	Home Depot
#6 x 1 drywall screws	1 lb	$ 6.47	$ 6.47	Home Depot
1/4 in steel plate, .5 ft^2	1	$ -	$ -	Scrap
Reflector Total			$ 70.81	
Frame				
1-1/2 in x 10 ft Galvanized Steel Pipe	1	$ 43.50	$ 43.50	Home Depot
1 in x 10 ft galvanized steel tube	1	$ -	$ -	SEF
2in male-male galvanized steel pipe nipple	1	$ 1.89	$ 1.89	Ace Hardware
Pipe Clamp, 1-7/8 OD, 2-hole mount	2	$ 2.57	$ 5.14	McMaster
1/4-20 x 3 zinc-plated screws, pack of 10	1	$ 5.84	$ 5.84	McMaster
1/4-20 x 1 zinc-plated screws, pack of 100	1	$ 9.75	$ 9.75	McMaster
1/4-20 zinc-plated nuts	14	$ -	$ -	Home Depot
U-clamp, 1/4-20 threads, pack of 10	1	$ 7.84	$ 7.84	McMaster
1/4 in. steel plate	1 ft^2	$ -	$ -	Scrap
Paino hinge, 3ft	1	$ -	$ -	SEF
1/2 x 1/2 steel box tube, 3 ft length	2	$ 5.57	$ 11.14	Home Depot
Frame-side Pulley	1	$ -	$ -	Rose Float Lab
Extension spring	1	$ 3.08	$ 3.08	McMaster
Motor-side pulley	1	$ -	$ -	Scrap
3/8-16 x 2 cap screw	1	$ -	$ -	Scrap
1/4 in washer (12 pack)	3	$ 1.18	$ 3.54	Home Depot
4"x4" 10 ft length	1	$ 10.59	$ 10.59	Home Depot
Frame Total			$ 102.31	
Tracking Circuit				
Motor	1	$ 18.44	$ 18.44	Amazon
Pipe, sch 40, .50 diameter, 36 in length	1	$ 7.62	$ 7.62	Home Depot
Wire, 22 awg	30 ft	$ -	$ -	Ian's Backpack
Photovoltaic panel	1	$ -	$ -	Mustang '60
Battery	1	$ 8.48	$ 8.48	Zoro
Photoresistors	3	$ -	$ -	Mustang '60
LM311 comparator	1	$ 1.95	$ 1.95	Radioshack
5V DC Relay	1	$ 1.95	$ 1.95	Radioshack
Tracking Circuit Total			$ 38.44	
Heliostat Total			**$ 211.56**	

Appendix E: Design Verification Plan

TEST PLAN									
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING	
						Quantity	Type	Start date	Finish date
1	Prototype dish construction	Small scale WBT: in order to test the abilities of the chosen material and manufacturing, we will construct a small scale prototype and use this to test the time it takes the model to boil a cup of water.	Max	Ian	CV	1	s	5/1/2015	6/13/2015
2	Ray Tracing	Perform basic ray tracing including bending analysis of reflector frame to verify size of reflector	Pass	Ian	CV	1	A	4/1/2015	5/1/2015
3	Daily setup time	First we will time ourselves multiples time performing all the necessary tasks in order to operate the product. We will then find volunteers to test out the product and record their usage of the product.	Max 10 min	Devin	DV	10	C	10/5/2015	11/5/2015
4	Maximum user input force	Using spring scales or force scale to apply all forces to the product, we will go through and perform all the tasks necessary to cook with the product and record the applied forces	Max 30 N	Devin	DV	1	D	10/5/2015	11/5/2015
5	Static heat spot relative to cooker	We will track the movement of the focus throughout a full daily use cycle	± 5 cm from static	Devin	DV	10	C	10/5/2015	11/5/2015

6	Wind speed while operable	We will document the performance of the mirror on days with and without wind to determine any correlations between wind and performance	Min 10 m/s before operation failure	Devin	DV	5	C	10/5/2015	11/5/2015
7	Maximum power to cooking surface	WBT: Through an adaption of the water boiling test, we can determine the power input to the stove at various levels of cloud cover the time it takes to boil water and extrapolate the power output of the stove	80-160 kW/m2	Ian	PV	10	C	10/5/2015	11/5/2015
8	Daily maintenance	Simulate a windy dusty day and time the necessary steps required to clean and maintain the system	5 minutes	Ian	DV	10	C	10/5/2015	11/5/2015

Appendix F: Testing Procedures

Daily Setup Test Protocol

Objective:

To determine the time required each day to setup the solar cooker before it can be used.

Materials:

Stopwatch

Procedure:

1. Before doing anything, start the stopwatch.
2. As soon as you start the stopwatch, begin setting up the device.
3. Reset to the starting position.
4. Setup cooking area.
5. Plug in the battery and start the tracking circuit.
6. Ensure seasonal tracking is correctly adjusted and change if needed.
7. Stop the timer.

Analysis:

1. Report total setup time.

Maintenance Test Protocol

Objective:

Quantify the time required to sufficiently maintain the device.

Materials:

Heliostat-Concentrator Solar Cooker
Stopwatch

Procedure:

1. Before doing anything, start the stopwatch.
2. Clean and polish the mirrors.
3. Paint any broken off bits from the frame.
4. Check string wear and replace if needed.
5. Perform any other necessary maintenance.
6. Stop the timer.

Analysis:

1. Report total setup time.

Maximum Input Force

Objective:

To ensure that all actions necessary for the operation of the device can be performed by the user.

Materials:

Spring Scale
Heliostat-Concentrator Solar Cooker

Procedure:

1) Perform all actions necessary for use of the device with the spring scale and record maximum force required.
   a) Place wrench on seasonal adjustment set screw, place spring scale at end of wrench, and slowly increase the force applied. Record the maximum force applied before screw turns.
   b) Place spring scale on seasonal adjustment (through the top support hole) and record max force required to slide the slider pipe throughout full range of motion.
   c) Place wrench and retighten set screw using the spring scale, record the maximum force.
   d) Use spring scale to rotate the heliostat back to starting position.

Analysis:

1) Report all tasks that exceed maximum limit of 30 N

Pre-cooking Setup Test Protocol

Objective:

To determine the time required each day to setup the solar cooker before it can be used.

Materials:

Stopwatch

Procedure:

1. Before doing anything, start the stopwatch.
2. As soon as you start the stopwatch, begin setting up the device.
3. Reset to the starting position.
4. Setup cooking area.
5. Plug in the battery and start the tracking circuit.
6. Ensure seasonal tracking is correctly adjusted and change if needed.
7. Stop the timer.

Analysis:

1. Report total setup time.

Static Heat Spot Test Protocol

Objective:

Quantify how stationary the heated area generated by the system is.

Materials:

Heliostat-Concentrator Solar Cooker
Cooking Stand
Nonflammable Surface
Nonflammable marking tool for nonflammable Surface
Time Lapse Camera
Windless but sunny setting

Procedure:

1. Setup Heliostat-concentrator system for cooking.
2. Setup cooking stand at the focal region.
3. Mark nonflammable surface with a polar grid.
4. Place marked nonflammable surface marked side down on cooking stand, centered (approximately).
5. Setup time-lapse camera focused on gridded area. Setup camera to take frame once a minute for the test duration. The test duration should range from sunrise to sunset. Be sure the camera will have sufficient battery and storage.
6. Record:
    a. Nonflammable surface used: material, shapes
    b. Polar grid scale
    c. Time lapse frame rate
    d. Start time and date
7. Begin recording at sunrise.
8. Monitor the test throughout the day.
9. Stop recording at sunset.
10. Playback time-lapse. Note range of lighted area of nonflammable surface.
11. Find centroid of this range and realign the gridded surface so that the lighted range centroid is coincident with the polar grid origin.
12. Repeat steps 5-8.

Analysis:

1. Review time-lapse. Calculate the maximum deviation of the centroid of the instantaneous light spot from the centroid of the overall range of the light sport. This deviation quantifies the mobility of the heat sport, which is important as temperature will be directly related to the visible radiation.

Static Heat Spot with Wind Test Protocol

Objective:

Quantify the effect of wind on the position of the hot spot.

Materials:

Heliostat-Concentrator Solar Cooker
Cooking Stand
Nonflammable Surface
Nonflammable marking tool for nonflammable Surface
Time Lapse Camera
Wind and sun
Anemometer
Wind direction sensor

Procedure:

1. Setup Heliostat-concentrator system for cooking
2. Setup cooking stand at the focal region
3. Mark nonflammable surface with a polar grid
4. Place marked nonflammable surface marked side down on cooking stand, centered (approximately)
5. Setup time-lapse camera focused on gridded area. Setup camera to take frame once a minute for the test duration. The test duration should range from sunrise to sunset. Be sure the camera will have sufficient battery and storage.
6. Record:
    a. Nonflammable surface used: material, shapes
    b. Polar grid scale
    c. Time lapse frame rate
    d. Start time and date
7. Setup anemometer and direction sensor near system
8. Begin recording at sunrise
9. If wind measurements must be taken manually, they should be taken every half hour.
    a. Record average wind direction and uncertainty
10. Stop recording at sunset.
11. Playback time-lapse. Note range of lighted area of nonflammable surface
12. Find centroid of this range and realign the gridded surface so that the lighted range centroid is coincident with the polar grid origin.
13. Repeat steps 5-8.

Analysis:

1. Review time-lapse. Calculate the maximum deviation of the centroid of the instantaneous light spot from the centroid of the overall range of the light sport. This deviation quantifies the mobility of the heat sport, which is important as temperature will be directly related to the visible radiation.
2. Compare this deviation to the deviation found in the Static Heat Spot test.

Appendix G: Detailed Analysis

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POWER ANALYSIS

CONSIDERATIONS
- DUST
- FRAME BEING-IN-THE-WAY NESS
- REFLECTIVE EFFICIENCIES
- GEOMETRIC ACCURACY
- AIR DISSIPATION

POWER ANALYSIS

GIVEN:

TYPICAL INSOLATION, q_{in} [kW/m²]
REFLECTOR GEOMETRY
REFLECTOR EFFICIENCY, η_1
CONCENTRATOR GEOMETRY
CONCENTRATOR EFFICIENCY, η_2

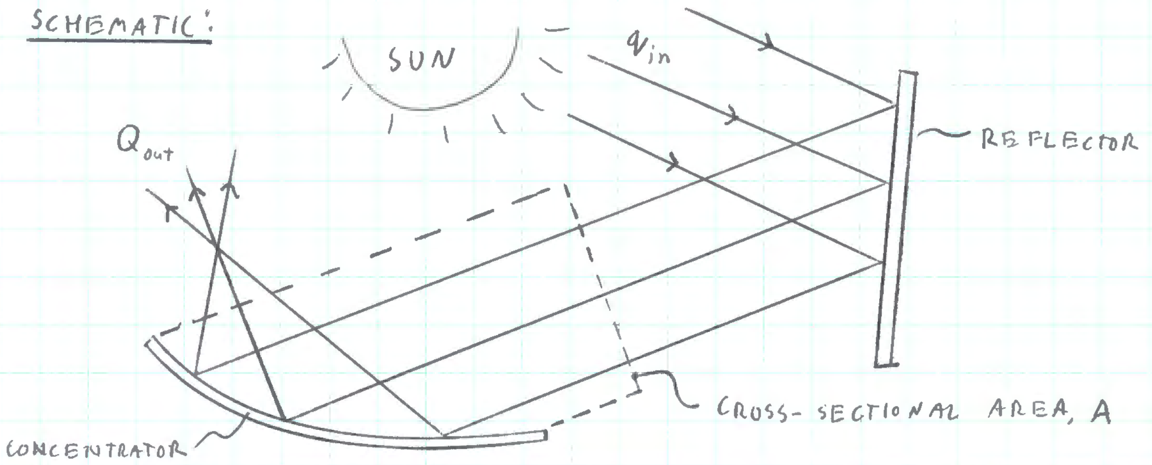
FIND:

POWER DELIVERED TO COOKING AREA AS A FUNCTION OF CONCENTRATOR SIZE

ASSUME:

1) EQUINOX CONDITIONS
2) NEGLIGIBLE INTERFERENCE FROM AIR
3) MANUFACTURING DEFECTS RESULT IN AN EFFECTIVE EFFICIENCY OF η_3
4) AVERAGE IRRADIATION AND INSOLATION VALUES

SCHEMATIC:



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POWER ANALYSIS – CONT'D

ANALYSIS

$$Q_{out} = q_{in} \eta_1 A \eta_2 \eta_3^2 \quad (1)$$

FOR GLASS MIRROR, $\eta_1 = 90\%$

FOR REFLECTIVE ALUMINIUM, $\eta_2 = 80\%$

FOR CONSTRUCTION ERROR, $\eta_3 = 80\%$

$$Q_{out} = q_{in} (.9)(.8)(.8)^2 A$$

$$Q_{out} = .4608 \; q_{in} A \quad (2)$$

FOR SLO, $q_{in} \simeq 4.87$ kWh/m²/day

$$q_{in} = 4.87 \; \text{kWh/m}^2\text{/day} \left(\frac{1 \text{ day}}{24 \text{ h}}\right)$$

$$q_{in} = 0.203 \; \text{kW/m}^2$$

SO,

$$Q_{out} = (.4068)(.203 \; \text{kW/m}^2) A$$

$$Q_{out} = (0.0935 \; \text{kW/m}^2) A \quad (3)$$

FOR A COOKING AREA OF Ø30 cm,

$$q_{out} = \frac{Q_{out}}{\frac{\pi}{4} D^2} \quad (4)$$

$$= \frac{(0.0935 \; \text{kW/m}^2) A}{\frac{\pi}{4} (.3 \text{ m})^2}$$

$$q_{out} = 1.323 \; \text{kW/m}^4 \; A$$

$$A = \frac{q_{out}}{1.323 \; \text{kW/m}^4} \quad (5)$$

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POWER ANALYSIS – CONT'D

FOR q_{out} DESIRED TO BE ABOUT 1.5 kW/m^2,

$$A = \frac{1.5 \cancel{kW/m^2}}{1.323 \cancel{kW/m^2}}$$

$$A = 1.134\ m^2$$

PRIMARY REFLECTOR SIZE

FIND:

NOMINAL OPTIMAL SIZE OF THE PRIMARY RELECTOR

GIVEN:

DUAL-MIRROR SYSTEM

ASSUMPTIONS:

1) EQUINOX CONDITIONS
2) RECTANGULAR PRIMARY REFLECTOR
3) DESIGN FOR USE IN SLO

ANALYSIS:

continued to page

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PROPRIETARY INFORMATION

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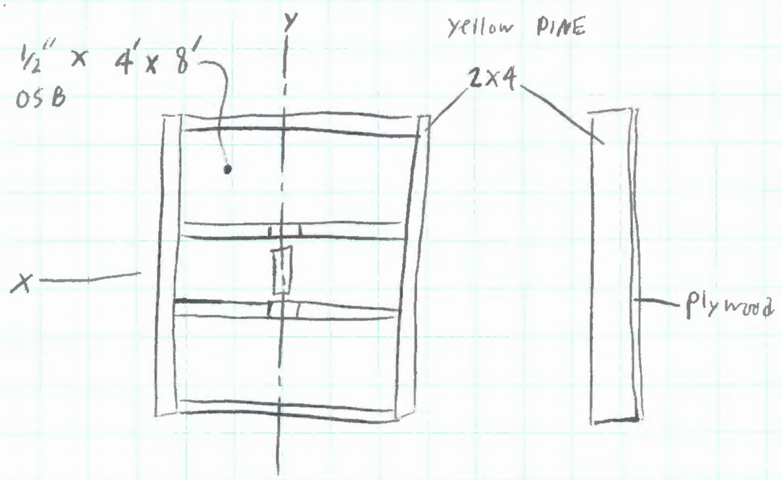
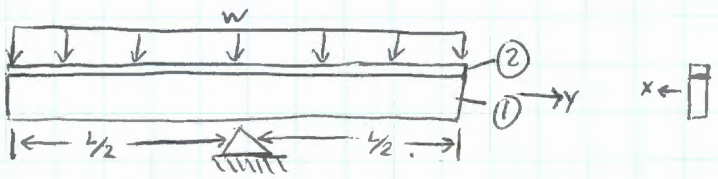
PRIMARY REFLECTOR DESIGN

CONSIDER A WOODEN FRAME:



CONSIDER BENDING ~~TH~~ ABOUT X-axis



①

$I_1 = \frac{1}{12} bh^3$

$= \frac{1}{12}(1.5\ in)(3.5\ in)^3$

$I_1 = 5.36\ in^4$

$w_1 = 11\ lbf / 8\ ft = 1.375\ lbf/ft$

$w_1 = .115\ lbf/in$

②

$I_2 = \frac{1}{12} bh^3$

$= \frac{1}{12}(1.5\ in)(0.25\ in)^3$

$I_2 = .001953\ in^4$

~~th~~ RIGIDLY FIX THE TWO TOGETHER

③

$I_3 = \frac{1}{12} bh$

$= \frac{1}{12}(1.5\ in)(3.75\ in)^3$

$I_3 = 6.5918\ in^4$

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Conducted PROTOTYPING IN M '60

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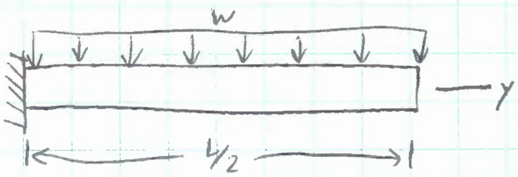
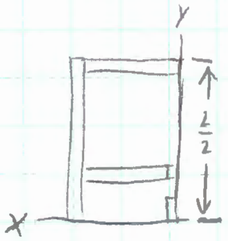
USING SYMMETRY, MODEL ~~HALF~~ 1/4th THE BEAM AS CANTILEVERED.





$$\delta_{max} = \frac{w\left(\frac{L}{2}\right)^4}{8EI}$$

FOR YELLOW PINE, $\rho_p = 44\ \text{lbs}/\text{ft}^3$

For 2x4 cross-section, $\lambda_p = A_c\, \rho_p$

$$= (1.5\ \text{in})(3.5\ \text{in})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)^2 (44\ \text{lbs}/\text{ft}^3)$$

$$\lambda_p \cong 1.60\ \text{lbs}/\text{ft}$$

FOR TYPICAL OSB, ~~ρ ~ 45~~ $\rho_{OSB} \simeq 40\ \text{lbs}/\text{ft}^3$ (50 lbs/piece)

HENCE,

~~$w = \lambda + \frac{1}{4}$~~

$$\lambda_{OSB} = A_c\, \rho_{OSB}$$

~~$= \left(\frac{15}{32}\ \text{in}\right)(24\ \text{in})$~~

$$= hw\, \rho_{OSB}$$

$$= \left(\tfrac{15}{32}\ \text{in}\right)(24\ \text{in})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)^2 (40\ \text{lbs}/\text{ft}^3)$$

$$\lambda_{OSB} = 3.125\ \text{lbs}/\text{ft}$$

$E_{pine} \cong 8\ \text{GPa} \Rightarrow 1.16\ \text{Mpsi}$

$E_{OSB} = 1.2\ \text{GPa} \Rightarrow 0.174\ \text{Mpsi}$

↳ NEGLIGIBLE, BY COMPARISON, FOR CONSERVATIVE ESTIMATES

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PROPRIETARY INFORMATION

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21 APRIL 2015 PRIMARY REFLECTOR DESIGN, CONT'D

$$\delta_{max} = \frac{(\lambda_p + \lambda_{osb}) \left(\frac{L}{2}\right)^4}{8 E I_3}$$

~~$$= \frac{(1.60 + 3.13) \ lbs/ft \left(\frac{1 ft}{12 in}\right)(48 in)^4}{8 (1.16 \times 10^6 \ lbs/in^2)(6.59 \ in^4)}$$~~ ~~lbs/ft~~ ~~$\frac{[F]/[L] \ [L]^4}{[F/L]^2 \ [L]^4}$~~

~~δ_{max}~~

$$= \frac{(1.60 + 3.13) \ \frac{lbs}{ft} \left(\frac{1 ft}{12 in}\right) \left(\frac{46 \ in}{2}\right)^4}{8 (1.16 \times 10^6 \ lbs/in^2)(6.59 \ in^4)}$$

$$\boxed{\delta_{max} = 0.034 \ \text{in}} = \delta_{max, 2x4}$$

Now TRY 1x4 instead of 2x4

~~$\Rightarrow I_4 =$~~

~~$\Rightarrow I_4 = I_3 \frac{(.75 in)}{(1.5 in)}$~~ NOT TRUE. "W" CHANGES

~~$I_4 = 3.24 \ in^4$~~

~~$\delta_{max, 1x4} = \delta_{max, 2x4} \frac{I_3}{I_4}$~~

~~$= 0.034 in \left(\frac{6.59 \ in^4}{3.24 \ in^4}\right)$~~

~~$\boxed{\delta_{max, 1x4} = 0.068 \ in} \simeq 1/16 \ in$~~

$$\lambda_{p, 1x4} = A_c \, \rho_p$$

$$= (.75 \ in)(3.5 \ in)(44 \ lbs/ft^3)\left(\frac{1 ft}{12 in}\right)^2$$

$$= .802 \ lbs/ft$$

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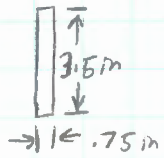
PRIMARY REFLECTOR DESIGN – CONT'D

$$I_4 = I_3 \frac{.75\text{ in}}{1.5\text{ in}}$$

$$I_4 = 3.29 \text{ in}^4$$



$$\delta_{max,\,1x4} = \frac{(\lambda_{P,\,1x4} + \lambda_{OSB})\left(\frac{L}{2}\right)^4}{8\,E\,I_4}$$

$$= \frac{(.802 + .313)\ \text{lbs/ft}\ \left(\frac{96\text{ in}}{2}\right)^4 \left(\frac{1\text{ ft}}{12\text{ in}}\right)}{8(1.16 \times 10^6\ \text{lbs/in}^2)(3.29\text{ in}^4)}$$

$$\delta_{max,\,1x4} = 0.0162 \text{ in} \approx 1/64 \text{ in}$$

NOTE: RESULTS DO NOT ACCOUNT FOR WEIGHT OF REFLECTIVE MAT'L

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23 APRIL 2015

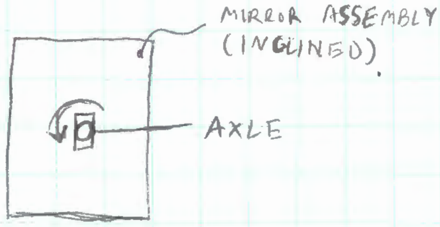
TRACKING MOTOR DESIGN / SELECTION

FIND: TORQUE REQUIRED TO ROTATE REFLECTOR IN WINTER SOLSTICE POSITION (WORST CASE) WITH AN ACCELERATION OF 1 RPM PER 2 SECONDS.

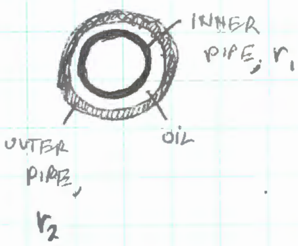
ASSUMPTIONS:

1. ~~FRICTION AT BEARINGS PRODUCES A TORQUE OF~~
2. μ FOR OILED SLEAVE BEARING IS ≈ 0.2
3. NEGLIGIBLE FRICTION AT LOWER BEARING

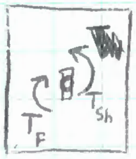
SCHEMATIC:

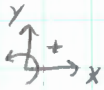


BEARING

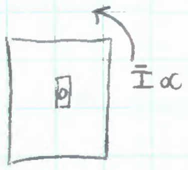


FBD





MAD



ANALYSIS

$$\sum T = \bar{I}\alpha$$

$$T_{sh} - T_F = \bar{I}\alpha$$

FIND T_F

$$T_F = T_{\text{top bearing}} + T_{\text{bottom bearing}} \rightarrow 0$$

$$T_F = \mu F_N r_1$$

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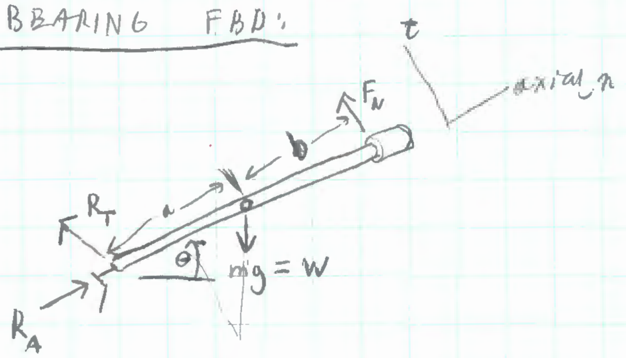
24 APRIL 2015 TRACKING MOTOR DESIGN/SELECTION – CONT'D

BEARING FBD:



$\Sigma F_n = 0$

$R_A \quad 0 = R_A - mg \sin\theta$

$R_A = mg \sin\theta$

$\Sigma F_t = 0$

$0 = R_t + F_N - mg\cos\theta$

$R_t = mg\cos\theta - F_N$

$\Sigma M_R \; (+) = 0$

$0 = -amg\cos\theta + F_N(a+b)$

$F_N = \dfrac{aW\cos\theta}{a+b}$

$F_N = \dfrac{a}{a+b} W\cos\theta$

SO,

$T_F = \mu r_i \dfrac{a}{a+b} W\cos\theta$

FIND α

~~$\alpha = \dfrac{1 \text{ RPM}}{2 \text{ sec}} \left(\dfrac{1 \text{ cycle}}{1 \text{ rev}}\right)\left(\dfrac{60 s}{1 \min}\right)$~~

$\alpha = \dfrac{1 \text{ REVOLUTION}/\text{min}}{2 \text{ SEC}} \left(\dfrac{2\pi \text{ rad}}{1 \text{ REV}}\right)\left(\dfrac{1 \min}{60 \text{ SEC}}\right)$

$\alpha = \dfrac{2\pi}{120} \text{ rad}/s^2$

$\alpha = 0.0524 \text{ rad}/s^2$

FIND T_{sh}

$T_{sh} - T_F = \bar{I}\alpha$

$T_{sh} = \bar{I}\alpha + T_F$

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TRACKING MOTOR SELECTION - CONT'D

$T_{sh} = \bar{I}\alpha + T_F$

$$T_{sh} = \bar{I}\alpha + \mu r_1 \frac{a}{a+b} W \cos\theta$$

~~$T_{sh} = ($~~

FOR CURRENT MODEL, AT WINTER SOLSTICE,

$\bar{I} = 77.37 \times 10^3 \ lb_m \, in^2$ ← DEPENDS ON SEASON

$r_1 = \frac{D_1}{2} = \frac{1.9 \, in}{2} = .95 \, in$

$a = b$

$W = 122 \ lb_f$

~~$\theta = 57°$~~ ~~← DEPENDS ON SEASON~~

$\theta = 34.6°$ ← DEPENDS ON LATITUDE

SO

$$T_{sh} = (77.37 \times 10^3 \ lb_m in^2)(0.0524 \ rad/s^2)\left(\frac{1 \ lb_f}{32.174 \ lb_m \ ft/s^2}\right)\left(\frac{1 \ ft}{12 \ in}\right) + (0.2)(0.95 \ in)\frac{a}{2a}(122 \ lb_f)\cos(34.6°)$$

$= 10.5 \ in \, lb_f + 9.54 \ in \, lb_f$

$$T_{sh} = 20.0 \ in \cdot lbf$$
$$T_{sh} = 1.67 \ ft \cdot lbf$$

NEXT: EXPLORE GEAR RATIOS?

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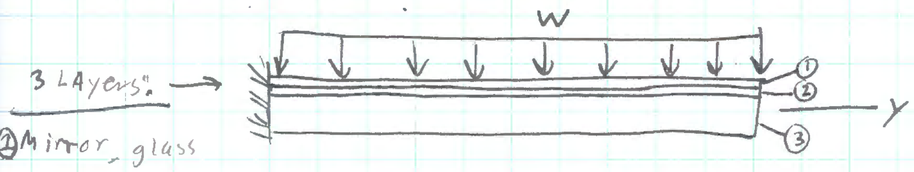
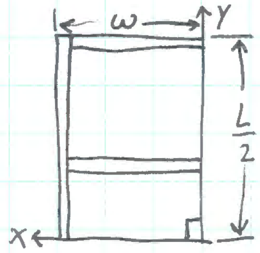
PRIMARY REFLECTOR DESIGN — CONT'D

CONTINUING USE OF SYMMETRY, USE THE FOLLOWING MODEL:





FIND λ_{mirror}

$$\lambda_{mirror} = A_c \, \rho_{mirror}$$

$$= h w \rho_{mirror}$$

$$= (.25 \text{ in})(24 \text{ in})(175 \text{ lbf/ft}^3)\left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^3$$

$$\lambda_{mirror} = .6076 \text{ lbf/in} \cdot \left(\frac{12 \text{ in}}{1 \text{ ft}}\right)$$

$$\lambda_{mirror} = 7.292 \text{ lbf/ft}$$

Find δ_{max} ~~and θ_{max}~~

$$\delta_{max} = \frac{w\left(\frac{L}{2}\right)^4}{8EI}$$

$$= \frac{(\lambda_{P,1\times4} + \lambda_{OSB} + \lambda_{mirror})\left(\frac{L}{2}\right)^4}{8 E I_4}$$

$$= \frac{(.804 + .313 + 7.292) \text{ lbf/ft} \left(\frac{96 \text{ in}}{2}\right)^4 \left(\frac{1 \text{ ft}}{12 \text{ in}}\right)}{8(1.16 \times 10^6 \text{ lbf/in}^2)(3.29 \text{ in}^4)}$$

$$\boxed{\delta_{max} = 0.122 \text{ in} \approx 1/8 \text{ in}}$$

Find θ_{max}

$$\theta_{max} = \frac{w\left(\frac{L}{2}\right)^3}{6EI}$$

$$\frac{6}{8}\left(\frac{L}{2}\right) \cdot \theta_{max} = \frac{w\left(\frac{L}{2}\right)^3}{6EI} \cdot \frac{6\left(\frac{L}{2}\right)}{8}$$

$$\frac{3}{8} L \, \theta_{max} = \frac{w\left(\frac{L}{2}\right)^4}{8EI}$$

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PRIMARY REFLECTOR DESIGN - CONT'D

$$\frac{3}{8} L\, \theta_{max} = \delta_{max}$$

$$\theta_{max} = \frac{8}{3L} \delta_{max}$$

$$= \frac{8}{3(96\,\text{in})} (.12183\,\text{in})$$

$$\theta_{max} = 0.00338\ \text{rad} \left(\frac{180^\circ}{\pi\ \text{rad}}\right)$$

$$\boxed{\theta_{max} = 0.194^\circ}$$

ASSUMES NO WIND LOADS

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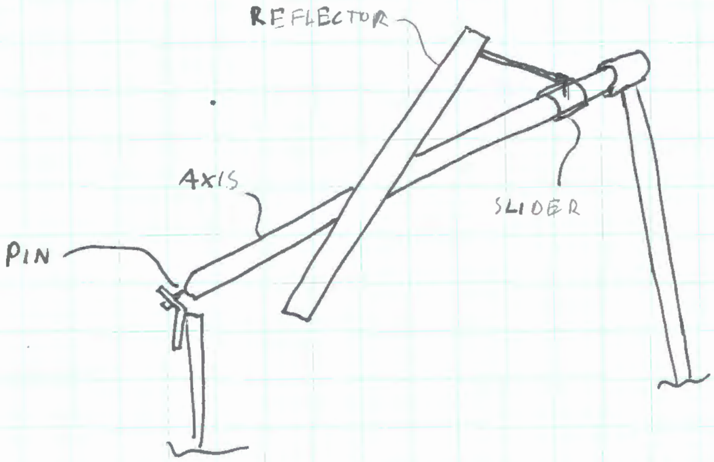
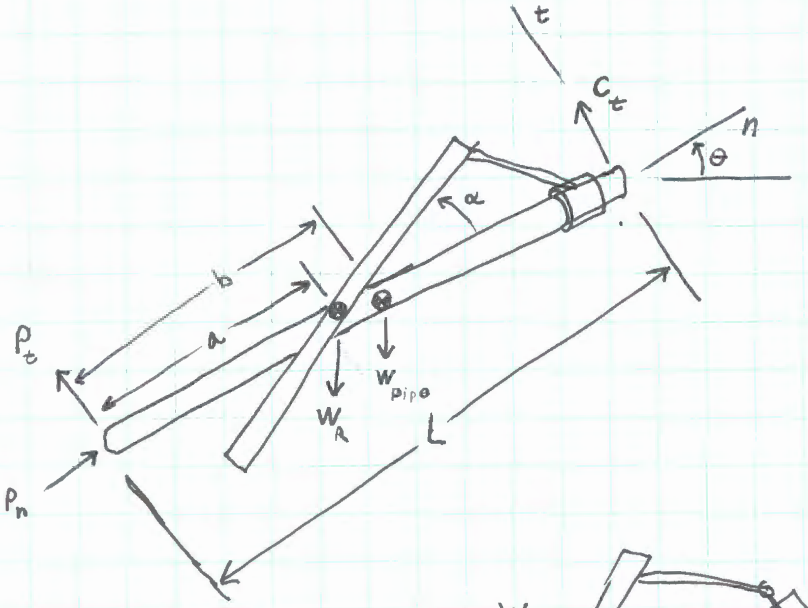
29 APRIL 2015

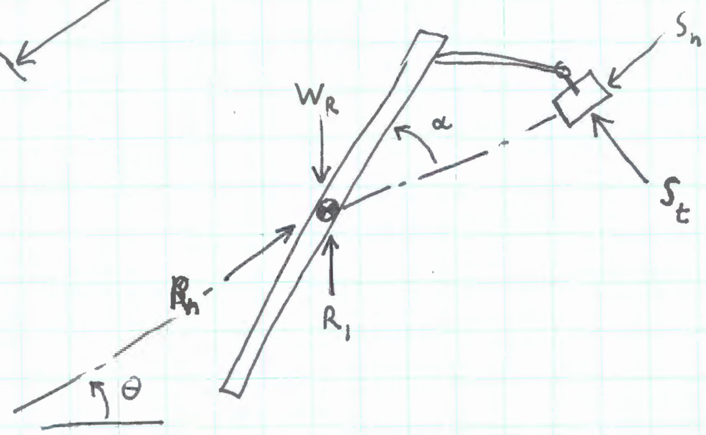
SCHEMATIC



FBDS



AXLE AND MIRROR



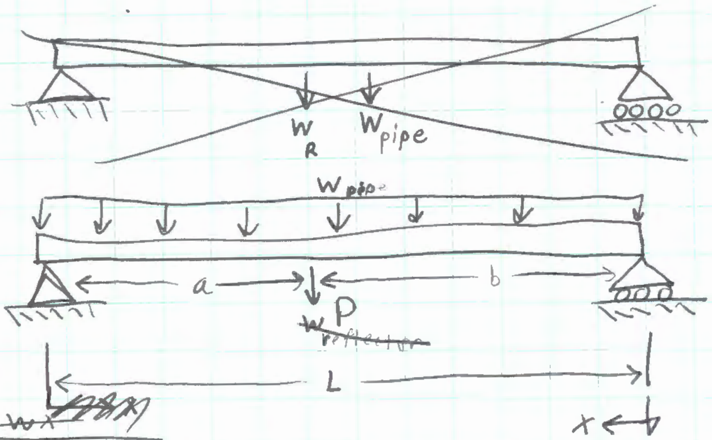
MIRROR AND SLIDER

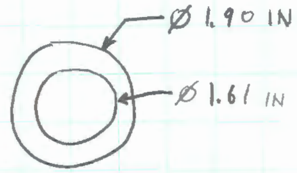
continued to page 67

continued from page 66

29 APRIL 2015

MODEL AXIS AS A SIMPLY SUPPORTED BEAM





~~$\delta = -\frac{w x (2 L ...)}{6 L E I}$~~

$$\delta = -\frac{w x}{24 E I}\left(L^3 - 2 L x^2 + x^3\right) - \frac{P b x}{6 L E I}\left(L^2 - b^2 - x^2\right)\Big|_{x=b}$$

$$= -\frac{w x}{24 E I}\left(L^3 - 2 b^2 L + b^3\right) - \frac{P b^2}{6 L E I}\left(L^2 - b^2 - b^2\right)$$

$$\delta = -\frac{w x}{24 E I}\left(L^3 - 2 b^2 L + b^3\right) - \frac{P a^2 b^2}{3 L E I}$$

USE:

$w = w_{pipe} = \rho_{pipe} A_c$

$L = 48\ in$

$\rho_{steel} = 500\ lbs/ft^3$

$a = b = 24\ in$

$E = 30 \times 10^6\ psi$

FIND I

$$I = \frac{\pi}{4}\left(r_o^4 - r_i^4\right) = \frac{\pi}{64}\left(D_o^4 - D_i^4\right) = \frac{\pi}{64}\left(1.90\ in^4 - 1.61\ in^4\right) = 0.3099\ in^4$$

FIND w_{pipe}

$$w_{pipe} = \rho_{pipe} A_c = \rho_{pipe} \frac{\pi}{4}\left(D_o^2 - D_i^2\right) = \frac{500\ lbs}{ft^3}\left(\frac{1\ ft}{12\ in}\right)^3\left(\frac{\pi}{4}\right)\left(1.90\ in^2 - 1.61\ in^2\right) = 0.2313\ lbs/in$$

continued to page 68

Signature Jason Davison Date 29 APRIL 2015

Witnessed And Understood By Date

PROPRIETARY INFORMATION

continued from page

24 APRIL 2015

FIND P

$$P = W_{Reflector} \cos\theta$$
$$= (85\ lb_f)\cos(34.6°)$$
$$P = 70.0\ lb_f$$

Find $\delta(x=b)$

$$\delta = -\frac{wb}{24EI}(L^3 - 2Lb^2 + b^3) - \frac{Pb^2}{6LEI}(L^2 - 2b^2)$$

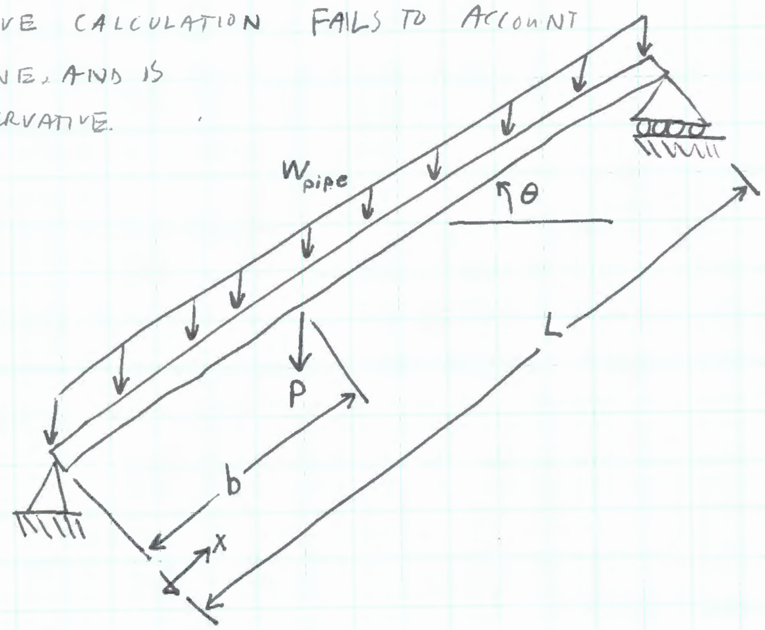
$$= -\frac{(.2313\ lbs/in)(24\ in)}{24(30\times10^6\ lbs/in^2)(.3099\ in^4)}\left[(48\ in)^3 - 2(48\ in)(24\ in)^2 + (24\ in)^3\right]$$

$$-\frac{(70.0\ lbs)(24\ in)^2}{6(48\ in)(30\times10^6\ lbs/in^2)(.3099\ in^4)}\left[(48\ in)^2 - 2(24\ in)^2\right]$$

$$= -1.720\times10^{-3}\ in - 17.339\times10^{-3}\ in$$

$$\boxed{\delta = -0.019\ in}$$

* NOTE: ABOVE CALCULATION FAILS TO ACCOUNT FOR INCLINE, AND IS THUS CONSERVATIVE.



$$|\delta| = -\frac{W_{pipe}\,x}{24EI}(L^3 - 2Lx^2 + x^3)\cos\theta - \frac{P_{\cos\theta}\,bx}{6LEI}(L^2 - b^2 - x^2)$$

continued to page

Signature [signature]

Date 24 APRIL 2015

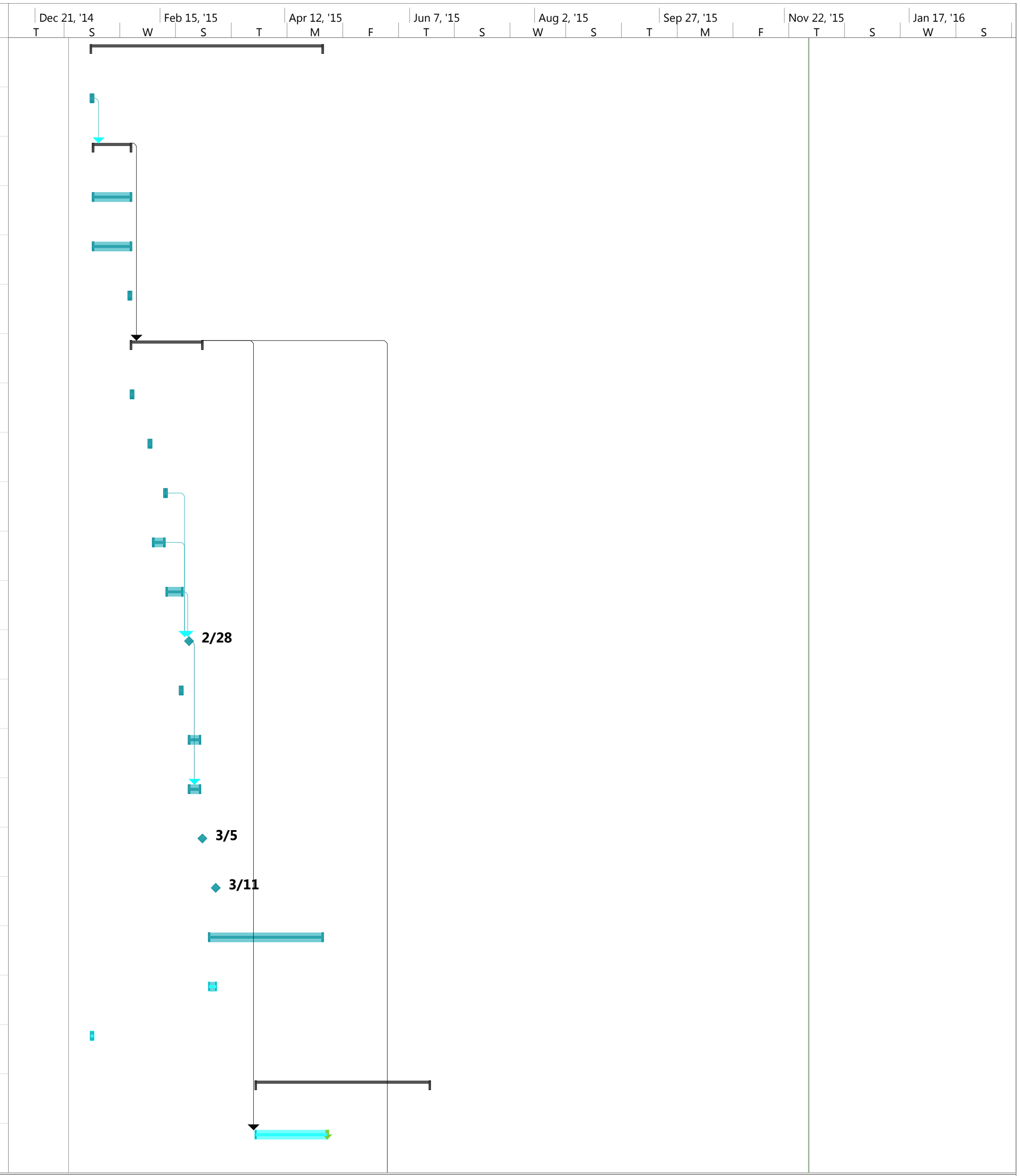
Witnessed And Understood By

Date

PROPRIETARY INFORMATION

Appendix H: Gantt Chart

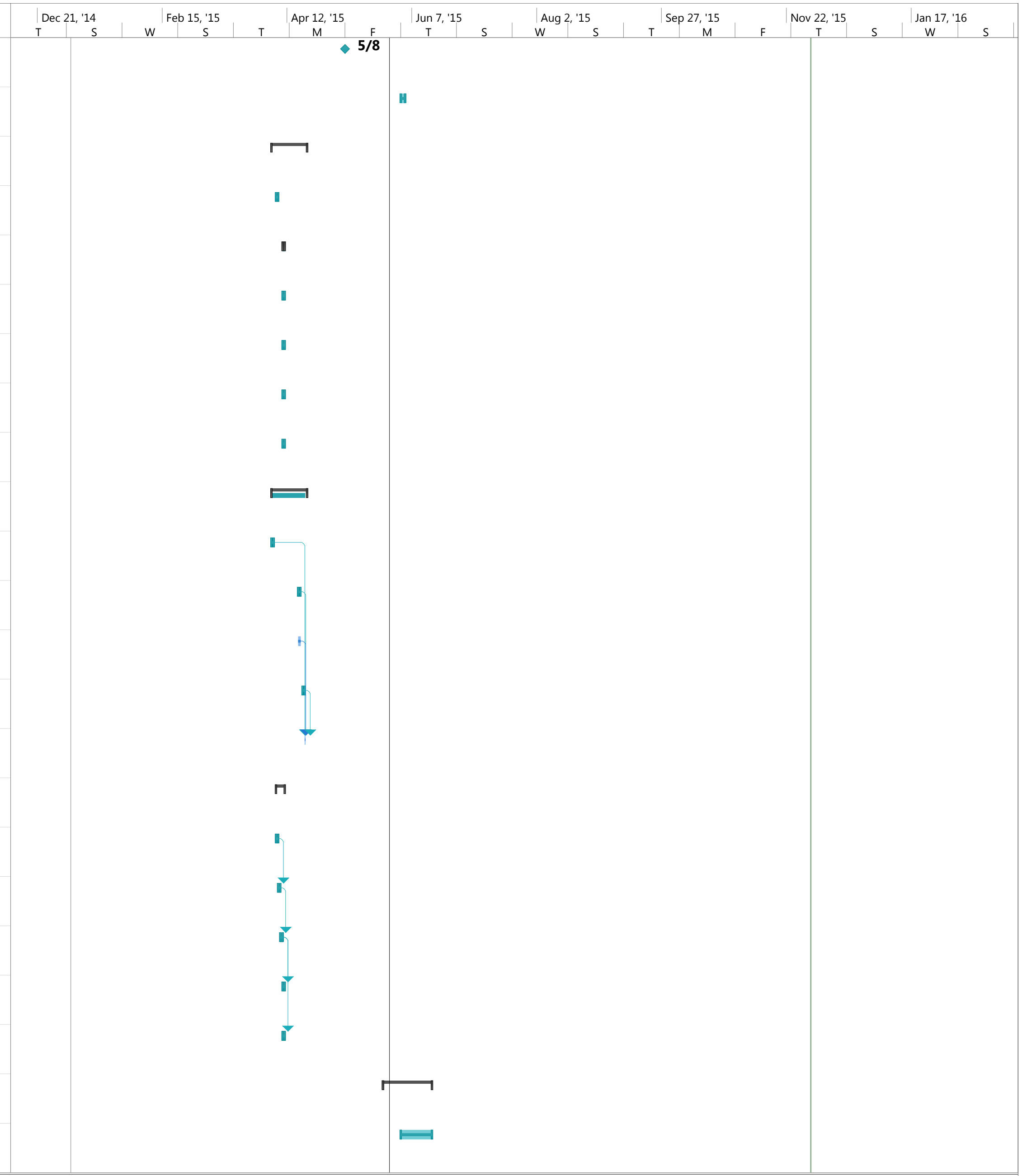
ID		Task Mode	Task Name	Duration	Start	Finish
1	✓		**WINTER**	**104 days**	**Thu 1/15/15**	**Wed 4/29/15**
2	✓		Letter of Introduction	3 hrs	Thu 1/15/15	Thu 1/15/15
3	✓		**Project Proposal**	**17 days**	**Fri 1/16/15**	**Mon 2/2/15**
4	✓		Background Research	17 days	Fri 1/16/15	Mon 2/2/15
5	✓		Patent Search	17 days	Fri 1/16/15	Mon 2/2/15
6	✓		Problem Definition	1 day	Sun 2/1/15	Mon 2/2/15
7	✓		**Preliminary Design Report**	**31.33 days**	**Mon 2/2/15**	**Thu 3/5/15**
8	✓		Brainstorming and Concept Ideation	1 day	Mon 2/2/15	Tue 2/3/15
9	✓		Prototyping Round 1	1 day	Tue 2/10/15	Wed 2/11/15
10	✓		Go No-Go Chart	1 day	Tue 2/17/15	Wed 2/18/15
11	✓		Pugh Matrix	5 days	Thu 2/12/15	Tue 2/17/15
12	✓		Decision Matrix	7 days	Wed 2/18/15	Wed 2/25/15
13	✓		Design Selection	0 days	Sat 2/28/15	Sat 2/28/15
14	✓		Gantt Chart	1 day	Tue 2/24/15	Wed 2/25/15
15	✓		Sketches of Top Concepts	5 days	Sat 2/28/15	Thu 3/5/15
16	✓		Preliminary 3D Model of Top Design	5 days	Sat 2/28/15	Thu 3/5/15
17	✓		Preliminary Design Review in Class	0 days	Thu 3/5/15	Thu 3/5/15
18	✓		Preliminary Design Review with Pete	0 days	Wed 3/11/15	Wed 3/11/15
19	✓		FMEA	51 days	Mon 3/9/15	Wed 4/29/15
20	✓		DV Planning	3 days	Mon 3/9/15	Thu 3/12/15
21	✓		Analysis Planning	1 day	Thu 1/15/15	Fri 1/16/15
22	✓		**SPRING**	**78 days**	**Mon 3/30/15**	**Tue 6/16/15**
23	✓		Critical Design Report	32 days	Mon 3/30/15	Fri 5/1/15



Project: Team Helios Gantt
Date: Thu 12/3/15

Task	Project Summary	Manual Task	Start-only	Deadline	
Split	Inactive Task	Duration-only	Finish-only	Progress	
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress	
Summary	Inactive Summary	Manual Summary	External Milestone		

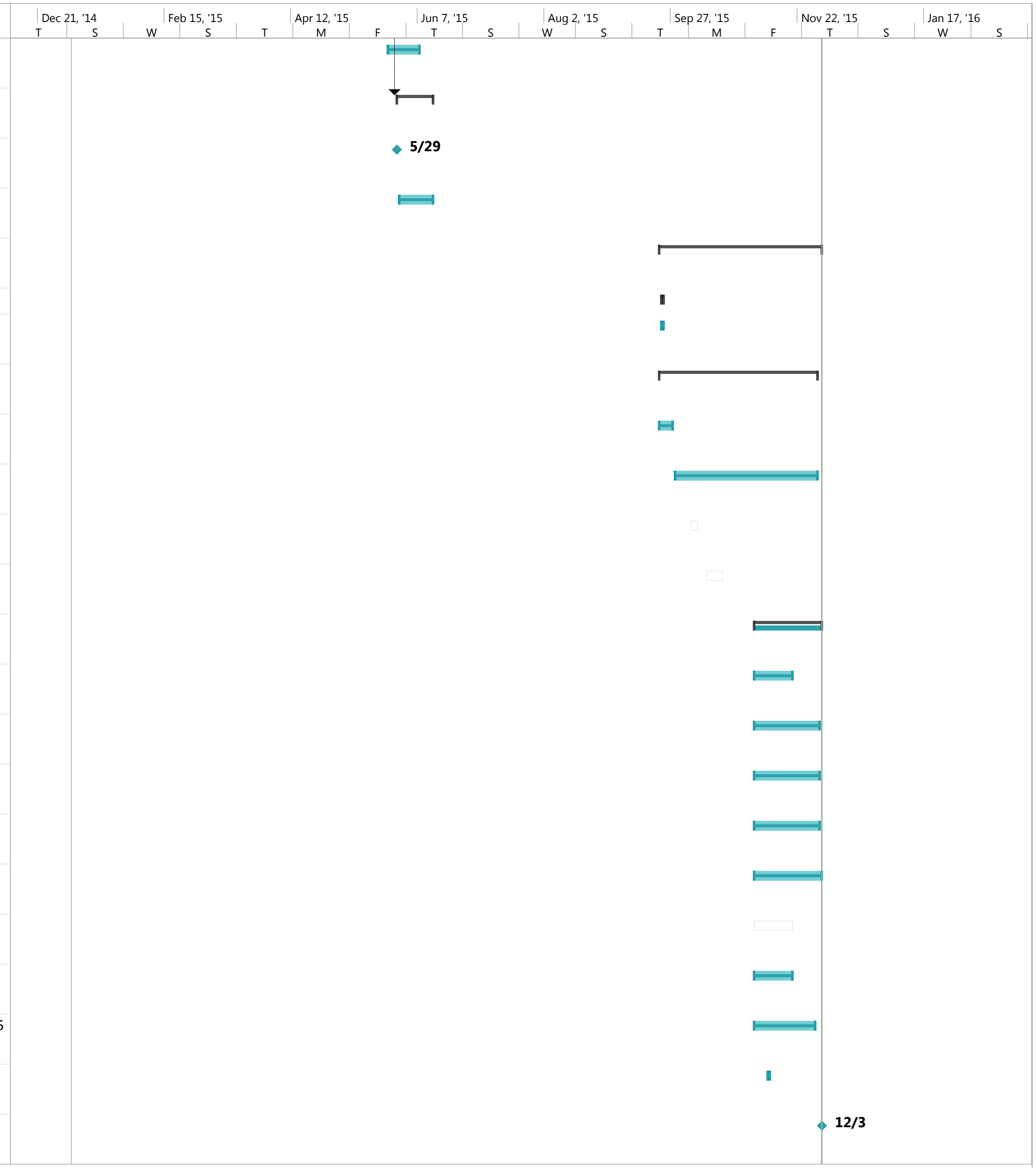
ID		Task Mode	Task Name	Duration	Start	Finish
24	✓		Critical Design Review with Pete	0 days	Fri 5/8/15	Fri 5/8/15
25	✓		Progress Report	2 days	Tue 6/2/15	Thu 6/4/15
26	✓		**Prototyping**	**16 days**	**Sun 4/5/15**	**Tue 4/21/15**
27	✓		Choose build style(s)	3 hrs	Tue 4/7/15	Tue 4/7/15
28	✓		**Component drawings**	**1 day**	**Fri 4/10/15**	**Sat 4/11/15**
29	✓		Dish sweep template	1 hr	Fri 4/10/15	Fri 4/10/15
30	✓		Wooden lath	0.5 hrs	Fri 4/10/15	Fri 4/10/15
31	✓		Reflective surface section patterns	1 hr	Fri 4/10/15	Fri 4/10/15
32	✓		Sweep Jig	2.5 hrs	Fri 4/10/15	Fri 4/10/15
33	✓		**Fabrication**	**16 days**	**Sun 4/5/15**	**Tue 4/21/15**
34	✓		Dish sweep template	2 hrs	Sun 4/5/15	Sun 4/5/15
35	✓		Wooden lath	1 hr	Fri 4/17/15	Fri 4/17/15
36	✓		Reflective surface section patterns	2 hrs	Fri 4/17/15	Fri 4/17/15
37	✓		Sweep Jig	1.5 hrs	Sun 4/19/15	Sun 4/19/15
38	✓		Assembly	1 hr	Sun 4/19/15	Sun 4/19/15
39	✓		**Analysis**	**4 days**	**Tue 4/7/15**	**Sat 4/11/15**
40	✓		Power delivered (working backward)	1 day	Tue 4/7/15	Wed 4/8/15
41	✓		Concentrator Size	1 day	Wed 4/8/15	Thu 4/9/15
42	✓		Reflector Size	1 day	Thu 4/9/15	Fri 4/10/15
43	✓		Axis Bending	1 day	Fri 4/10/15	Sat 4/11/15
44	✓		Motor Torque/Speed	1 day	Fri 4/10/15	Sat 4/11/15
45	✓		**Drawings**	**22 days**	**Mon 5/25/15**	**Tue 6/16/15**
46	✓		Concentrator Assembly	2 wks	Tue 6/2/15	Tue 6/16/15



Project: Team Helios Gantt
Date: Thu 12/3/15

Task	Project Summary	Manual Task	Start-only	Deadline
Split	Inactive Task	Duration-only	Finish-only	Progress
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress
Summary	Inactive Summary	Manual Summary	External Milestone	

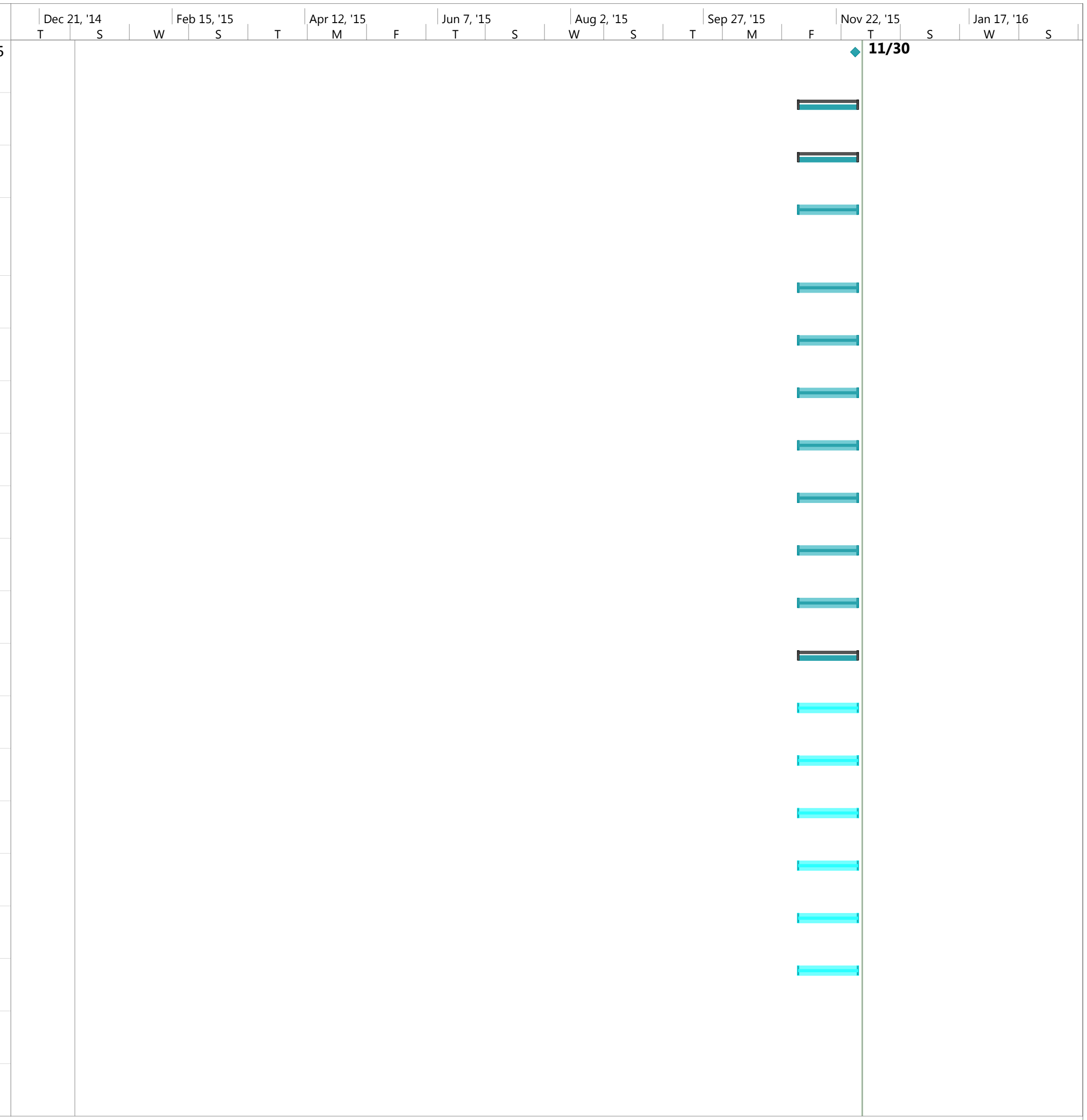
ID	Task Mode	Task Name	Duration	Start	Finish
47		Frame Assembly	2 wks	Mon 5/25/15	Mon 6/8/15
48		**Construction**	**16 days**	**Fri 5/29/15**	**Sun 6/14/15**
49		Purchase Parts	0 days	Fri 5/29/15	Fri 5/29/15
50		Manufacturing	15 days	Sat 5/30/15	Sun 6/14/15
51		**FALL**	**72 days**	**Tue 9/22/15**	**Thu 12/3/15**
52		**Analysis**	**1 day**	**Wed 9/23/15**	**Thu 9/24/15**
53		Tracking circuit	1 day	Wed 9/23/15	Thu 9/24/15
54		**Construction**	**70 days**	**Tue 9/22/15**	**Tue 12/1/15**
55		Heliostat: prototype	6 days	Tue 9/22/15	Mon 9/28/15
56		Heliostat: full scale	63 days	Tue 9/29/15	Tue 12/1/15
57		~~Concentrator: prototype~~	~~3 days~~	~~Tue 10/6/15~~	~~Fri 10/9/15~~
58		~~Concentrator: full scale~~	~~7 days~~	~~Tue 10/13/15~~	~~Tue 10/20/15~~
59		**Product Testing**	**30 days**	**Tue 11/3/15**	**Thu 12/3/15**
60		Wind Speed while Operable	17 days	Tue 11/3/15	Fri 11/20/15
61		Static Heat Spot	29 days	Tue 11/3/15	Wed 12/2/15
62		Daily Maintenance	29 days	Tue 11/3/15	Wed 12/2/15
63		Setup Time	29 days	Tue 11/3/15	Wed 12/2/15
64		Maximum power to cooking surface	30 days	Tue 11/3/15	Thu 12/3/15
65		~~Water Boiling Test~~	~~17 days~~	~~Tue 11/3/15~~	~~Fri 11/20/15~~
66		Ray Tracing	17 days	Tue 11/3/15	Fri 11/20/15
67		Maximum Input Force	27 days	Tue 11/3/15	Mon 11/30/15
68		Product Analysis	1 day	Mon 11/9/15	Tue 11/10/15
69		**Project Expo**	**0 days**	**Thu 12/3/15**	**Thu 12/3/15**



Project: Team Helios Gantt
Date: Thu 12/3/15

Task	Project Summary	Manual Task	Start-only
Split	Inactive Task	Duration-only	Finish-only
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks
Summary	Inactive Summary	Manual Summary	External Milestone
Deadline	Progress	Manual Progress	

ID	Task Mode	Task Name	Duration	Start	Finish
70		Print Poster	0 days	Mon 11/30/15	Mon 11/30/15
71		**Final Design Report**	**25 days**	**Fri 11/6/15**	**Tue 12/1/15**
72		**Report Sections**	**25 days**	**Fri 11/6/15**	**Tue 12/1/15**
73		Title Page, Table of Contents, List of tables, figures, nomenclature, Executive Summary	25 days	Fri 11/6/15	Tue 12/1/15
74		Introduction	25 days	Fri 11/6/15	Tue 12/1/15
75		Background	25 days	Fri 11/6/15	Tue 12/1/15
76		Design Development	25 days	Fri 11/6/15	Tue 12/1/15
77		Design Specifications	25 days	Fri 11/6/15	Tue 12/1/15
78		Product Realization	25 days	Fri 11/6/15	Tue 12/1/15
79		Testing	25 days	Fri 11/6/15	Tue 12/1/15
80		Conclusions	25 days	Fri 11/6/15	Tue 12/1/15
81		**Appendices**	**25 days**	**Fri 11/6/15**	**Tue 12/1/15**
82		QFD, Decision matrices	25 days	Fri 11/6/15	Tue 12/1/15
83		Final Drawings	25 days	Fri 11/6/15	Tue 12/1/15
84		List of Vendors	25 days	Fri 11/6/15	Tue 12/1/15
85		Vendor Data Sheets	25 days	Fri 11/6/15	Tue 12/1/15
86		Detailed Analysis	25 days	Fri 11/6/15	Tue 12/1/15
87		Gantt Chart	25 days	Fri 11/6/15	Tue 12/1/15
88		Print and bind sponsor and advisor copies			
89		Upload PDF to library, obtain receipt			



Project: Team Helios Gantt
Date: Thu 12/3/15

Task	Project Summary	Manual Task	Start-only	Deadline	
Split	Inactive Task	Duration-only	Finish-only	Progress	
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress	
Summary	Inactive Summary	Manual Summary	External Milestone		

Appendix I: Potential Failure Modes and Effects Analysis

Potential
Failure Mode and Effect Analysis
(Design FMEA)

FMEA Number:

System: Concentrator
Subsystem: Frame
Component: -

Design Responsibility: Ian Davison

Prepared By (Orig.): Ian Davison
FMEA Date (Orig.) 3/11/2015
Revised By: Ian Davison
Revision Date: 12/2/2015 **(Rev.)** A

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
Maintain proper shape for reflective material	Shape change	Efficiency drop	3	Thermal warping	3	9	None	-				0
			3	Warping under the weight of collected rainwater	7	21	Integrate drainage holes in concentrator	I. Davison 5 Oct. 2015				0
		Focal point translation	2	Thermal warping	3	6	None	-				0
			2	Warping under the weight of collected rainwater	6	12	Integrate drainage holes in concentrator	I. Davison 5 Oct. 2015	None	2	6	12
Prevent rigid body motion of concentrator	Rigid body motion	Efficiency drop	3	Foundation settling	4	12	Add a feature to allow for calibration of the frame position relative to the foundation	I. Davison 5 Oct. 2015	None	3	4	12
			3	Frame corrosion	3	9	Paint frame	I. Davison 5 Oct. 2015	Non-corrosive material selected for frame	3	2	6
		Focal point translation	2	Foundation settling	7	14	Add a feature to allow for calibration of the frame position relative to the foundation	I. Davison 5 Oct. 2015	None	2	7	14
			2	Frame corrosion	2	4	Paint frame	I. Davison 5 Oct. 2015	Non-corrosive material selected for frame	2	1	2
		Optical system alignment failure	7	Frame picked up by wind	5	35	Design braces for high wind scenarios	I. Davison 5 Oct. 2015	Frame to be installed in-ground	7	2	14
						0						0

Potential
Failure Mode and Effect Analysis
(Design FMEA)

FMEA Number:

System: Concentrator
Subsystem: Concentrator Surface
Component:

Design Responsibility: Ian Davison

Prepared By (Orig.): Ian Davison
FMEA Date (Orig.) 3/11/2015
Revised By: Ian Davison
Revision Date: 12/2/2015 **(Rev.)** A

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occur	Crit
Focus sunlight	Warping	Focal point translation	2	Water weight	7	14	Integrate drainage holes in concentrator surface	I. Davison 5 Oct. 2015	None	2	7	14
			2	Material contraction	7	14	Choose material with low coeficient of thermal expansion	I. Davison 29 Oct. 2015	None	2	7	14
			1	Thermal deformation	10	10	Choose material with low coeficient of thermal expansion	I. Davison 29 Oct. 2015	None	1	10	10
		Efficiency Drop	3	Water weight	7	21	Integrate drainage holes in concentrator surface	I. Davison 5 Oct. 2015	None	3	7	21
			3	Material contraction	6	18	Choose material with low coeficient of thermal expansion	I. Davison 29 Oct. 2015	None	3	6	18
			3	Thermal deformation	6	18	Choose material with low coeficient of thermal expansion	I. Davison 29 Oct. 2015	None	3	6	18
	Wrong shape	Low efficiency	6	Improper construction	9	54	Experiment with different construction techniques to learn most accurate methods. Consult a manufacturing engineer.	I. Davison 30 May 2015	Experimented with multiple construction techniques and selected the most reliable	6	7	42
Reflect sunlight (surface finish)	Scratched surface	Low efficiency	5	Wind-blown debris, dust	8	40	Advise users to protect surface when not in use	I. Davison 5 Oct. 2015	Covered surface when not in use	5	4	20
			5	Animal intrusion	6	30	Advise users to protect surface when not in use	I. Davison 5 Oct. 2015	Covered surface when not in use	5	4	20
	Dirty surface	Low efficiency	6	Wind-blown debris, dust	10	60	Recommend regular cleaning	I. Davison 5 Oct. 2015	Wiped down surface as needed	6	5	30
			4	Bird poop	9	36	Recommend regular cleaning	I. Davison 5 Oct. 2015	None. Bird poop likelihood observed to be very low	4	1	4
Safeguard user	Allow user to come to harm	Burn someone	9	Inadeqaute safeguards	8	72	None	I. Davison 1 Dec. 2015	Maximum power is physically not high enough to cause burns	9	3	27
		Blind someone	9	Inadeqaute safeguards	8	72	Require eye protection while in operation	I. Davison 23 Nov. 2015	Sunglasses required of those nearby during operation	9	3	27
						0						0

Potential
Failure Mode and Effect Analysis
(Design FMEA)

FMEA Number:

System: Primary Reflector
Subsystem: Frame
Component: -

Design Responsibility: Devin Mast

Prepared By (Orig.): Ian Davison
FMEA Date (Orig.) 3/11/2015
Revised By: Ian Davison
Revision Date: 12/2/2015 **(Rev.)** A

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occur	Crit
Support Reflector	Bolt failure	Cracked/broken reflector	8	Strong wind loads	2	16	Confirm bolt size provides FS of 2 for worst case wind load	D. Mast 5 Oct. 2015	Analysis confirms FS of at least 2 for worst case loading	8	1	8
			8	Fatigue	4	32	Upsize bolts	D. Mast 5 Oct. 2015	Bolts upsized	8	1	8
Seasonal Adjustment	Improperly calibrated	Improper focus	6	User error	7	42	Etch approximate seasonal slider placement into rotating pipe	D. Mast 5 Oct. 2016	None	6	7	42
			5	Adjustment creep	5	25	Incorporate additional locking feature	D. Mast 5 Oct. 2015	Recommend daily check for proper seasonal positioning	5	1	5
Maintain rotation axis parallel to Earth's	Rigid body translation	Low efficiency	5	Ground shifting	3	15	Build on a foundation	D. Mast 5 Oct. 2015	Reflector frame will be installed in-ground	5	1	5
	Warping of frame	Low efficiency	1	Thermal deformation	10	10	Select material with low coefficient of thermal	D. Mast 22 Oct. 2015	None	1	10	10
Safeguard user	Allow user to come to harm	Pinch user	8	Unguarded pinch point	7	56	Paint pinch points red	D. Mast 2 Dec. 2015	Joints designed to minimize pinch severity and likelihood	6	5	30
						0						0

Potential
Failure Mode and Effect Analysis
(Design FMEA)

FMEA Number:

System: Primary Reflector
Subsystem: Reflector
Component: -

Design Responsibility: Devin Mast

Prepared By (Orig.): Ian Davison
FMEA Date (Orig.) 3/11/2015
Revised By: Ian Davison
Revision Date: 12/2/2015 **(Rev.)** A

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
Reflect sunlight parallel to earth axis	Anti-planar deformation	Low efficiency	5	Impact to frame	7	35	Improve frame rigidity	D. Mast 5 Oct. 2015	Frame reinforced	5	4	20
			4	Deformation under its own weight	6	24	Improve frame rigidity	D. Mast 5 Oct. 2015	Frame reinforced	4	3	12
			5	Strong wind loads	9	45	Improve frame rigidity	D. Mast 5 Oct. 2015	Frame reinforced	5	7	35
			2	Thermal warping	10	20	Select material with lower coefficient of thermal expansion	D. Mast 5 Oct. 2015	None	2	10	20
	Scratched surface	Low efficiency	5	Wind-blown debris, dust	8	40	Advise users to protect surface when not in use	D. Mast 5 Oct. 2015	Users advised to cover surface when not in use	5	5	25
			5	Animal intrusion	6	30	Advise users to protect surface when not in use	D. Mast 5 Oct. 2015	Animal intrusion determined to be unlikely	5	2	10
	Dirty surface	Low efficiency	6	Wind-blown debris, dust	10	60	Advise users to protect surface when not in use	D. Mast 5 Oct. 2015	Users advised to cover surface when not in use	6	5	30
			4	Bird poop	9	36	Recommend regular cleaning	D. Mast 5 Oct. 2015	None. Bird poop likelihood observed to be very low	4	1	4
						0						0

Potential
Failure Mode and Effect Analysis
(Design FMEA)

FMEA Number:

System: Primary Reflector
Subsystem: Daily Tracking System
Component: Electric Circuit

Design Responsibility: Devin Mast

Prepared By (Orig.): Ian Davison
FMEA Date (Orig.) 3/10/2015
Revised By: Ian Davison
Revision Date: 12/2/2015 **(Rev.)** A

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occur	Crit
Motor	Short Circuit	Overheating	5	Water intrusion	4	20	Shield motor from condensate	D. Mast 5 Oct. 2015				0
			4	Loose wiring	4	16	Use manufacturer specified crimps	D. Mast 5 Oct. 2016				0
			4	Insulation degradation	5	20	Tie down cables and wires away from moving parts	D. Mast 5 Oct. 2017				0
		Spark	5	Loose wiring	4	20	Use manufacturer specified crimps	D. Mast 5 Oct. 2018				0
			5	Insulation degradation	5	25	Tie down cables and wires away from moving parts	D. Mast 5 Oct. 2019				0
		Tracking stops	7	Water intrusion	4	28	Enclose motor assembly	D. Mast 5 Oct. 2020				0
			7	Loose wiring	4	28	Use manufacturer specified crimps	D. Mast 5 Oct. 2021				0
			7	Insulation degradation	5	35	Tie down cables and wires away from moving parts	D. Mast 5 Oct. 2022				0
	Open Circuit	Tracking Stops	7	Loose wiring	4	28	Use manufacturer specified crimps	D. Mast 5 Oct. 2023				0
			7	Corrosion	3	21	Enclose motor assembly	D. Mast 5 Oct. 2024				0
Battery	Open Circuit	Tracking stops	7	Loose wiring	4	28	Use manufacturer specified crimps	D. Mast 5 Oct. 2025				0
			7	Corrosion	3	21	Enclose motor assembly	D. Mast 5 Oct. 2026				0
	Short Circuit	Tracking stops	7	Water intrusion	2	14	Enclose battery	D. Mast 5 Oct. 2027				0
			7	Loose wiring	3	21	Use manufacturer specified crimps	D. Mast 5 Oct. 2028				0
		Chemical Leak	8	Water intrusion	2	16	Enclose battery	D. Mast 5 Oct. 2029				0

Potential

Failure Mode and Effect Analysis

(Design FMEA)

FMEA Number:

System: Primary Reflector
Subsystem: Daily Tracking System
Component: Electric Circuit

Design Responsibility: Devin Mast

Prepared By (Orig.): Ian Davison
FMEA Date (Orig.) 3/10/2015
Revised By: Ian Davison
Revision Date: 12/2/2015 **(Rev.)** A

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occur	Crit
		Chemical Leak	8	Loose wiring	2	16	Use manufacturer specified crimps	D. Mast 5 Oct. 2030				0
	Low voltage	Tracking stops	7	Battery aging	3	21	None					0
	Spring Fracture	Inconsistent tracking	6	Excessive cycling	1	6	None					0
Drive train	Spring Set	Inconsistent tracking	6	Excessive pre-load	3	18	Specify maximum pre-load	D. Mast 5 Oct. 2015	Spring selected operates well within possible loading scenarios	6	1	6
			6	Excessive cycling	1	6	Advise against unecessary cycling	D. Mast 5 Oct. 2015	Condemn uneccessary cycling	6	1	6
	String breaks	Heliostat swings freely	7	Weathering	6	42	Protect string from weathering	D. Mast 5 Oct. 2015	Recommend regular string replacement	7	2	14
			7	Mechanical wear	8	56	Choose a more wear-resistant string	D. Mast 5 Oct. 2015	Recommend regular string replacement	7	2	14
	Slip	Inconsistent tracking	6	Mechanical wear	7	42	Choose a more wear-resistant string	D. Mast 5 Oct. 2015	Recommend regular string replacement	7	2	14
Photovoltaic panel	Open circuit	Battery does not charge	7	Loose wiring	4	28	Use manufacturer specified crimps	D. Mast 5 Oct. 2015	Solder connection points	7	3	21
			7	Impact	4	28	Install photovoltaic cell away from impact zones	D. Mast 5 Oct. 2015	None	7	4	28
			7	Corrosion	3	21	Protect connections from weathering	D. Mast 5 Oct. 2015	Weatherproof connections	7	2	14
	Low voltage	Battery does not charge	7	Faulty panel	2	14	Choose panel with high reliability ratings	D. Mast 27 Oct. 2015	None	7	2	14
Safeguard user	Harm user	Electric shock	8	Loose wiring	2	16	Specify careful insulation measures	D. Mast 5 Oct. 2015	None	8	2	16
						0						0

Severity

1	Negligible (No discernible effect)
2	Inconvenience/annoyance (No functional issues)
3	Issue (Functionality decreased, but still useable)
4	How bad is it?
5	How bad is it?
6	Significant function degredation
7	Loss of major function, no injury
8	Total loss of major function, minor injury
9	Critical. Total loss of major function, serious injury
10	Death/sever injury. Catastrophic failure

Occurrence

1	Extremely remote	0.00001%
2		0.001%
3		0.01%
4	Remote	0.1%
5	Unlikely	
6	Unlikely	
7	Possible	1%
8		5%
9	Probable	10%
10	Will occur	100%

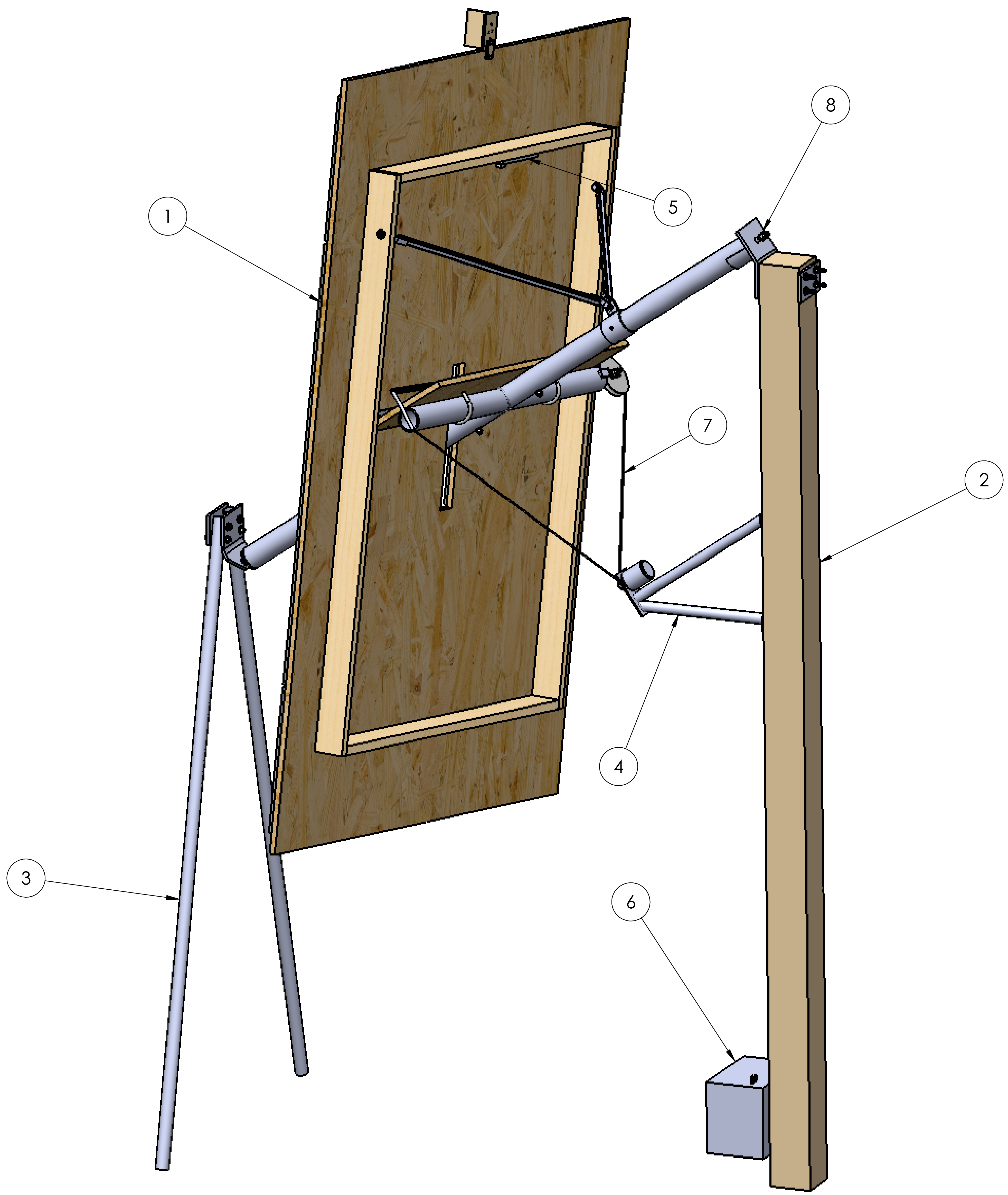
Appendix J: Technical Drawings

FULL BOM

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R051	REAR UPRIGHT ASSEMBLY	1
1.1	R101	REAR UPRIGHT POST	1
1.2	R011	TOP BENT STEEL PLATE WITH PIPE FITTING	1
1.2.1	T001	TOP BENT STEEL PLATE	1
1.2.2	T002	HALF PIPE	1
1.3	R009	SUPPORT BRACKET PLATE	1
1.4	N/A	WASHER FOR .25 INCH	8
1.5	N/A	1/4-20 NUT	4
1.6	91286A128	1/4-20 X 5 STEEL BOLT	4
2	R200	FRONT UPRIGHT ASSEMBLY	1
2.1	R010	BOTTOM BRACKET PLATE	1
2.2	R007	1.5 STEEL PIPE LEG	2
2.3	R008	BOTTOM BENT STEEL PLATE	1
2.4	N/A	WASHER FOR .25 INCH	10
2.5	N/A	1/4-20 NUT	5
2.6	91286A128	1/4-20 X 2 STEEL BOLT	4
2.7	R012	MILLED PIVOT BOLT	1
3	R500	TRACKING STAGE ASSEMBLY	1
3.1	R001	1.5" STEEL ROTATING PIPE	1
3.2	R004	PLYWOOD SUPPORT FOR HINGE	1
3.3	R034	PIANO HINGE	2
3.4	R013	MIRROR ASSEMBLY	1
3.4.1	M001	PLYWOOD BACKING	1
3.4.2	M002	PLANE MIRROR	4
3.4.3	M004	1X3 BOARD HORIZONTAL	2
3.4.4	M005L	1X3 BOARD SHORT, LEFT SIDE	1
3.4.5	M005R	1X3 BOARD TALL, RIGHT SIDE	1
3.4.6	90130A012	RUBBER SEALING WASHER	12
3.4.7	R036	FENDER WASHER	12
3.4.8	N/A	1/4-20 X 1.5 HEX CAP BOLT	2
3.4.9	N/A	WASHER FOR .25 INCH	6
3.4.10	N/A	1/4-20 NYLON LOCK NUT	2
3.4.11	N/A	#6 X 3/4 WOOD SCREW	40
3.4.12	M003	HALF SIZE PLANE MIRROR	1
3.5	R015	SEASONAL ADJUSTMENT SLIDER PIPE	1
3.5.1	SP001	SLIDER PIPE	1
3.6	3201T54	PIPE CLAMP	2
3.7	R903	SUPPORT STRUT	2
3.8	91375A532	1/4-20 x .125 SETSCREW	2
3.9	R902	SLIDER PIN	1
3.10	R800	PHOTOCOMPARATOR ASSEMBLY	1
3.10.1	P001	PHOTOCOMPARATOR BASE	1
3.10.2	P002	PHOTOCOMPARATOR DIVIDER	1
3.10.3	N/A	PHOTORESISTOR	2
3.10.4	P004	CONNECTOR BRACKET	1
3.10.5	N/A	#4-40 X .19 WOOD SCREW	6
3.11	R901	PULLEY	1
3.12	9640K151	EXTENSION SPRING	1
3.13	91286A128	1/4-20 X 3 STEEL BOLT	2
3.14	N/A	3/8"-16 X 2 CAP SCREW	1
3.15	N/A	1/4-20 NUT	2
3.16	N/A	WASHER FOR .25 INCH	4
3.17	N/A	1/4-20 X 1.5 HEX CAP BOLT	1
3.18	N/A	1/4-20 NYLON LOCK NUT	1
4	N/A	3/8"-16 LOCKNUT	1
5	M400	MOTOR MOUNT ASSEMBLY	1
5.1	a12032000ux0190	12V DC 5 RPM GEARMOTOR	1
5.2	R020	MOTOR MOUNT	1
5.3	M503	MOTOR PULLEY	1
5.4	91400A170	#6-40 X .25 STEEL SCREW	1
5.5	91735A102	#4-40 X .25 MACHINE SCREW	3
7	N/A	#6 X 3/4 WOOD SCREW	4
8	R700	TRACKING CIRCUIT	1
9	R750	BATTERY	1
10	S001	STRING	1

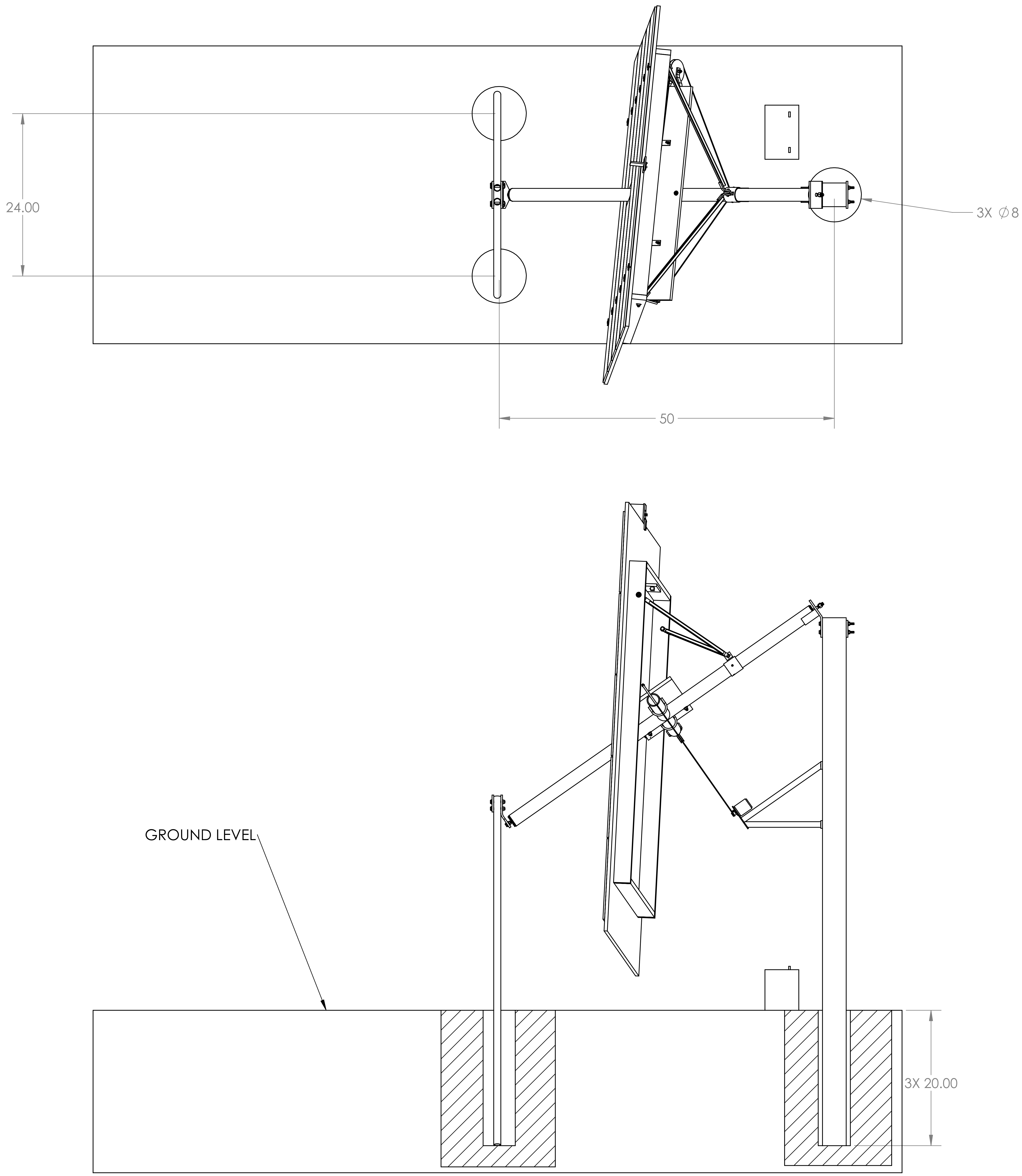
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

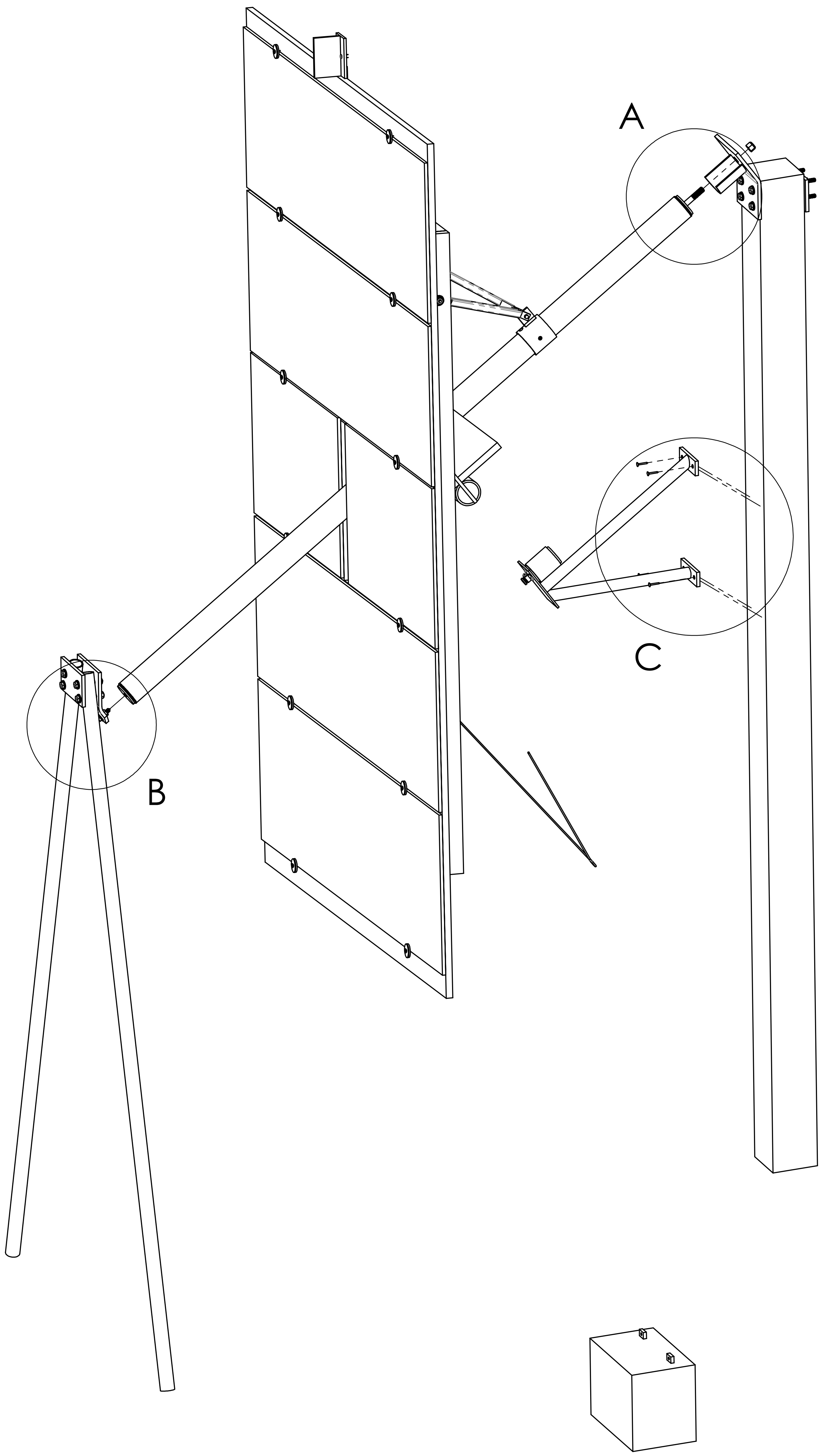


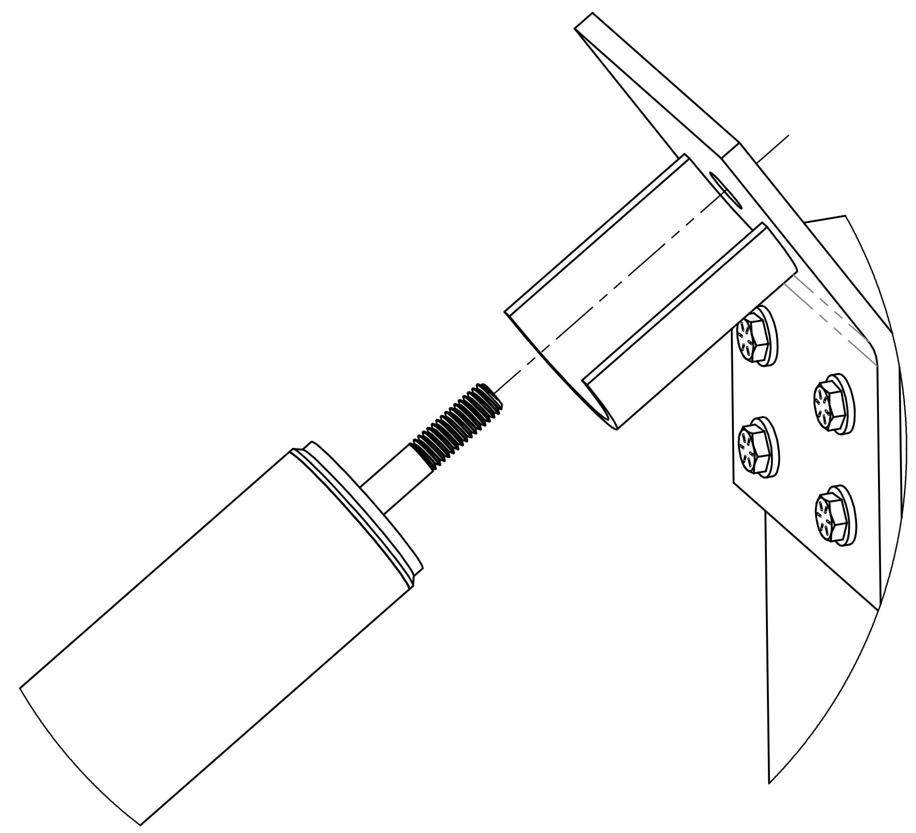
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R500	TRACKING STAGE ASSEMBLY	1
2	R051	REAR UPRIGHT ASSEMBLY	1
3	R200	FRONT UPRIGHT ASSEMBLY	1
4	M400	MOTOR MOUNT ASSEMBLY	1
5	R700	TRACKING CIRCUIT	1
6	R750	BATTERY	1
7	S001	STRING	1
8	N/A	3/8"-16 LOCKNUT	1
9	N/A	#6 X 3/4 WOOD SCREW	4

Lab Section: 03	SHEET 2 of 5	Title: REFLECTOR ASSEMBLY		Drwn. By: DEVIN MAST
Dwg. #: R000	Nxt Asb: N/A	Date: 12/03/15	Scale: 1:8	Chkd. By: I. DAVISON

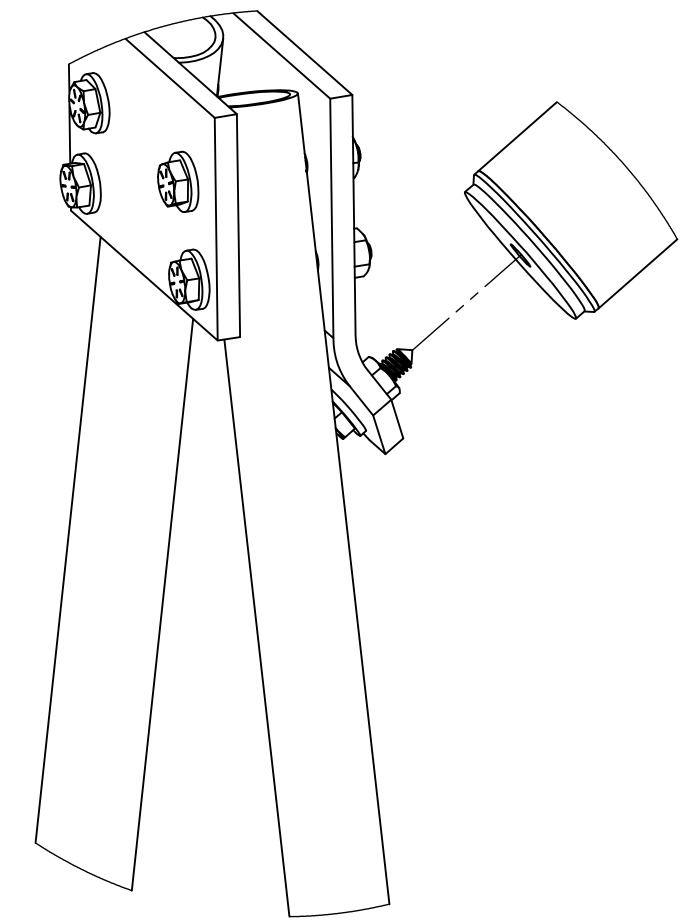


Lab Section:03	SHEET 3 of 5	Title: REFLECTOR ASSEMBLY		Drwn. By: I. DAVISON
Dwg. #: R000	Nxt Asb: N/A	Date: 12/8/2015	Scale: 1:12	Chkd. By:

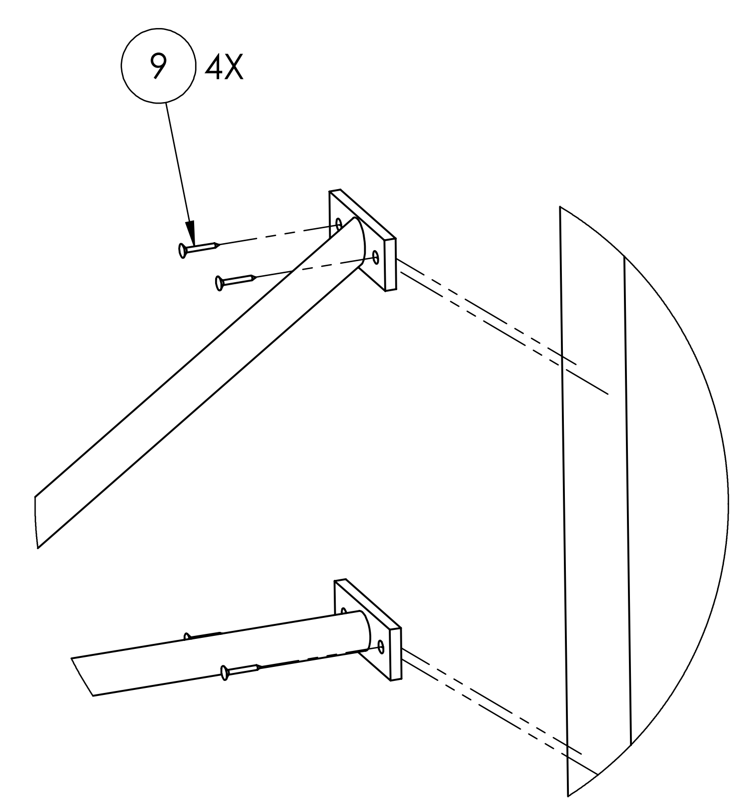




DETAIL A
SCALE 1 : 2

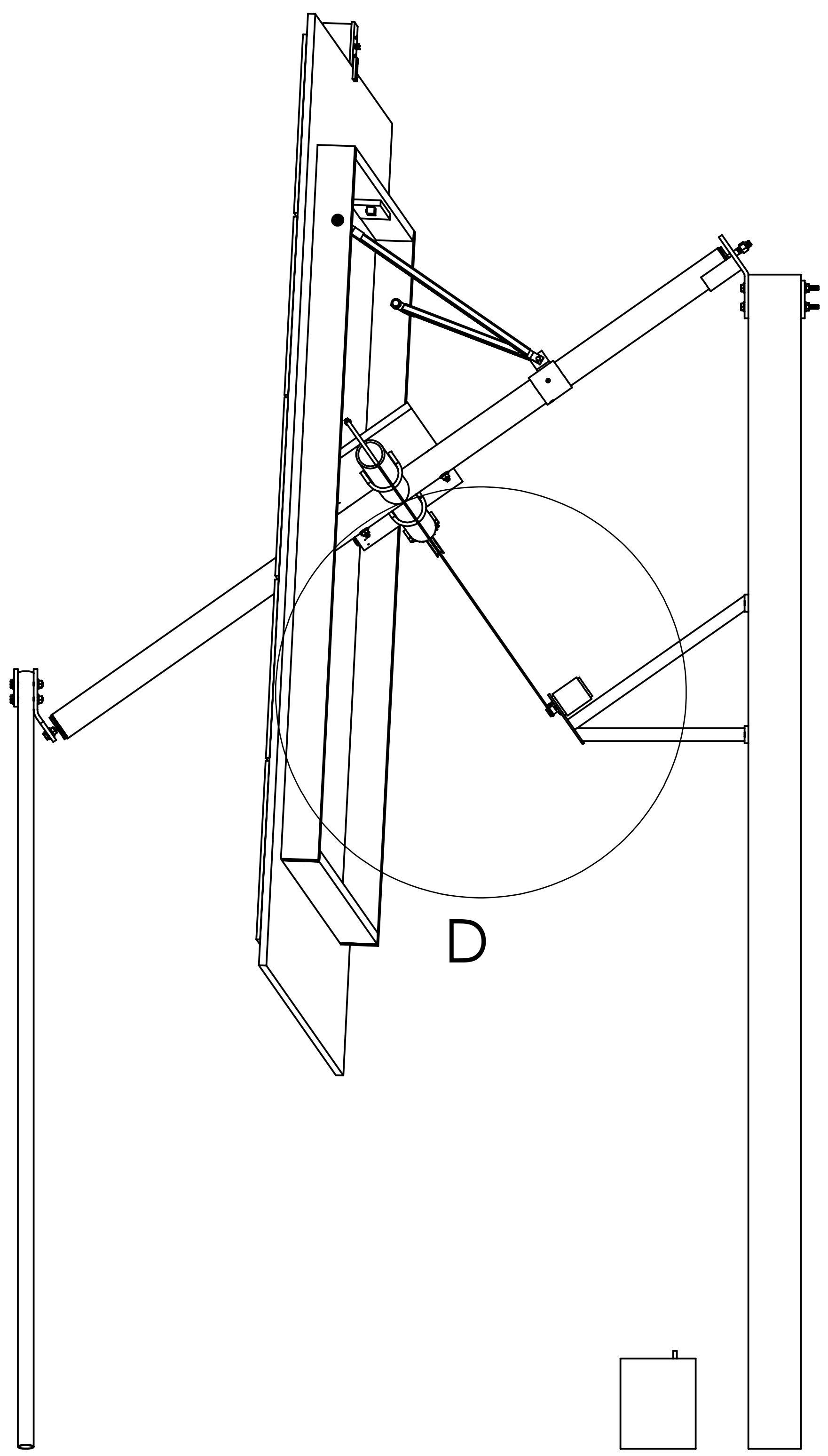


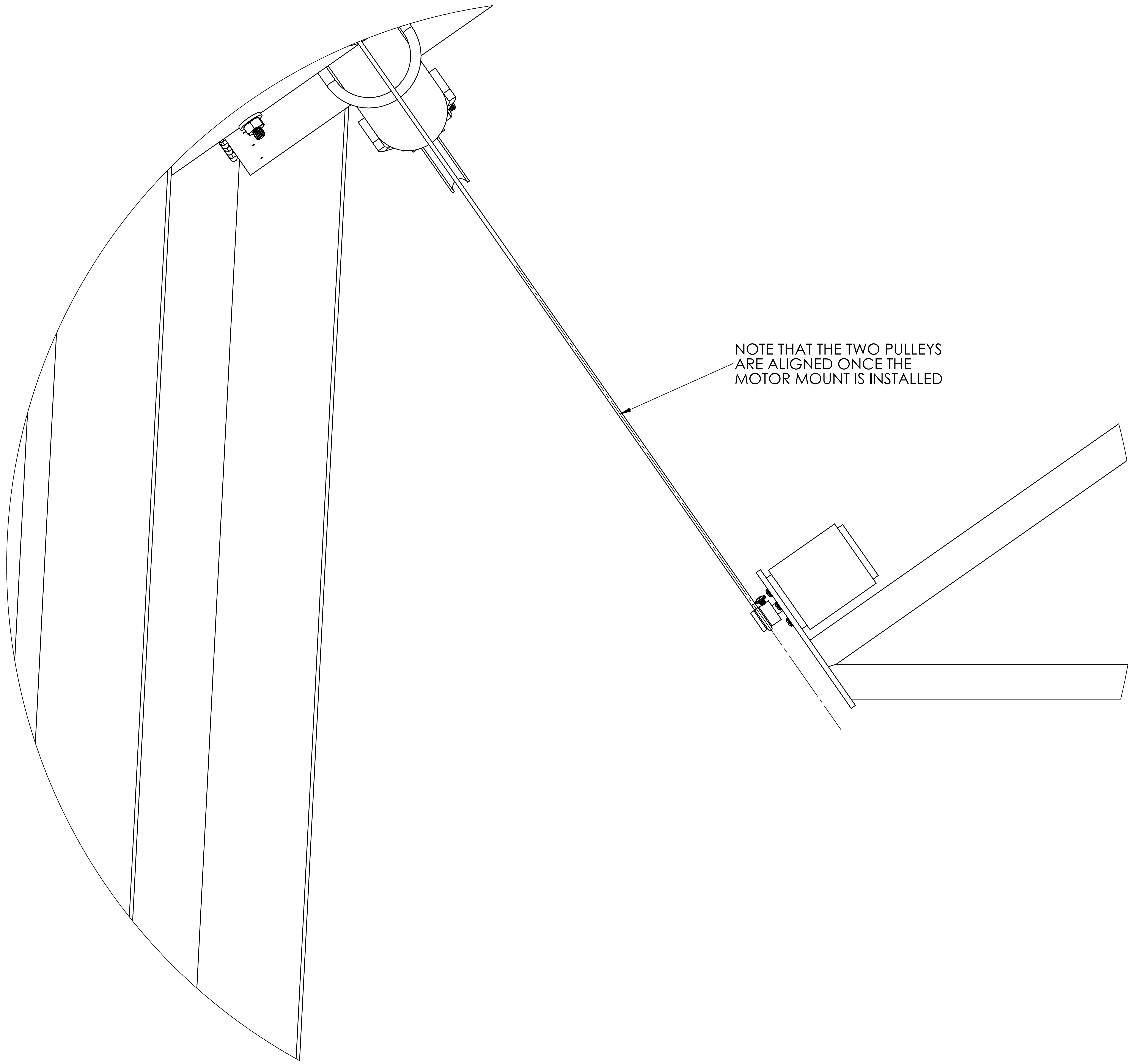
DETAIL B
SCALE 1 : 2



DETAIL C
SCALE 1 : 4

Lab Section: 03	SHEET 4 of 5	Title: REFLECTOR ASSEMBLY		Drwn. By: DEVIN MAST
Dwg. #: R000	Nxt Asb: N/A	Date: 12/03/15	Scale: 1:24	Chkd. By: I. DAVISON





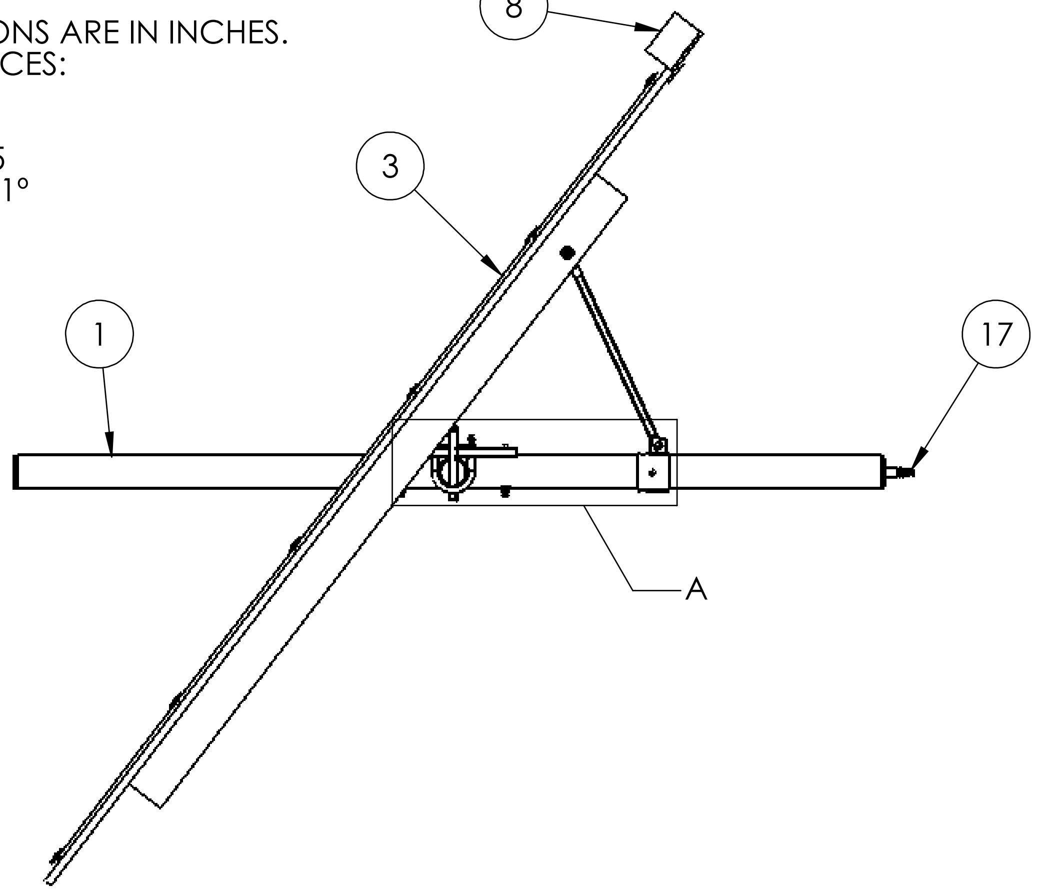
DETAIL D

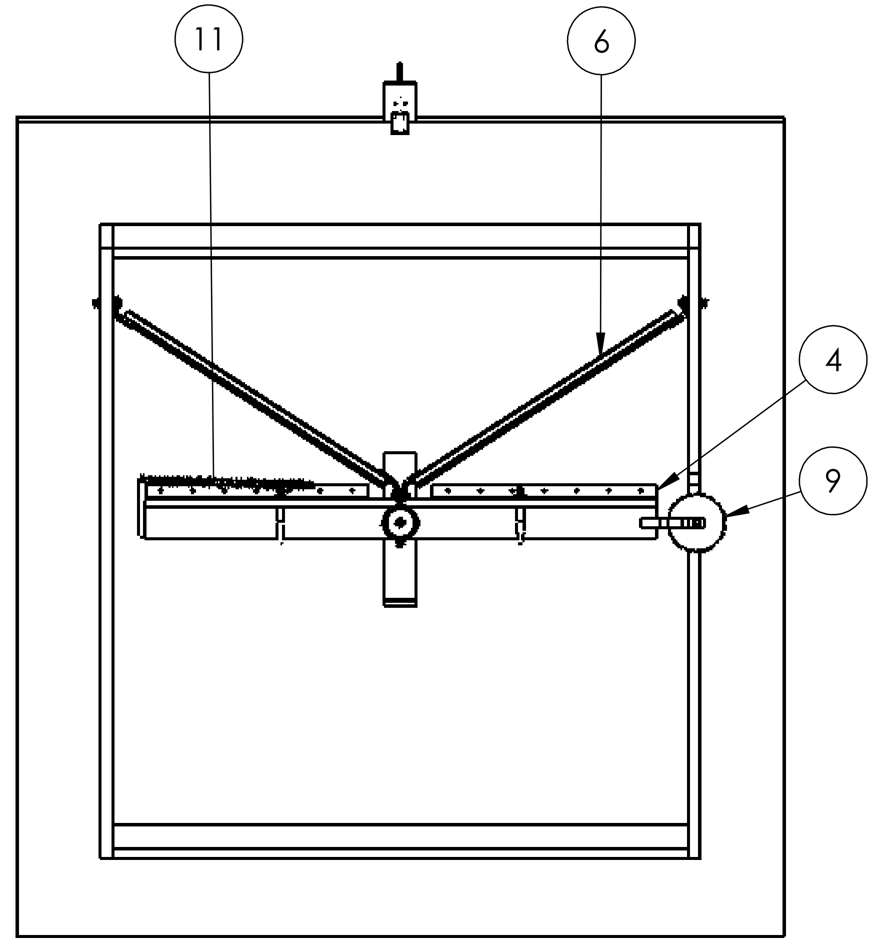
SCALE 1 : 2

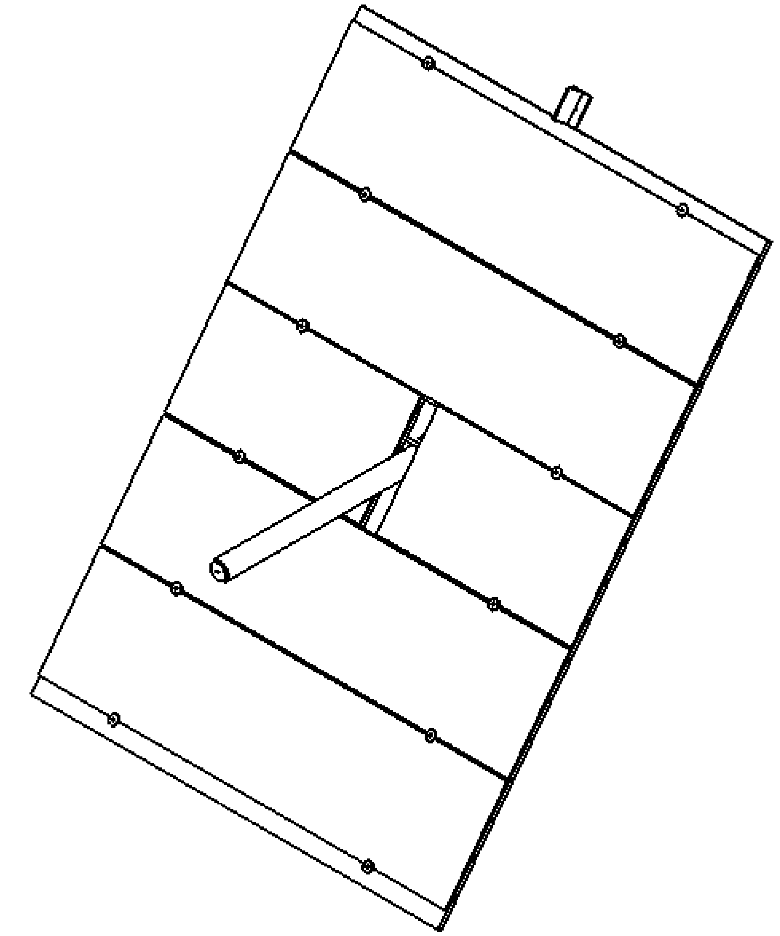
Lab Section: 03	SHEET 5 of 5	Title: REFLECTOR ASSEMBLY		Drwn. By: DEVIN MAST
Dwg. #: R000	Nxt Asb: N/A	Date: 12/03/15	Scale: 1:8	Chkd. By: I. DAVISON

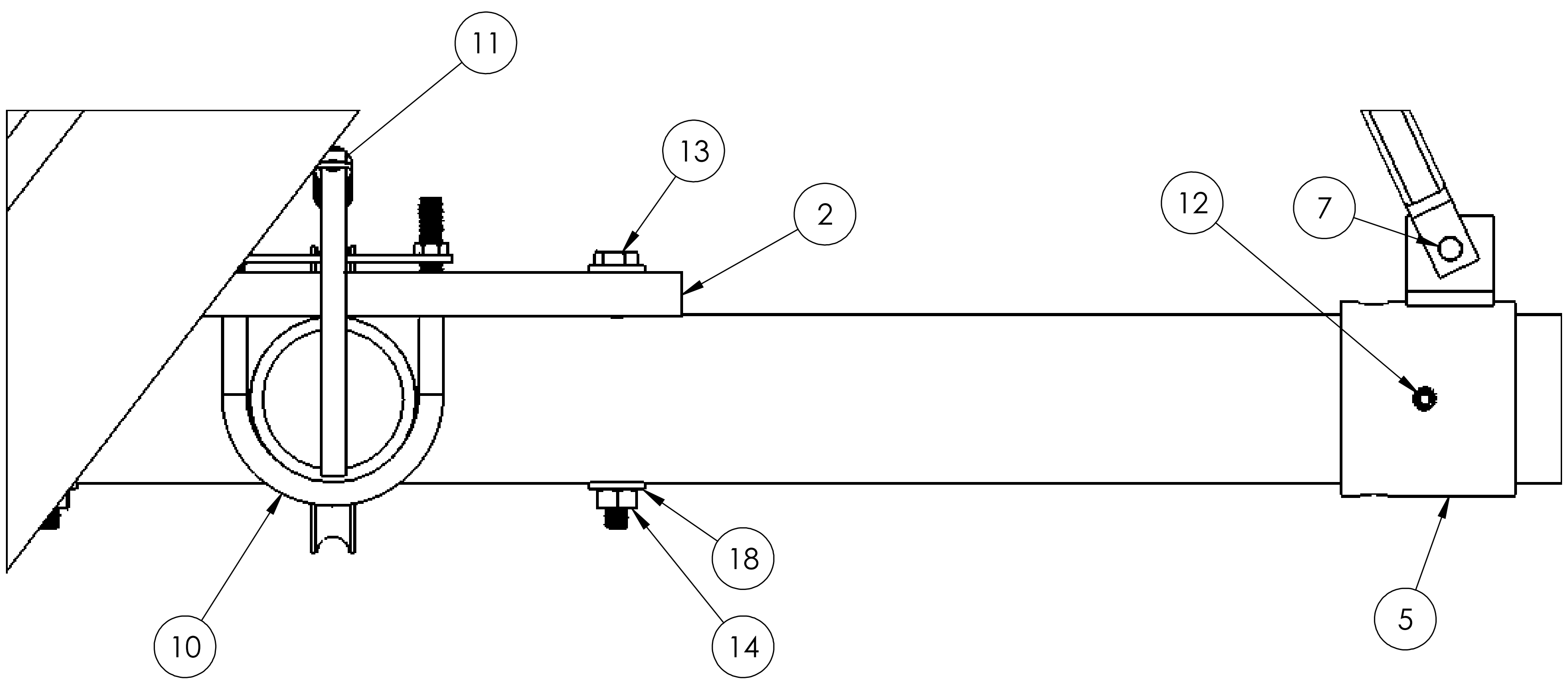
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°





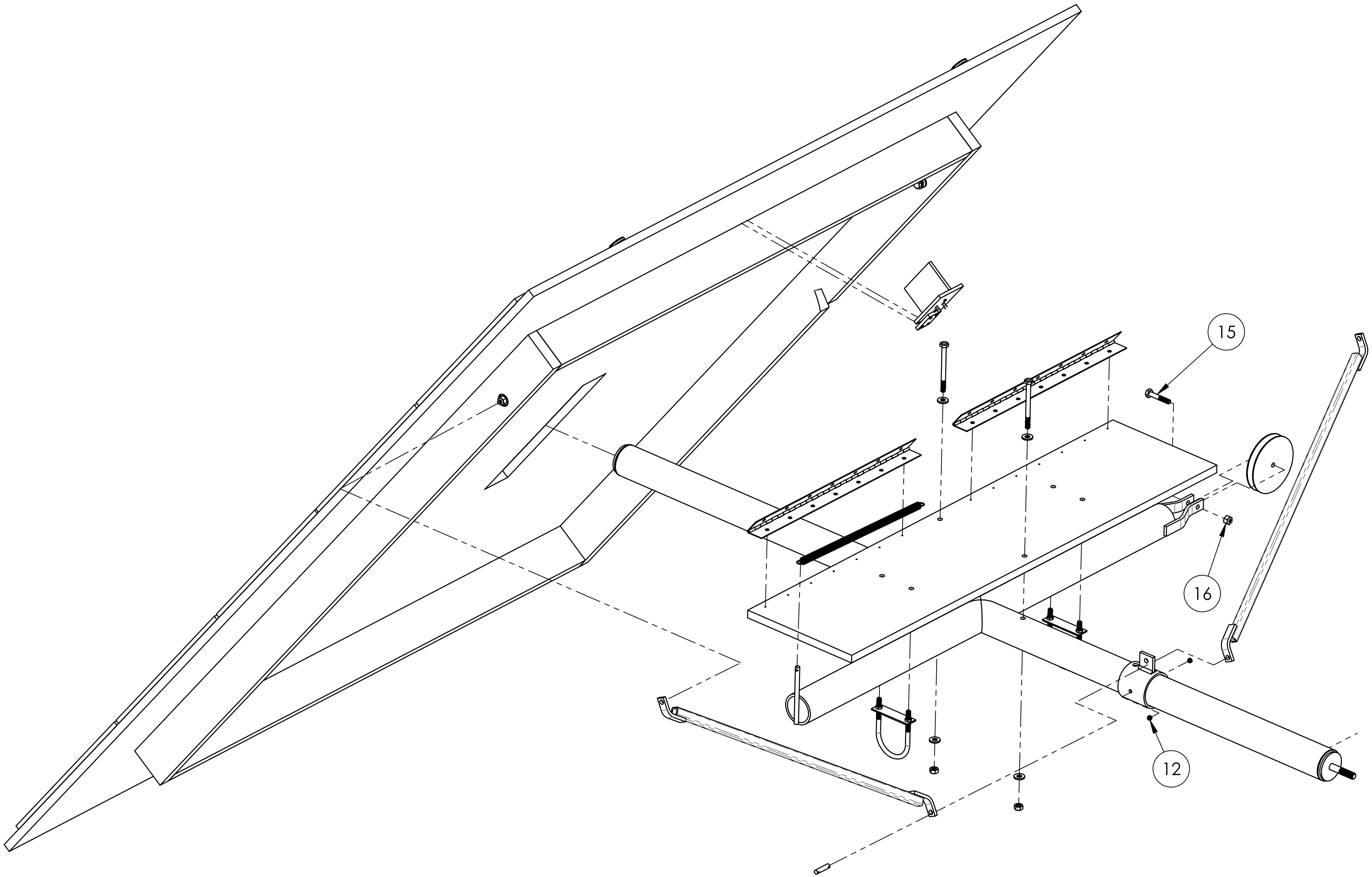




DETAIL A
SCALE 1 : 2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R001	1.5" STEEL ROTATING PIPE	1
2	R004	PLYWOOD SUPPORT FOR HINGE	1
3	R013	MIRROR ASSEMBLY	1
4	R034	PIANO HINGE	2
5	R015	SEASONAL ADJUSTMENT SLIDER PIPE	1
6	R903	SUPPORT STRUT	2
7	R902	SLIDER PIN	1
8	R800	PHOTOCOMPARATOR ASSEMBLY	1
9	R901	PULLEY	1
10	3201T54	PIPE CLAMP	2
11	9640K151	EXTENSION SPRING	1
12	91375A532	1/4-20 x .125 SETSCREW	2
13	91286A128	1/4-20 X 3 STEEL BOLT	2
14	N/A	1/4-20 NUT	2
15	N/A	1/4-20 X 1.5 HEX CAP BOLT	1
16	N/A	1/4-20 NYLON LOCK NUT	1
17	N/A	3/8"-16 X 2 CAP SCREW	1
18	N/A	WASHER FOR .25 INCH	4

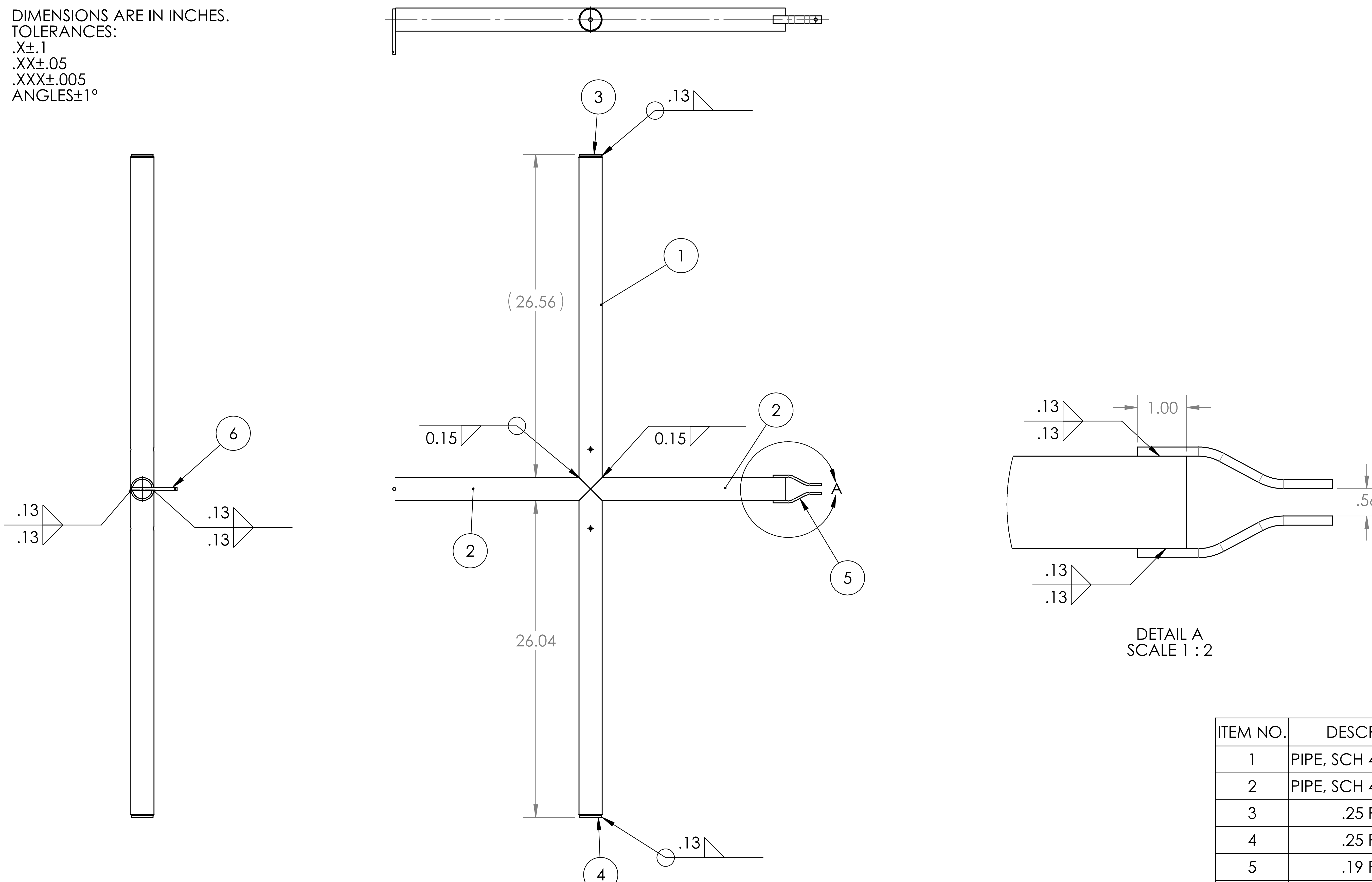
Lab Section: 03	SHEET 1 of 2	Title: TRACKING STAGE ASSEMBLY		Drwn. By: I. DAVISON
Dwg. #: R500	Nxt Asb: R000	Date: 12/03/15	Scale: 1:12	Chkd. By:



Lab Section: 03	SHEET 2 of 2	Title: TRACKING STAGE ASSEMBLY		Drwn. By: I. DAVISON
Dwg. #: R500	Nxt Asb: R000	Date: 12/03/15	Scale: 1:6	Chkd. By:

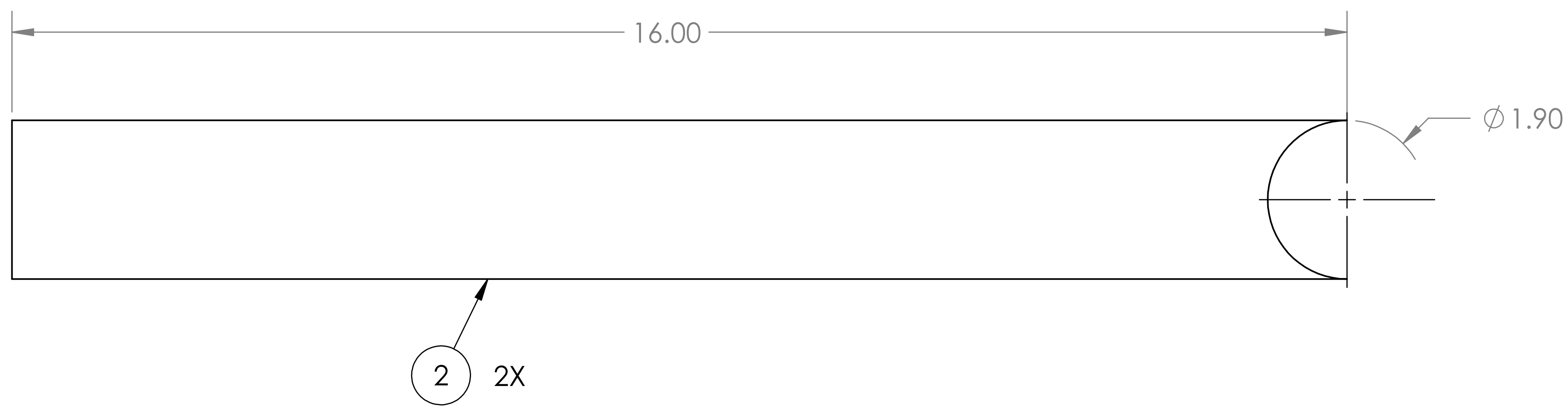
UNLESS OTHERWISE SPECIFIED:

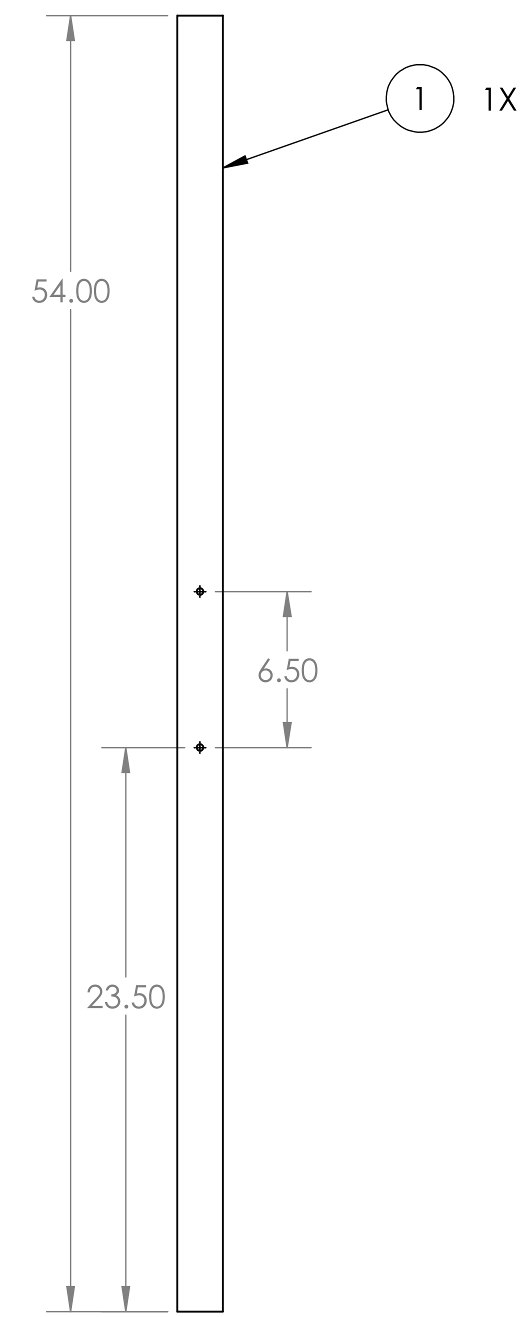
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



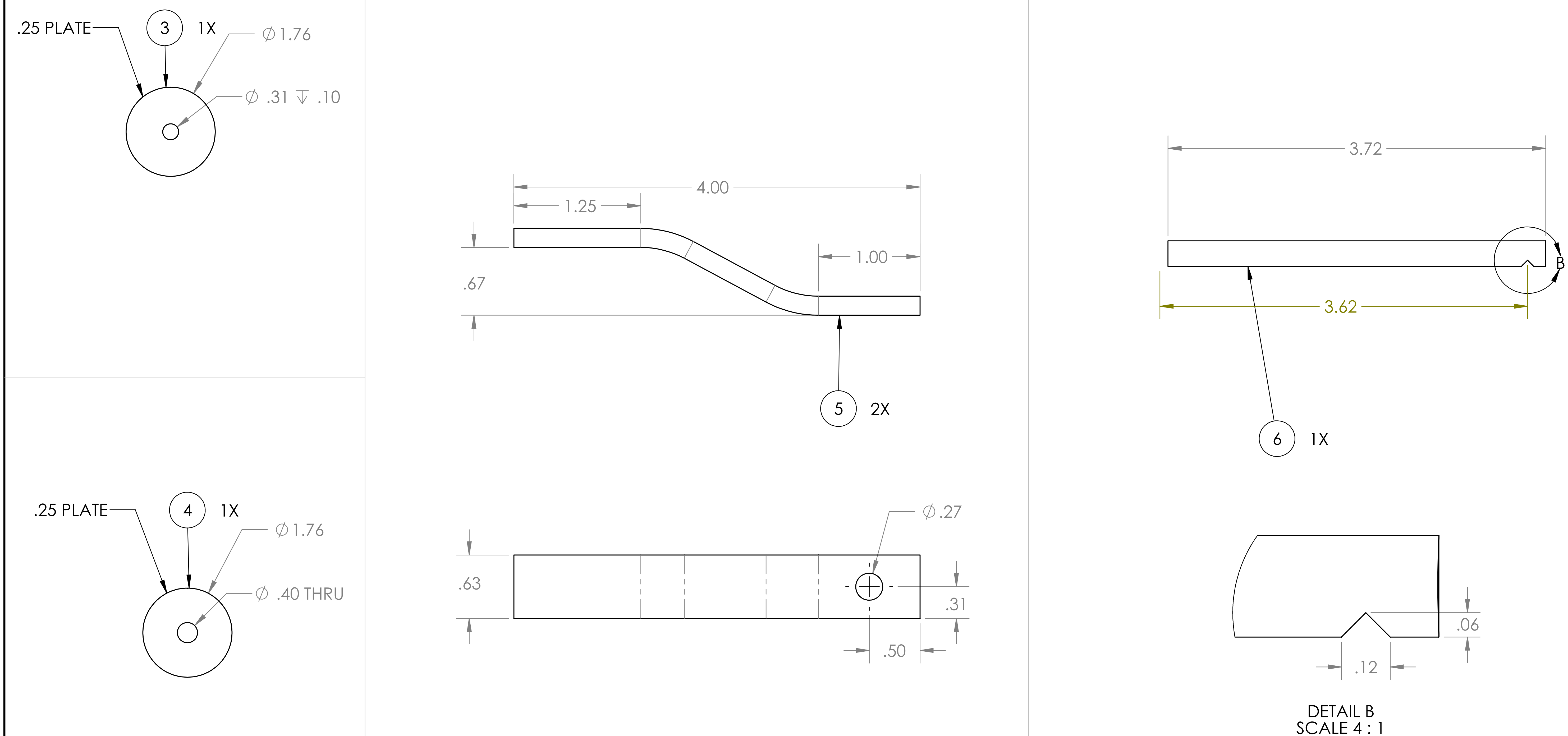
ITEM NO.	DESCRIPTION	LENGTH	QTY.
1	PIPE, SCH 40, 1.50 DIA.	54	1
2	PIPE, SCH 40, 1.50 DIA.	16	2
3	.25 PLATE		1
4	.25 PLATE		1
5	.19 PLATE	4.15	2
6	.25 ROUND STOCK	3.80	1

Lab Section: 03	SHEET 1 of 3	Title: 1.5" STEEL ROTATING PIPE		Drwn. By: I. DAVISON
Dwg. #: R001	Nxt Asb: R500	Date: 12/03/15	Scale: 1:2	Chkd. By:





Lab Section: 03	SHEET 2 of 3	Title: 1.5" STEEL ROTATING PIPE	Drwn. By: I. DAVISON
Dwg. #: R001	Nxt Asb: R500	Date: 12/03/15 Scale: 1:16	Chkd. By:



Lab Section: 03	SHEET 3 of 3	Title: 1.5" STEEL ROTATING PIPE		Drwn. By: I. DAVISON
Dwg. #: R001	Nxt Asb: R500	Date: 12/03/15	Scale: 1:16	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
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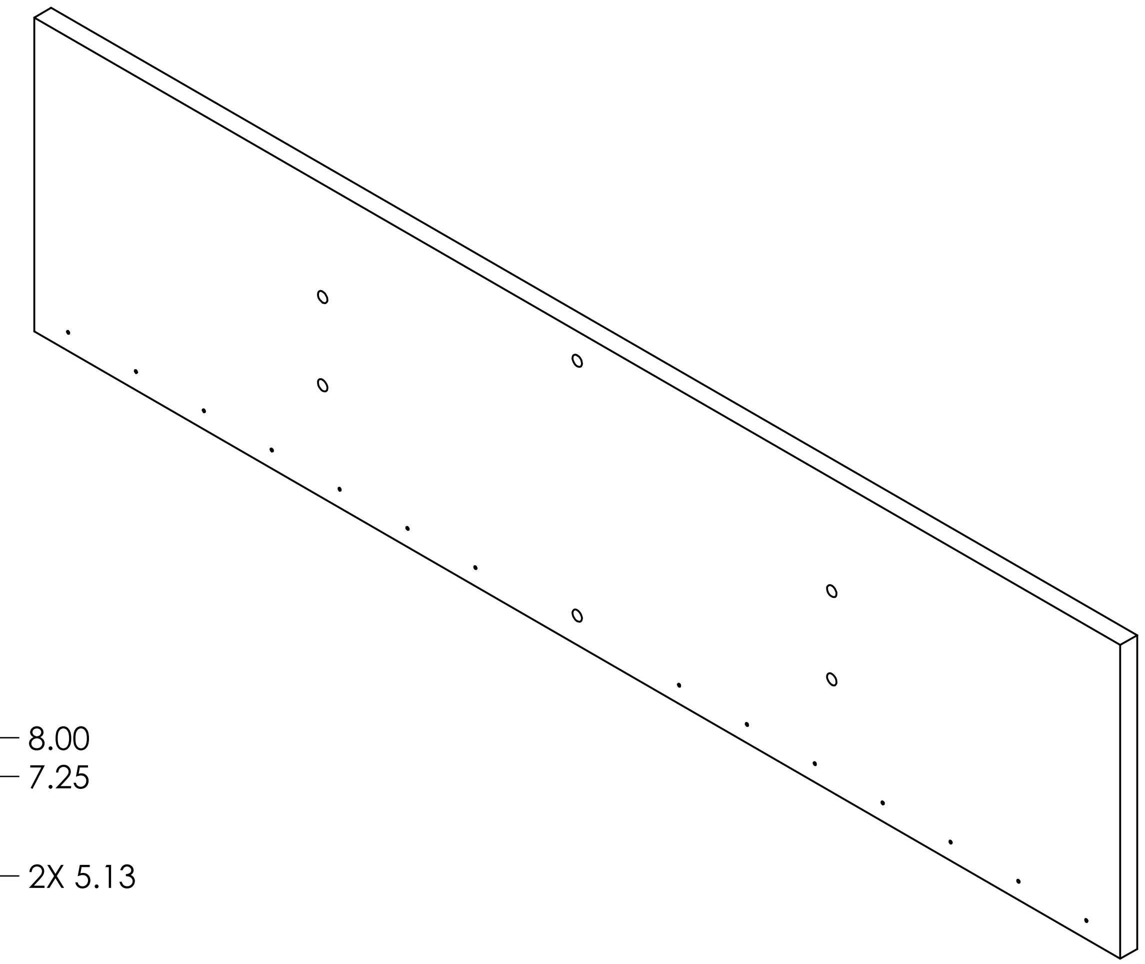
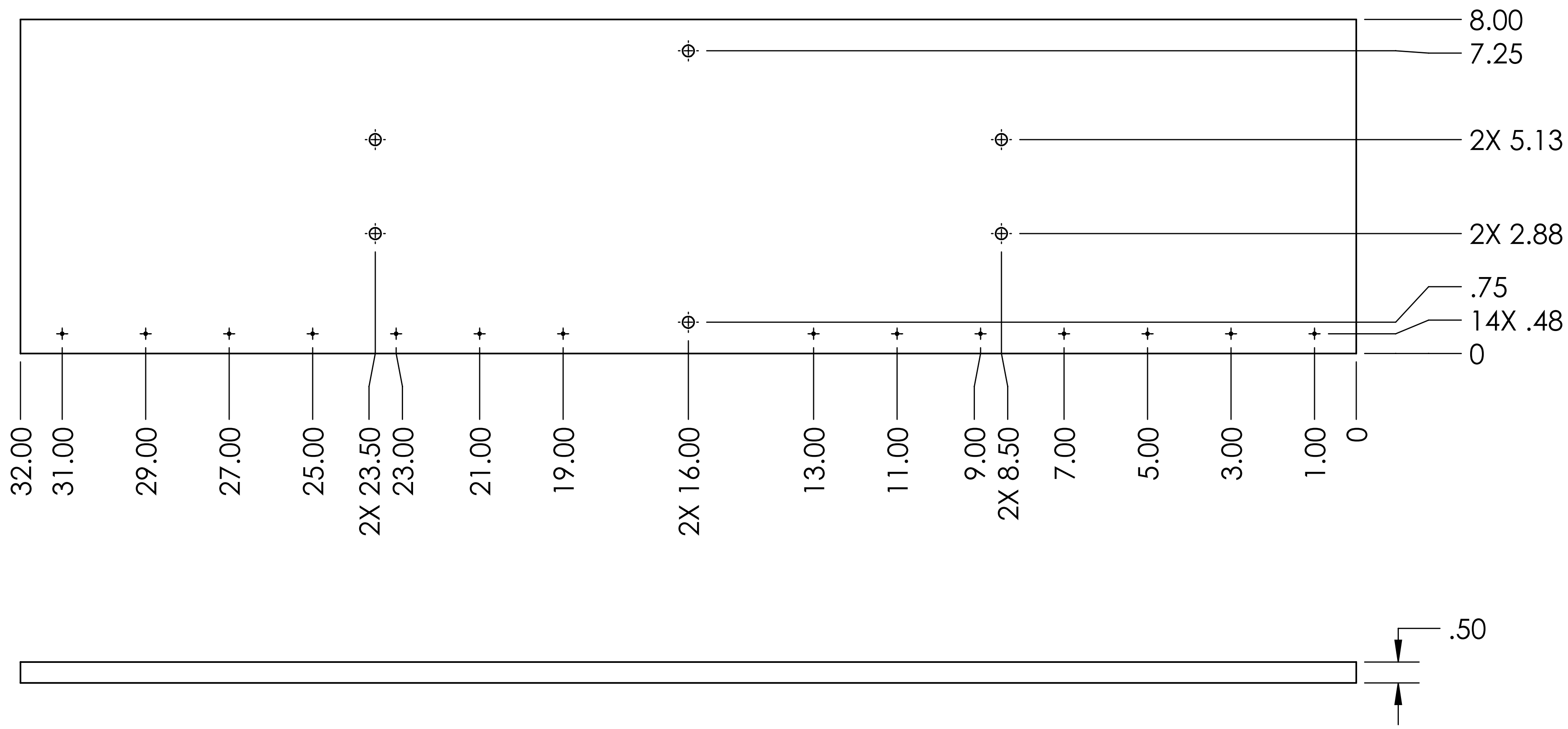
.XX±.05
.XXX±.005
ANGLES±1°



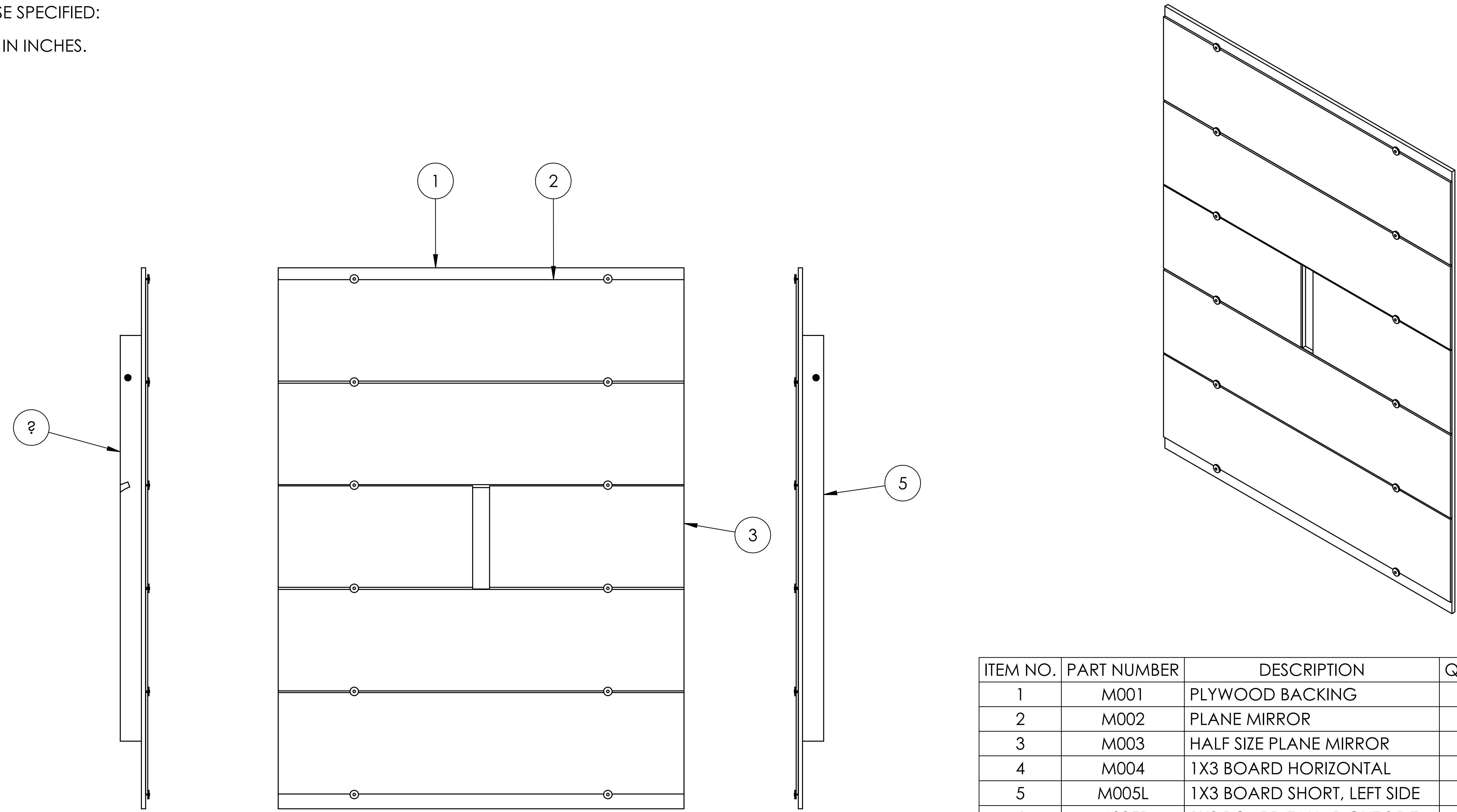


MATERIAL: 1/2 INCH OSB

Lab Section: 03	SHEET 1 of 1	Title: PLYWOOD SUPPORT FOR HINGE		Drwn. By: I. DAVISON
Dwg. #: R004	Nxt Asb: R500	Date: 12/03/15	Scale: 1:4	Chkd. By:

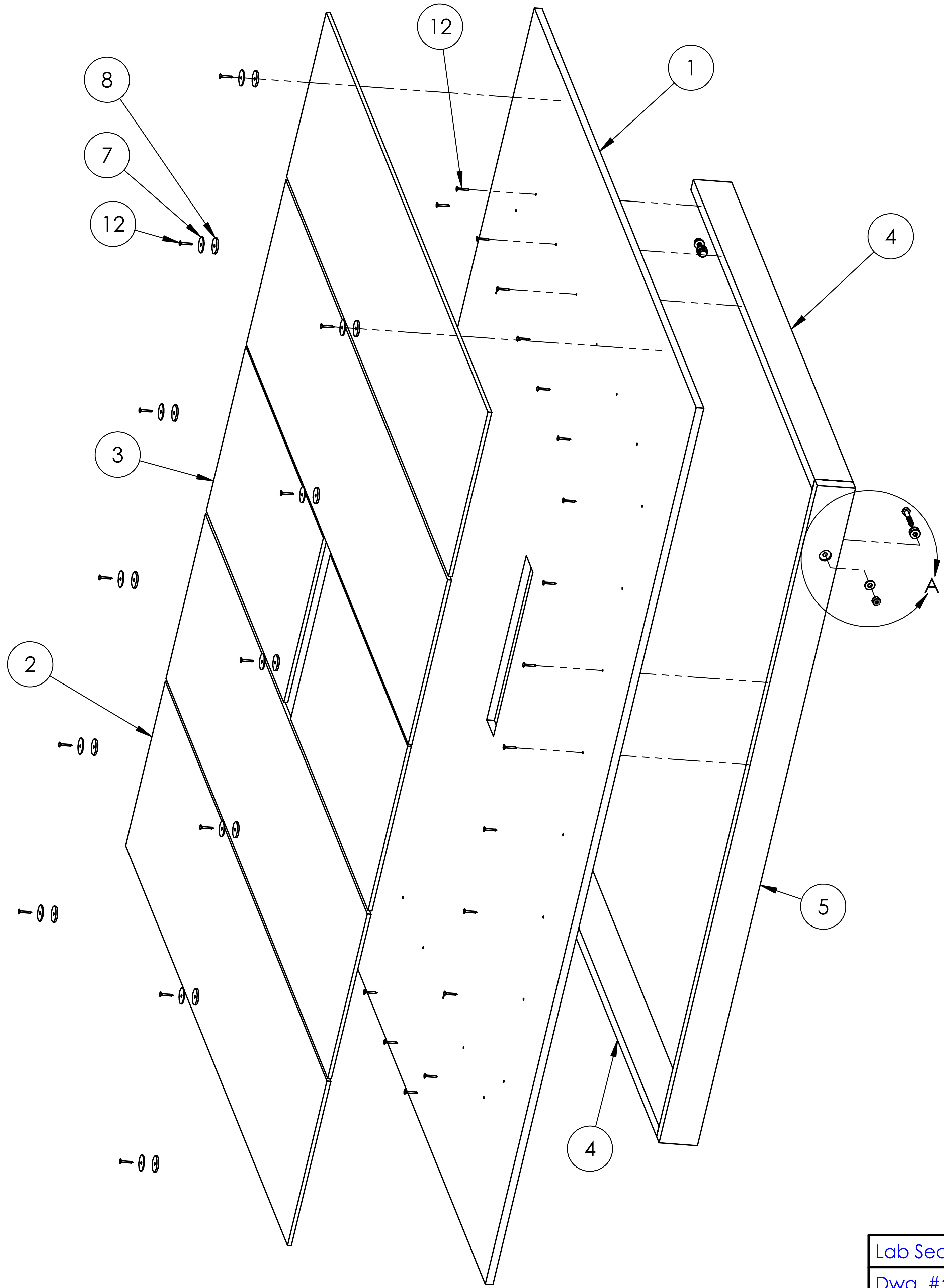
UNLESS OTHERWISE SPECIFIED:

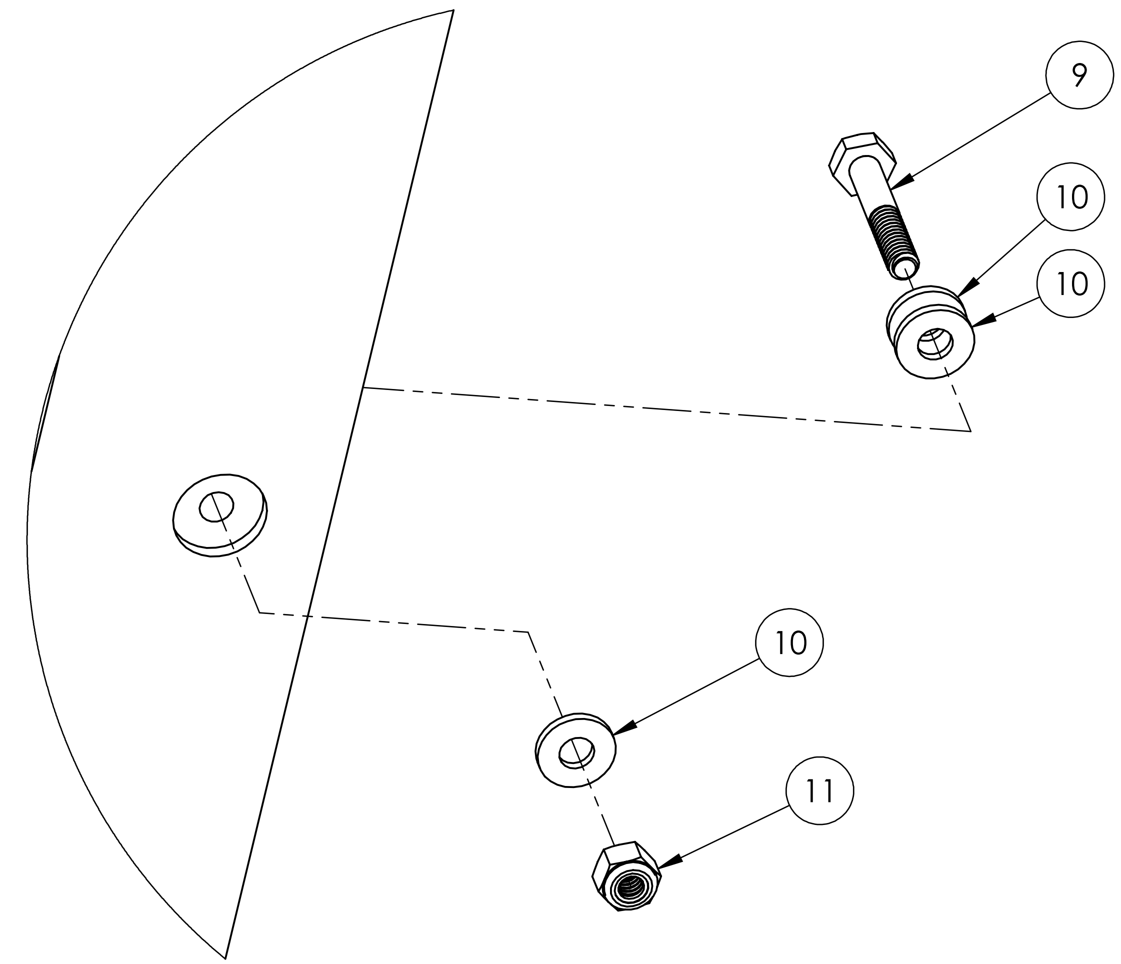
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	M001	PLYWOOD BACKING	1
2	M002	PLANE MIRROR	4
3	M003	HALF SIZE PLANE MIRROR	1
4	M004	1X3 BOARD HORIZONTAL	2
5	M005L	1X3 BOARD SHORT, LEFT SIDE	1
6	M005R	1X3 BOARD TALL, RIGHT SIDE	1
7	R036	FENDER WASHER	12
8	90130A012	RUBBER SEALING WASHER	12
9	N/A	1/4-20 X 1.5 HEX CAP BOLT	2
10	N/A	WASHER FOR .25 INCH	6
11	N/A	1/4-20 NYLON LOCK NUT	2
12	N/A	#6 X 3/4 WOOD SCREW	40

Lab Section: 03	SHEET 1 of 2	Title: MIRROR ASSEMBLY	Drwn. By: I. DAVISON
Dwg. #: R013	Nxt Asb: R500	Date: 12/03/15	Scale: 1:12	Chkd. By:





DETAIL A
SCALE 1 : 1.5

ITEM NO.	PartNo	DESCRIPTION	QTY.
1	M001	PLYWOOD BACKING	1
2	M002	PLANE MIRROR	4
3	M003	HALF SIZE PLANE MIRROR	1
4	M004	1X3 BOARD HORIZONTAL	2
5	M005L	1X3 BOARD SHORT, LEFT SIDE	1
6	M005R	1X3 BOARD TALL, RIGHT SIDE	1
7	R036	FENDER WASHER	12
8	90130A012	RUBBER SEALING WASHER	12
9	N/A	1/4-20 X 1.5 HEX CAP BOLT	2
10	N/A	1/4-20 NYLON LOCK NUT	2
11	N/A	WASHER FOR .25 INCH	6
12	N/A	#6 X 3/4 WOOD SCREW	40

Lab Section: 03	Assignment #	Title: MIRROR ASSEMBLY		Drwn. By: I. DAVISON
Dwg. #: R013	Nxt Asb: R500	Date: 12/03/15	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
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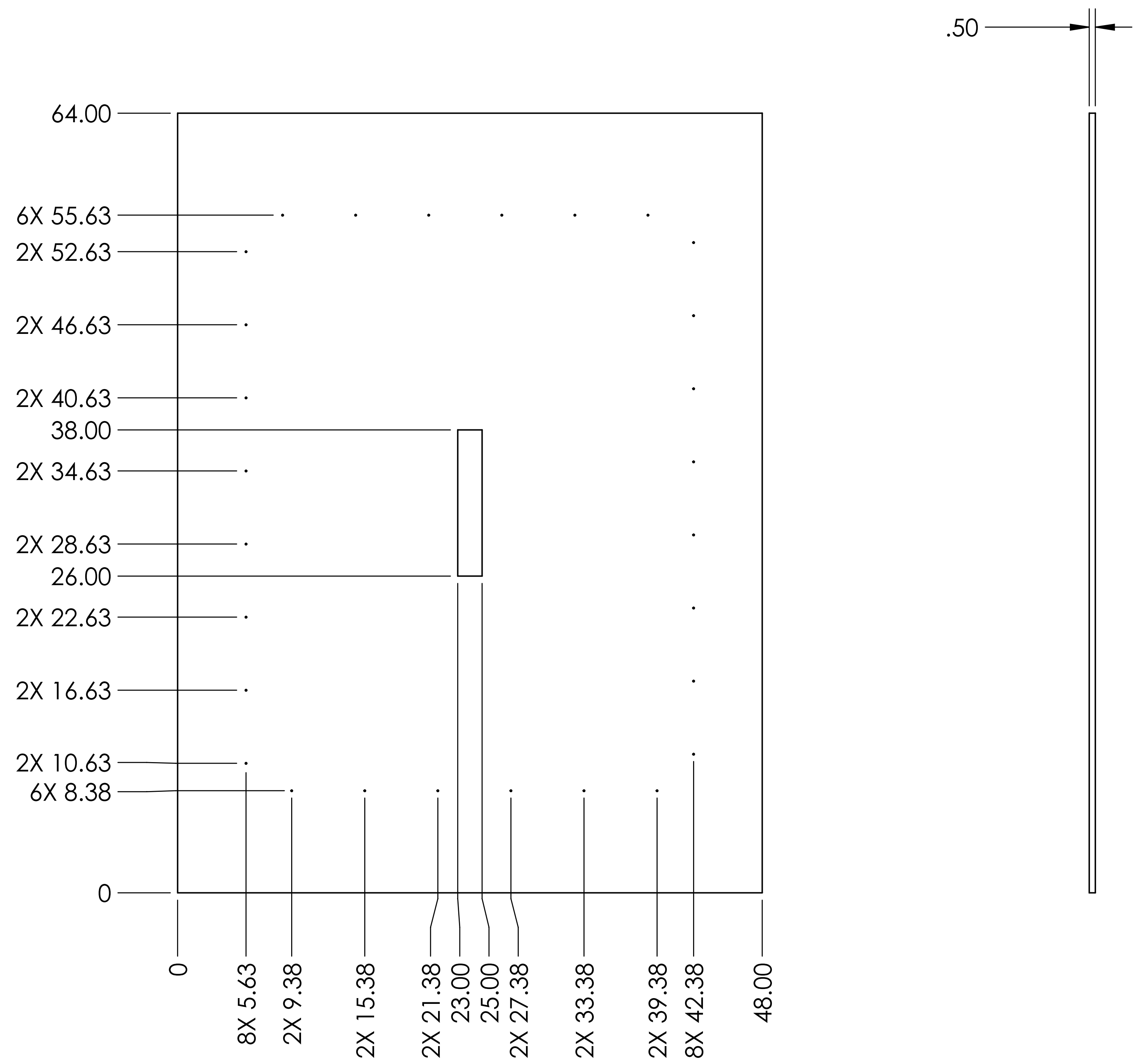
.XX±.05
.XXX±.005
ANGLES±1°



MATERIAL: 1/2 INCH OSB

Lab Section: 03	SHEET 1 of 1	Title: PLYWOOD BACKING		Drwn. By: I. DAVISON
Dwg. #: M001	Nxt Asb: R013	Date: 12/8/2015	Scale: 1:12	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
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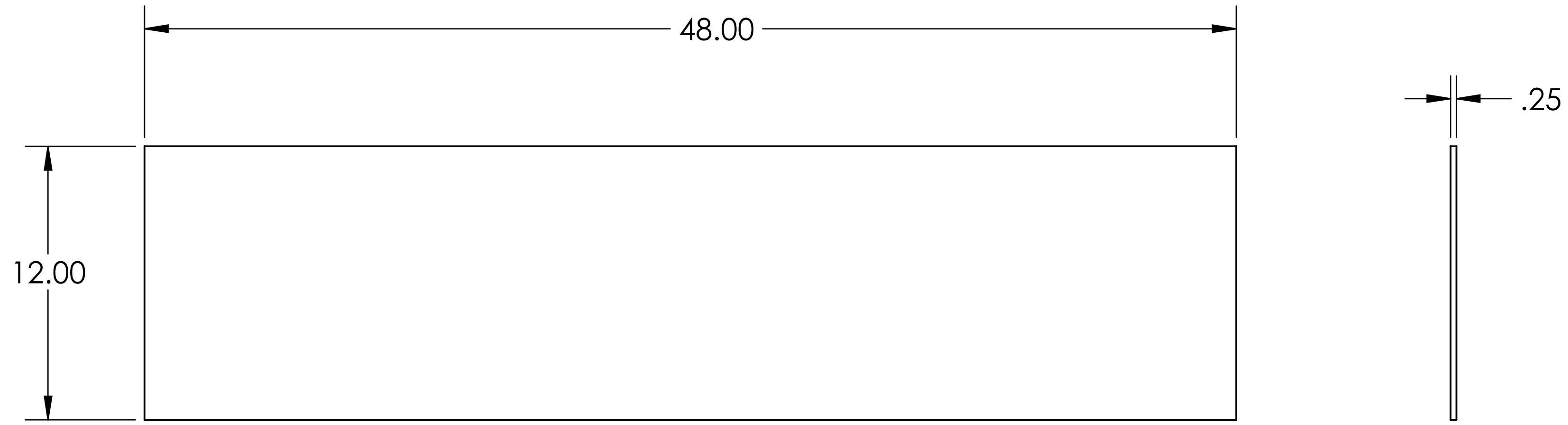
.XX±.05
.XXX±.005
ANGLES±1°

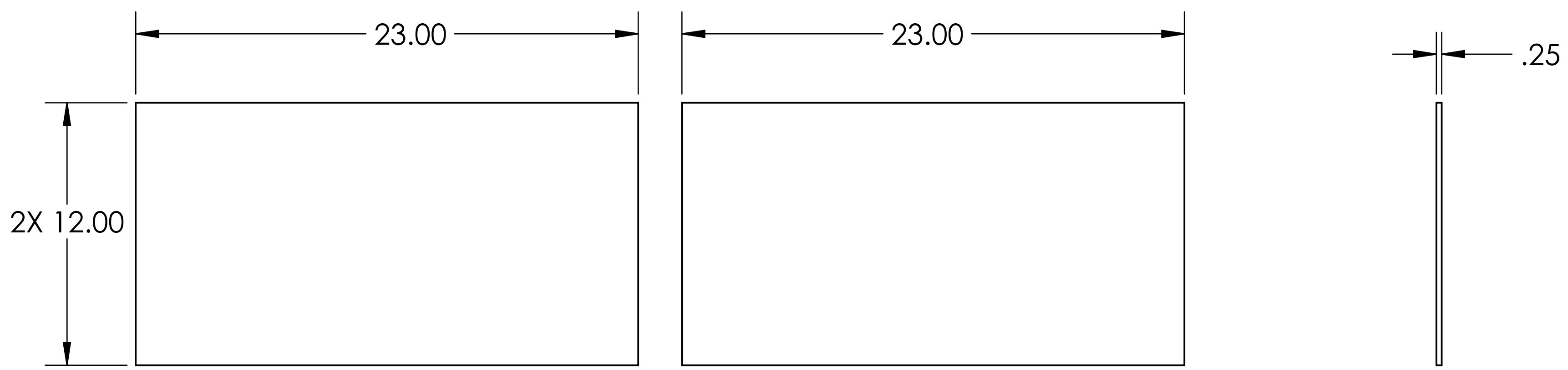


MATERIAL: GLASS MIRROR, SILVERED

Lab Section: 03	SHEET 1 of 1	Title: PLANE MIRROR		Drwn. By: I. DAVISON
Dwg. #: M002	Nxt Asb: R013	Date: 12/8/2015	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



MATERIAL: GLASS MIRROR, SILVERED

Lab Section: 03	SHEET 1 of 1	Title: HALF SIZE PLANE MIRROR		Drwn. By: I. DAVISON
Dwg. #: M003	Nxt Asb: R013	Date: 12/8/2015	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
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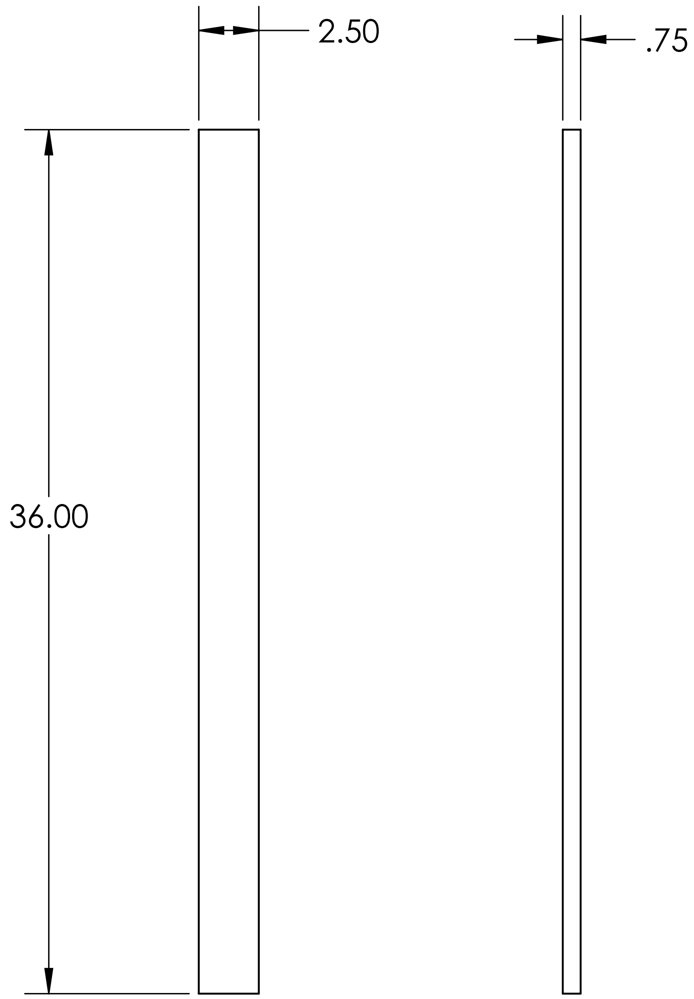
.XX±.05
.XXX±.005
ANGLES±1°



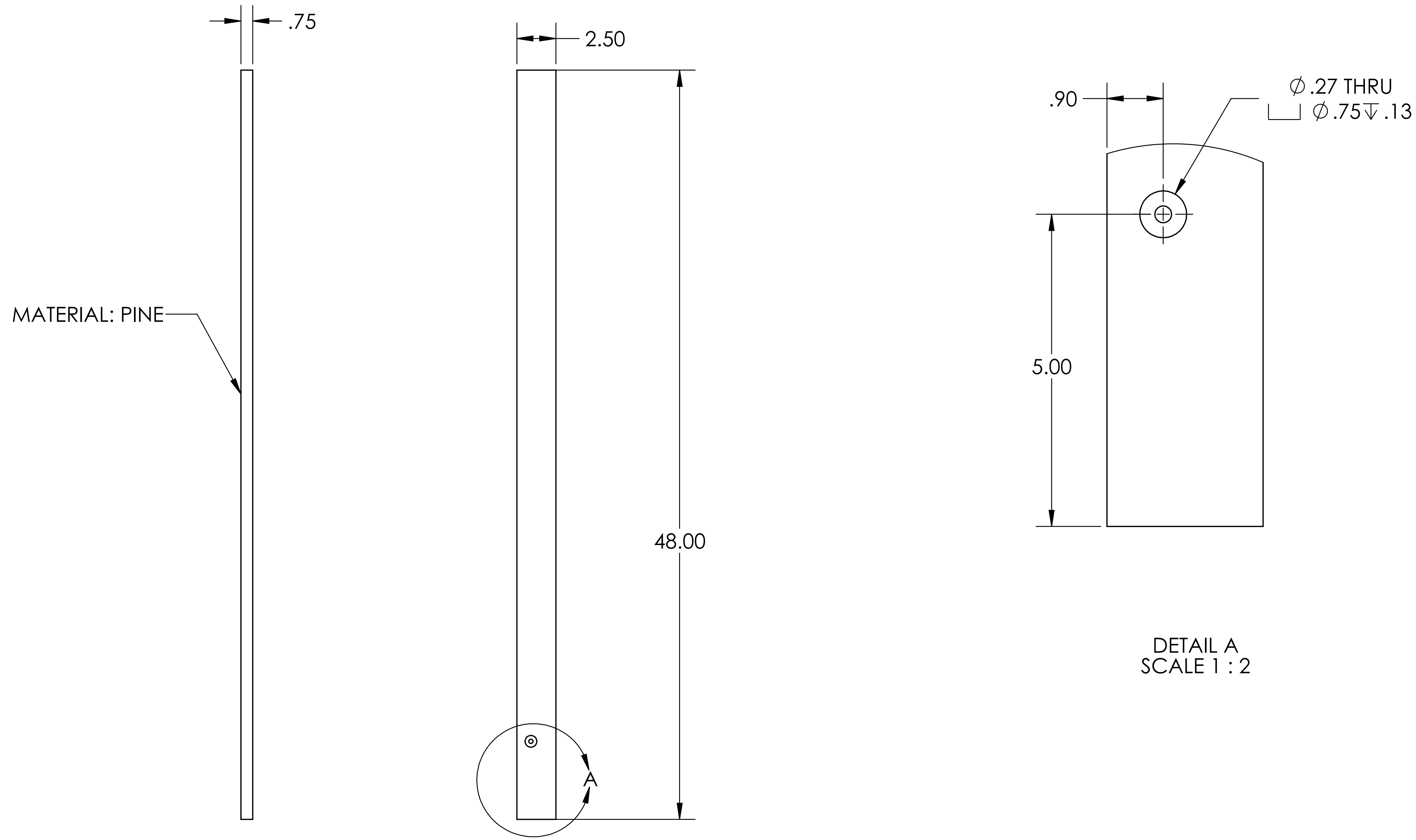
MATERIAL: PINE

Lab Section: 03	SHEET 1 of 1	Title: 1X3 BOARD HORIZONTAL		Drwn. By: I. DAVISON
Dwg. #: M004	Nxt Asb: R013	Date: 12/8/2015	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

M005L

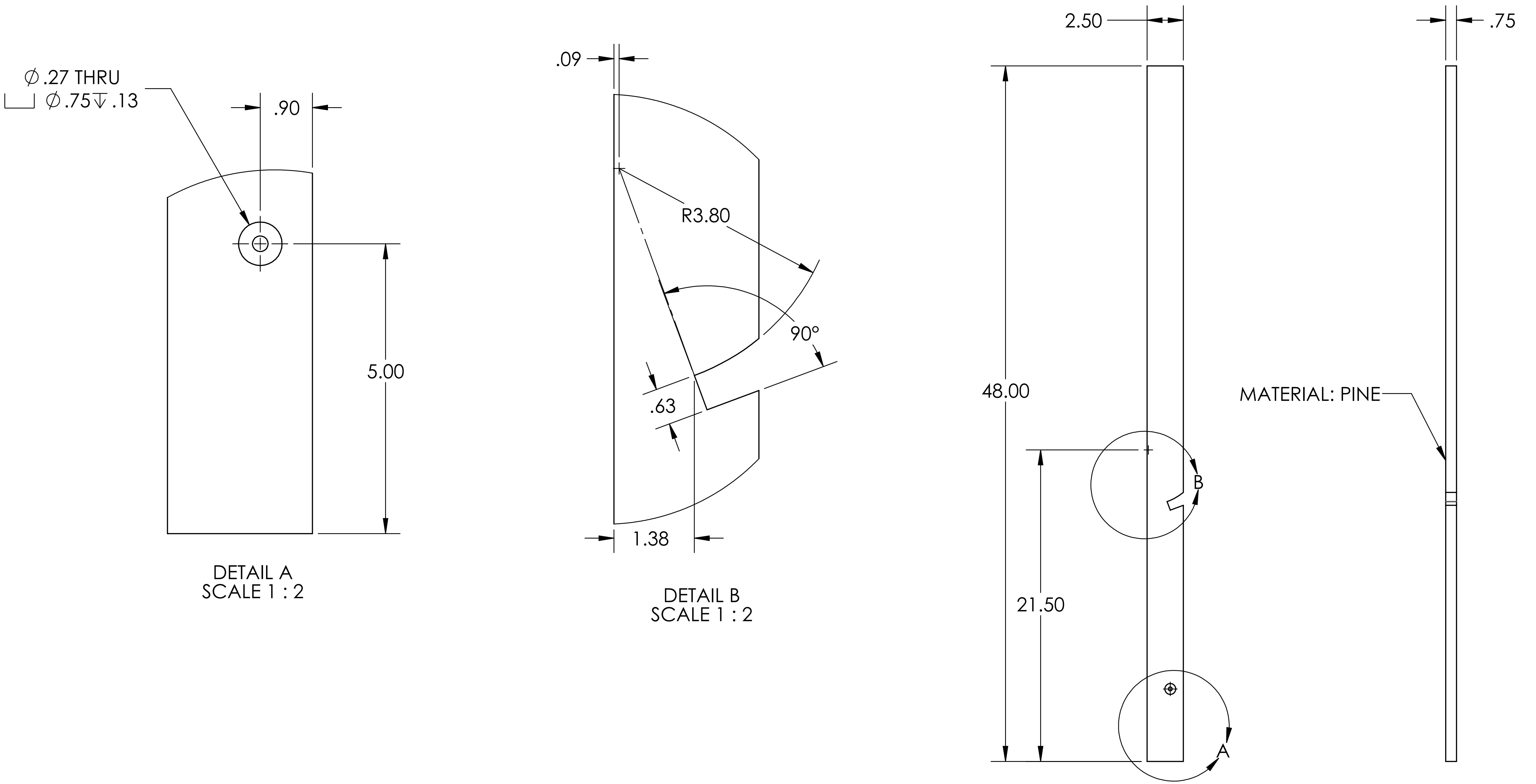


Lab Section: 03	SHEET 1 of 1	Title: 1X3 BOARD SHORT, LEFT SIDE		Drwn. By: I. DAVISON
Dwg. #: M005L	Nxt Asb: R013	Date: 12/8/2015	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

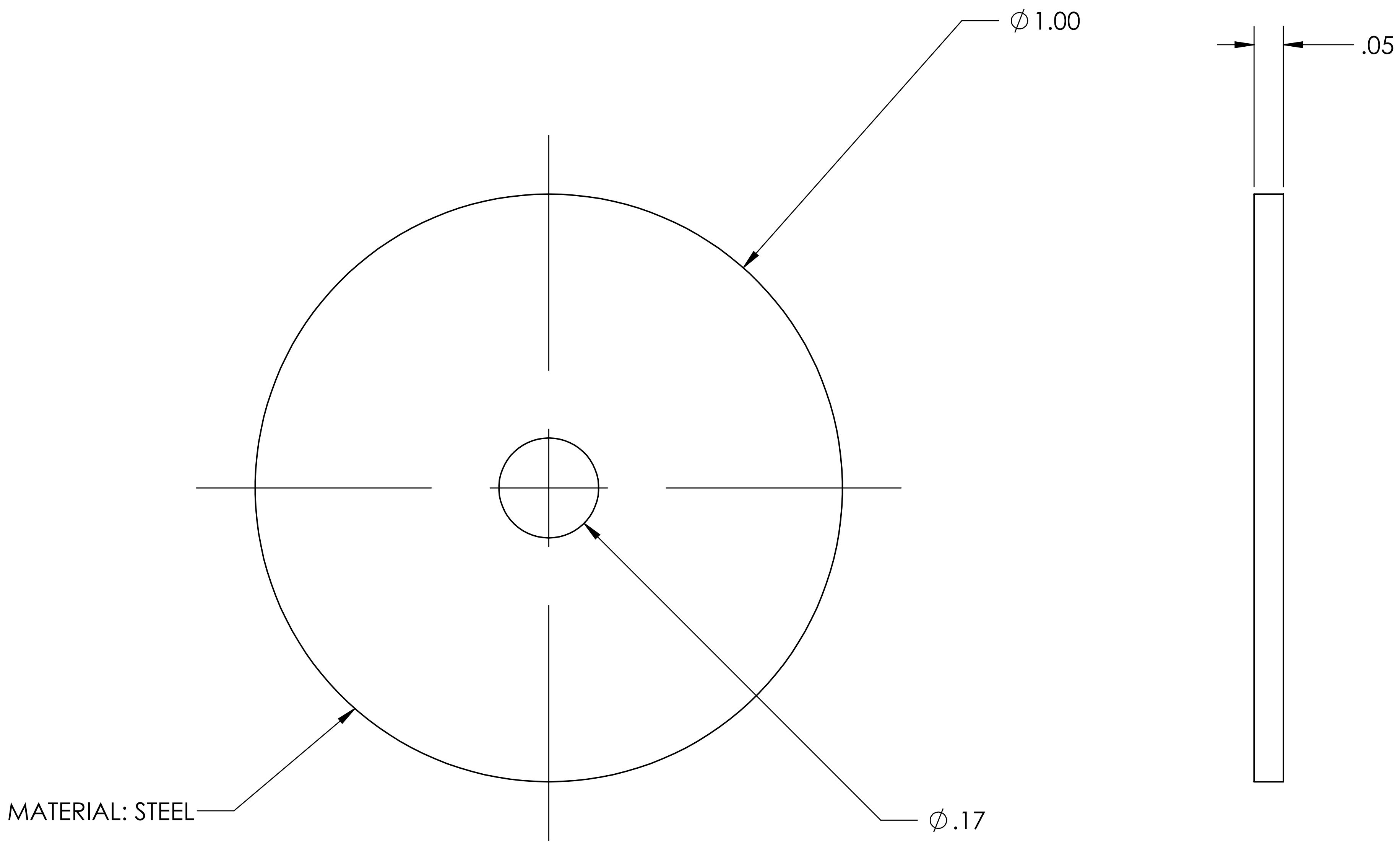
M005R



Lab Section: 03	SHEET 1 of 1	Title: 1X3 BOARD TALL, RIGHT SIDE		Drwn. By: I. DAVISON
Dwg. #: M005R	Nxt Asb: R013	Date: 12/8/2015	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

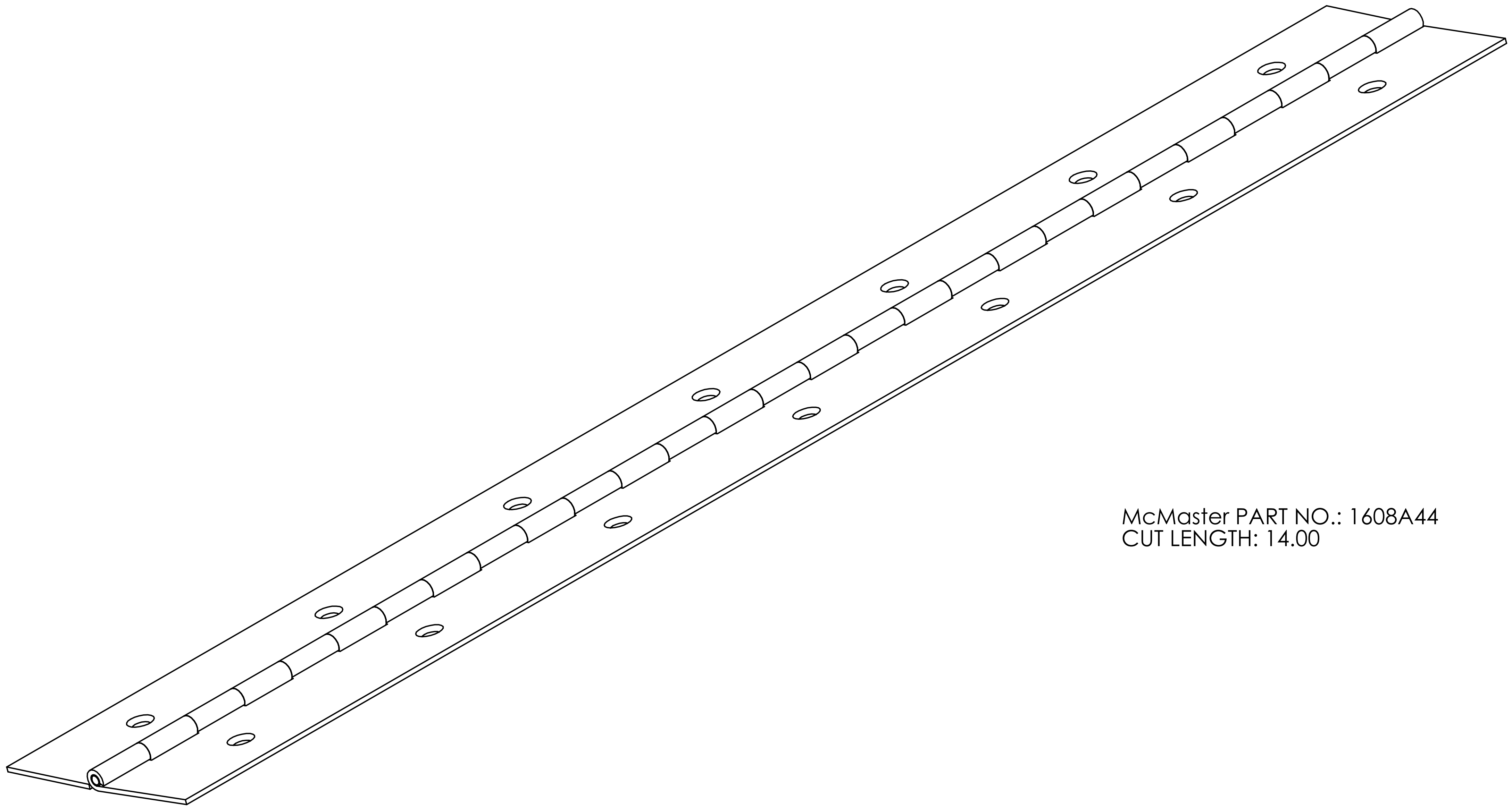
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



Lab Section: 03	SHEET 1 of 1	Title: FENDER WASHER		Drwn. By: I. DAVISON
Dwg. #: R036	Nxt Asb: R013	Date: 12/8/2015	Scale: 4:1	Chkd. By:

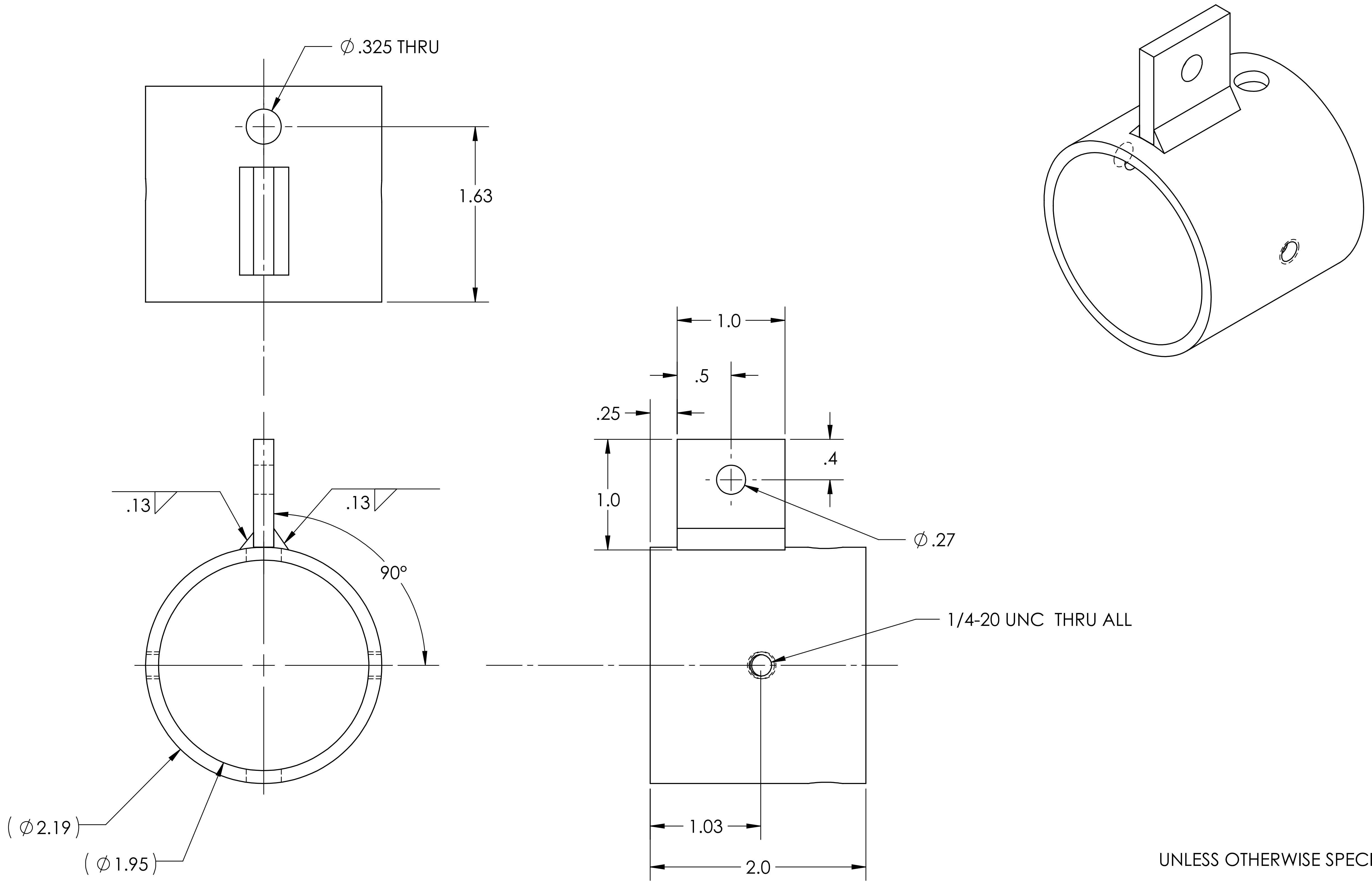
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



McMaster PART NO.: 1608A44
CUT LENGTH: 14.00

Lab Section: 03	SHEET 1 of 1	Title: PIANO HINGE		Drwn. By: I. DAVISON
Dwg. #: R034	Nxt Asb: R500	Date: 12/8/2015	Scale: 1:1	Chkd. By:



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

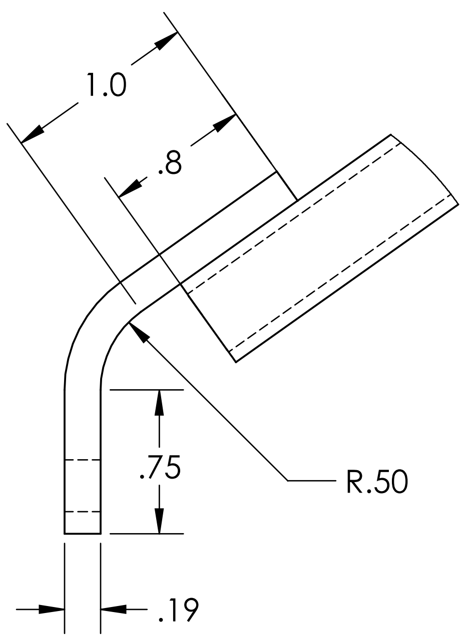
Lab Section: 03	SHEET 1 of 1	Title: SEASONAL ADJUSTMENT SLIDER PIPE		Drwn. By: DEVIN MAST
Dwg. #: R015	Nxt Asb: R500	Date: 12/8/2015	Scale: 1:1	Chkd. By: I. DAVISON

.13

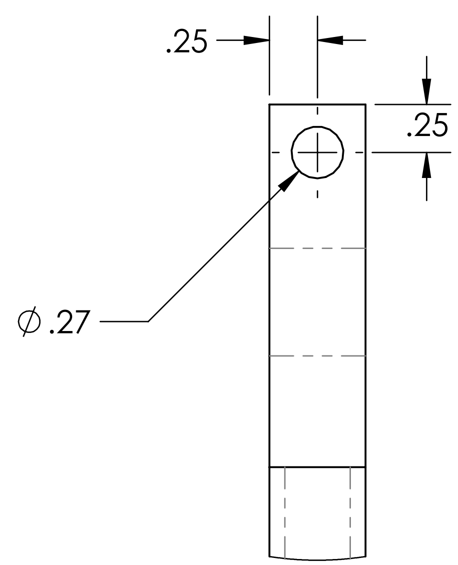
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

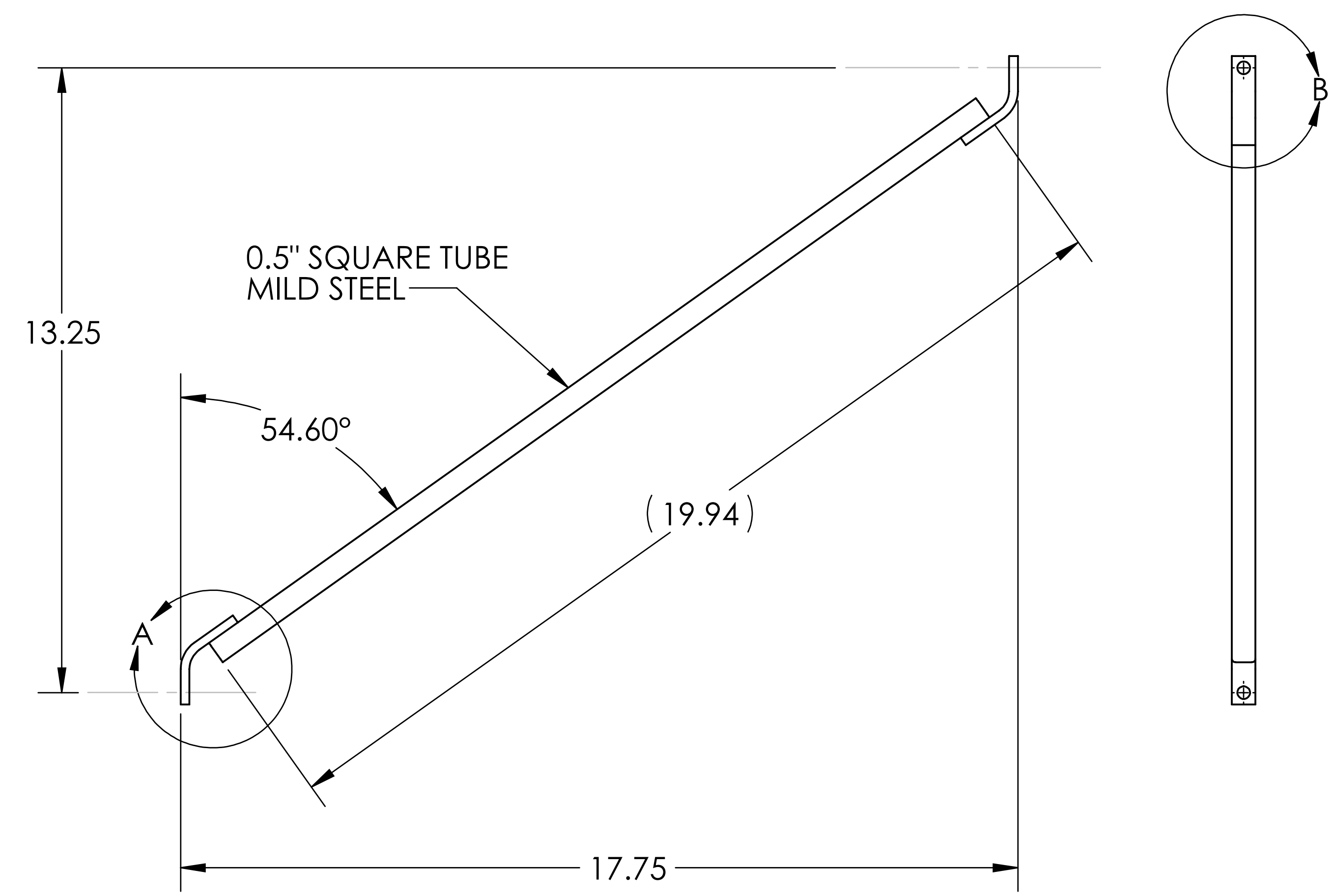
DIMENSIONS IN DETAIL VIEWS
A AND B ARE TYPICAL OF
BOTH ANGLED TABS



DETAIL A
SCALE 1 : 1



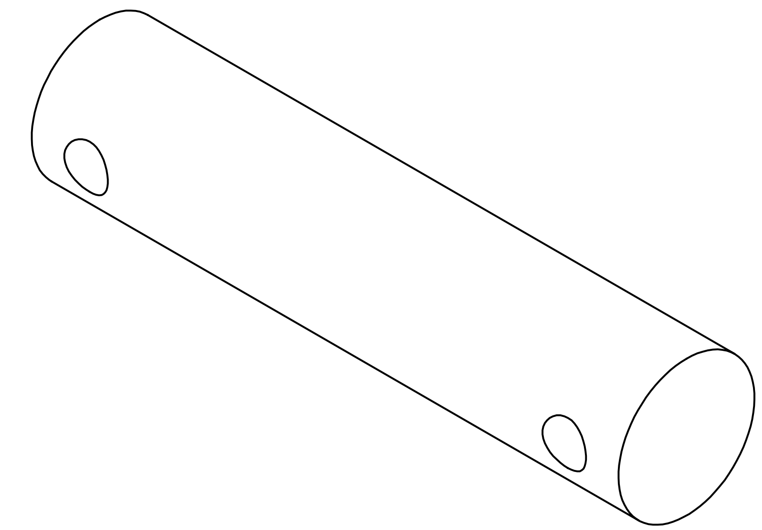
DETAIL B
SCALE 1 : 1

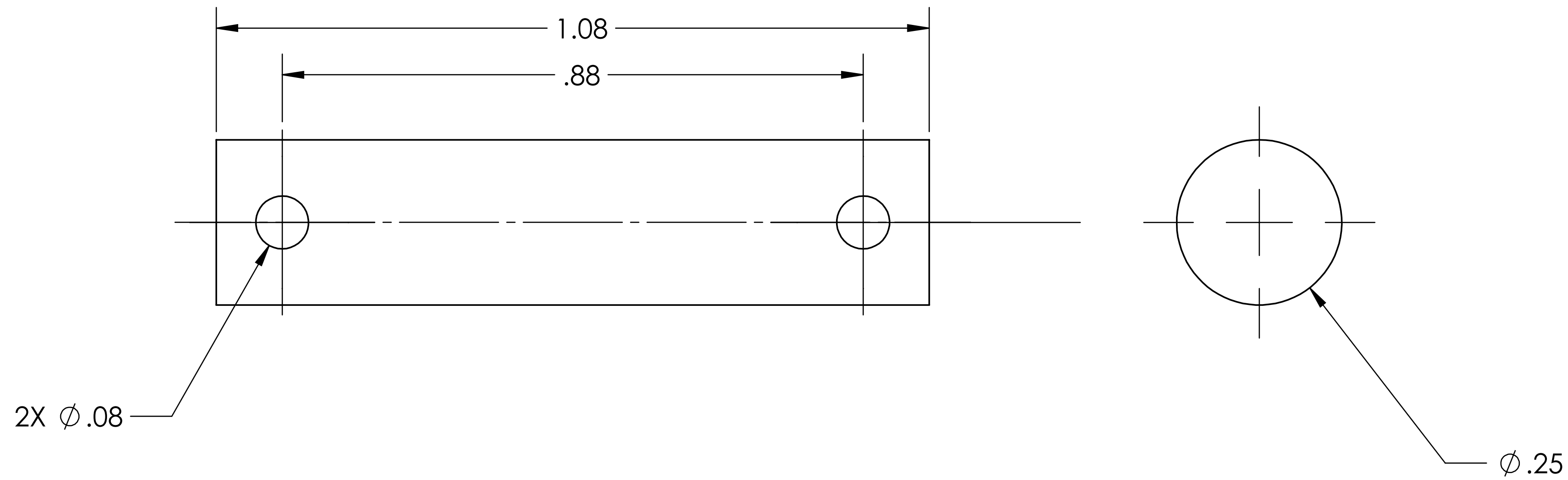


Lab Section: 03	SHEET 1 of 1	Title: SUPPORT STRUT		Drwn. By: I. DAVISON
Dwg. #: R903	Nxt Asb: R500	Date: 12/03/15	Scale: 1:12	Chkd. By: DEVIN MAST

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



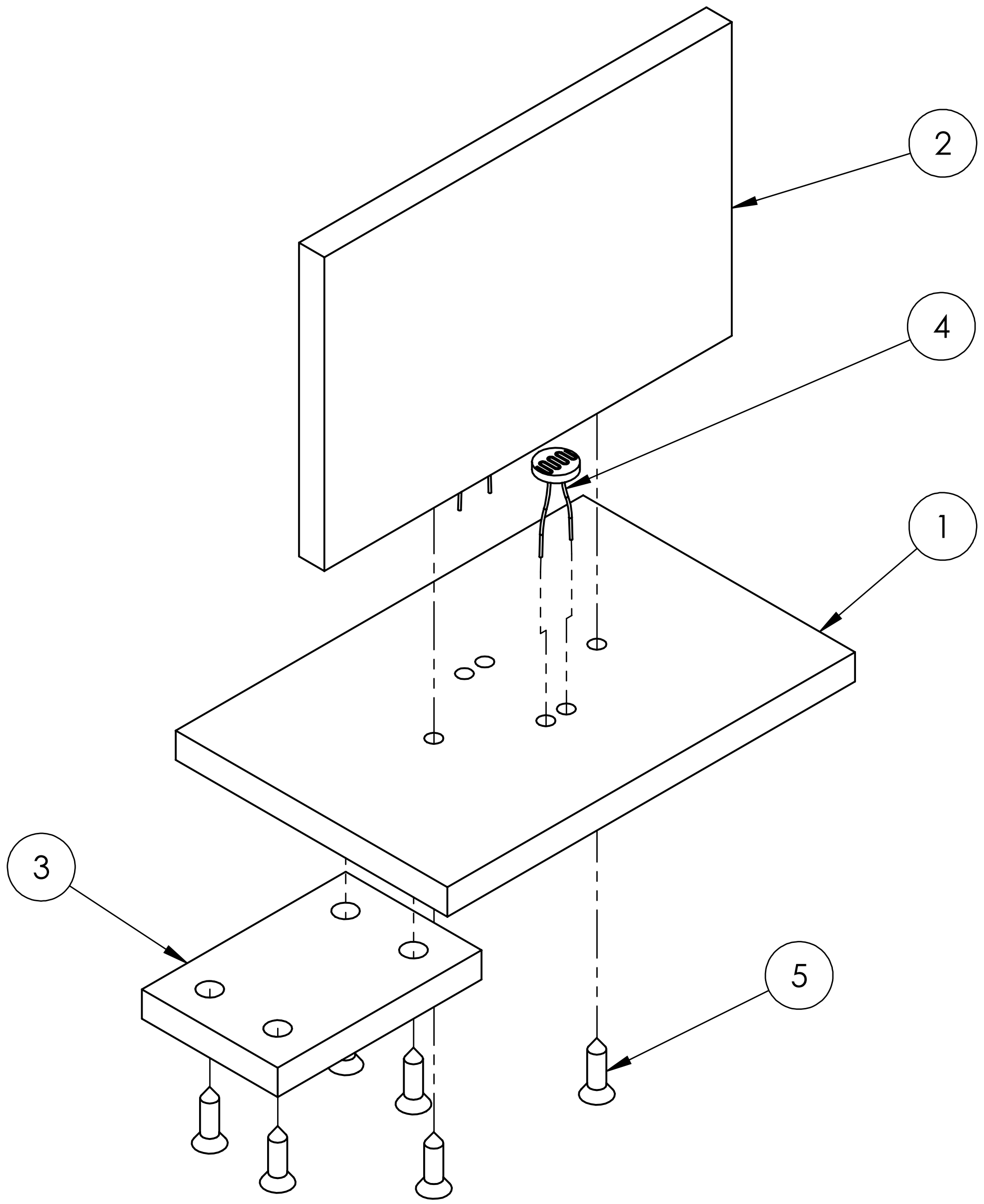


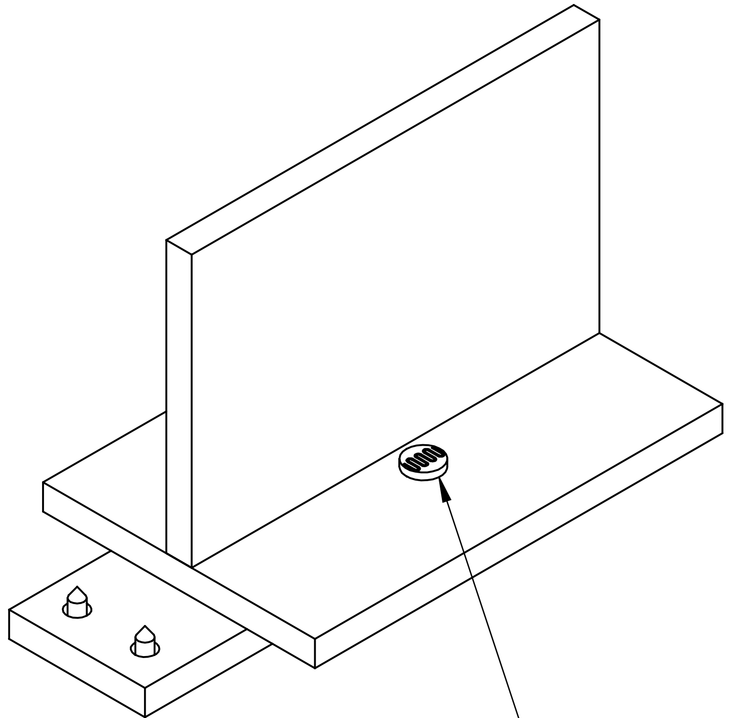
MATERIAL: MILD STEEL

Lab Section: 03	SHEET 1 of 1	Title: SLIDER PIN		Drwn. By: I. DAVISON
Dwg. #: R902	Nxt Asb: R500	Date: 12/03/15	Scale: 4:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°





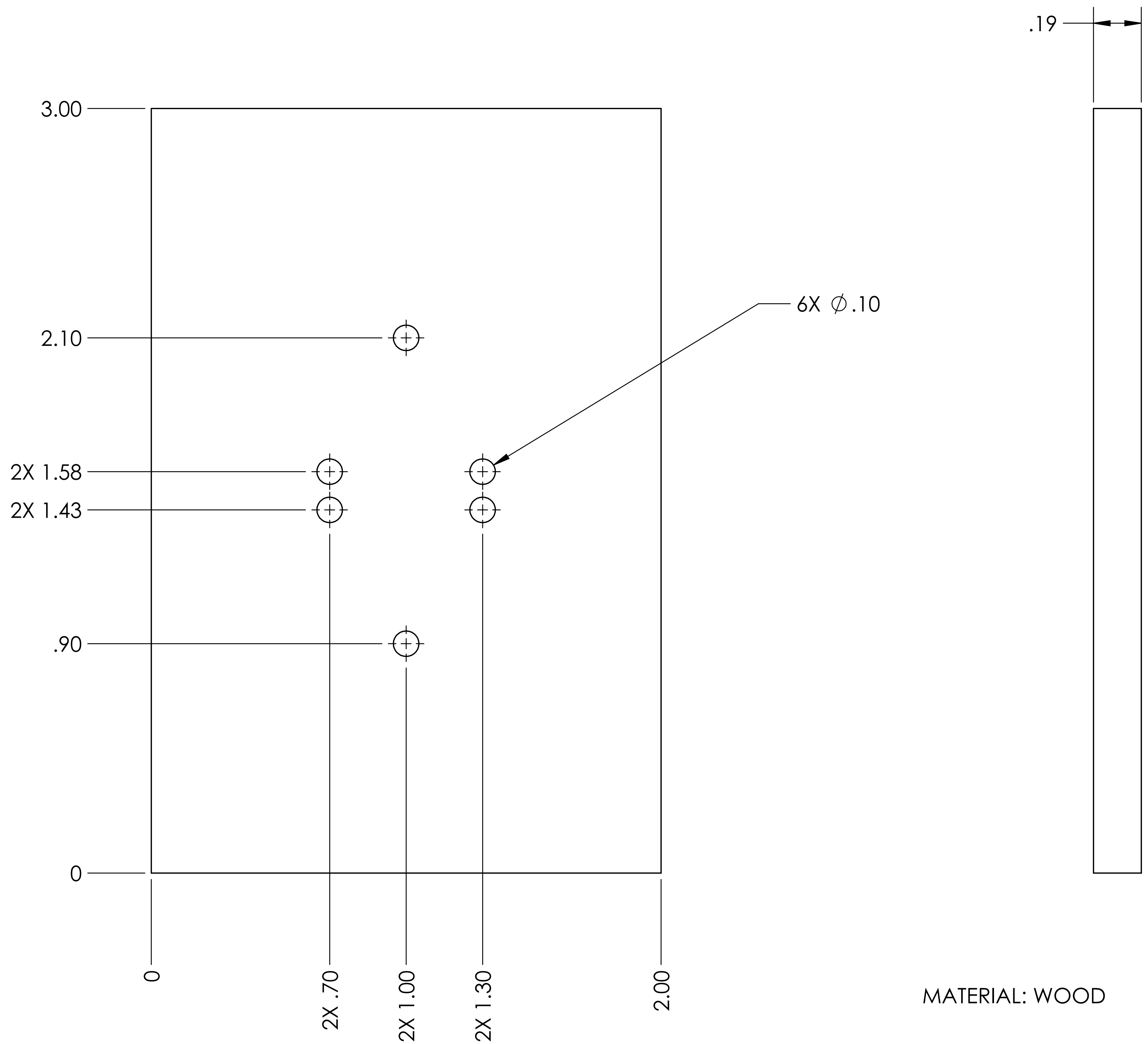
MATERIAL: WOOD

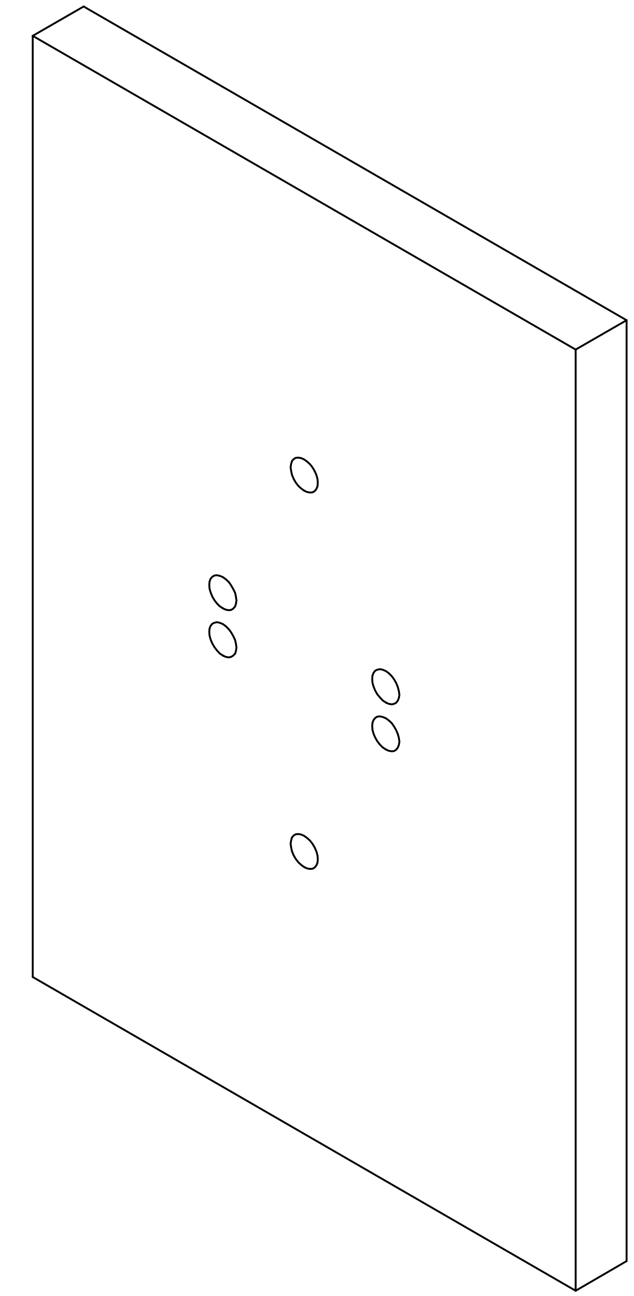
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P001	PHOTOCOMPARATOR BASE	1
2	P002	PHOTOCOMPARATOR DIVIDER	1
3	P004	CONNECTOR BRACKET	1
4	N/A	PHOTORESISTOR	2
5	N/A	#4-40 X .19 WOOD SCREW	6

Lab Section: 03	SHEET 1 of 1	Title: PHOTOCOMPARATOR ASSEMBLY	Drwn. By: I. DAVISON
Dwg. #: R800	Nxt Asb: R500	Date: 12/03/15 / Scale: 1:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



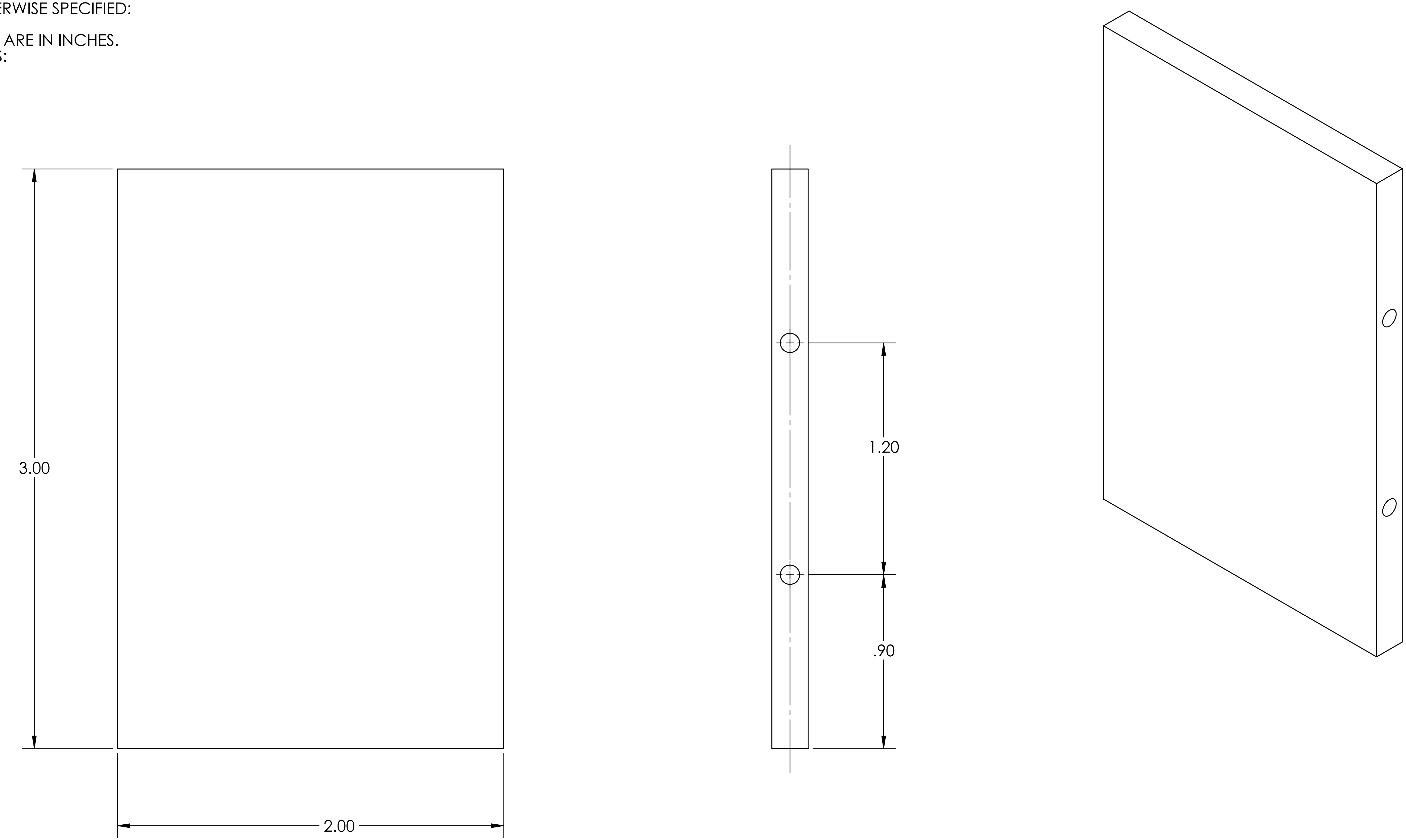


MATERIAL: WOOD

Lab Section: 03	SHEET 1 of 1	Title: PHOTOCOMPARATOR BASE		Drwn. By: I. DAVISON
Dwg. #: P001	Nxt Asb: R800	Date: 12/8/2015	Scale: 2:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

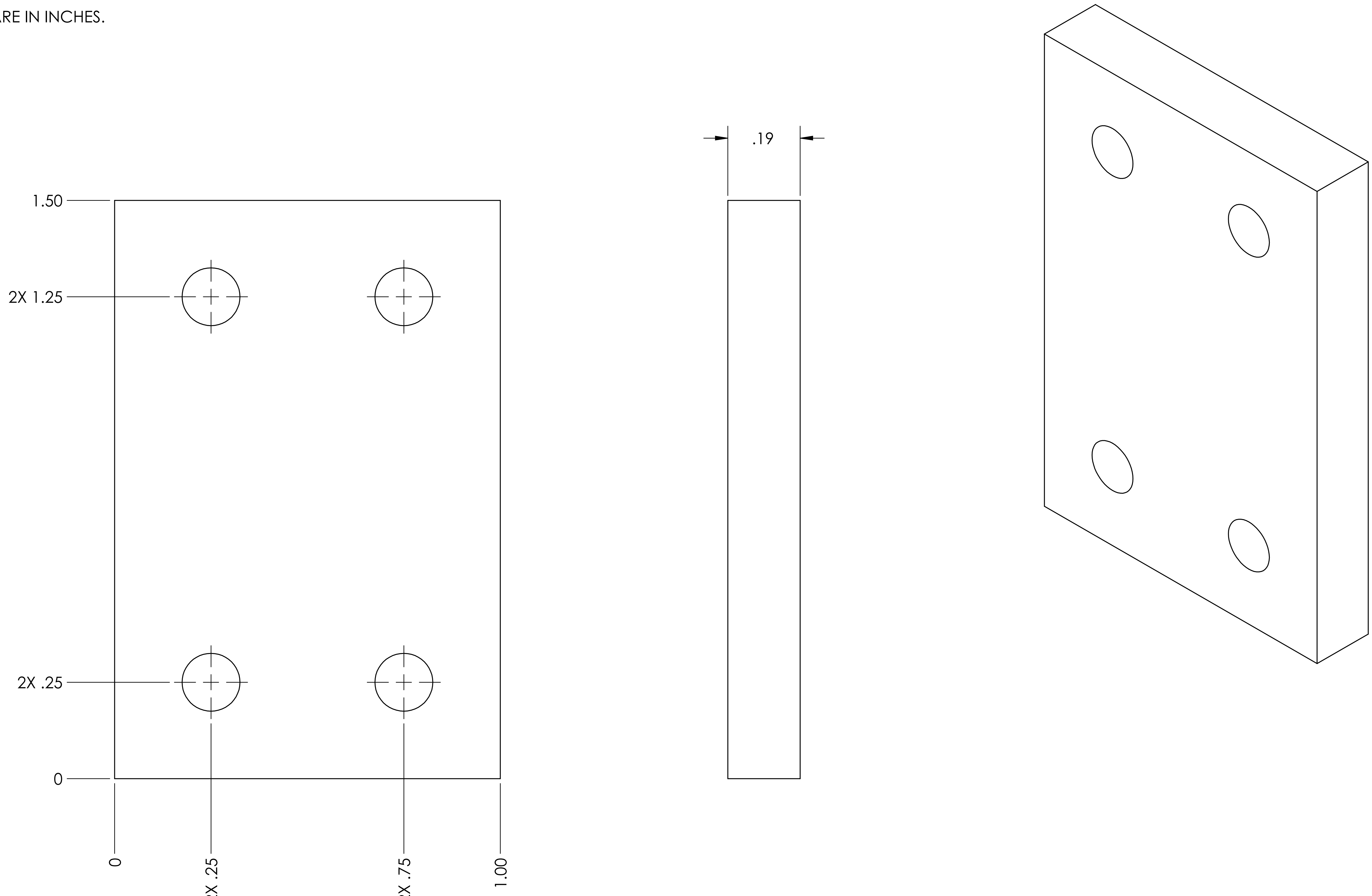


MATERIAL: WOOD

Lab Section: 03	SHEET 1 of 1	Title: PHOTOCOMPARATOR DIVIDER		Drwn. By: I. DAVISON
Dwg. #: P002	Nxt Asb: R800	Date: 12/8/2015	Scale: 2:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

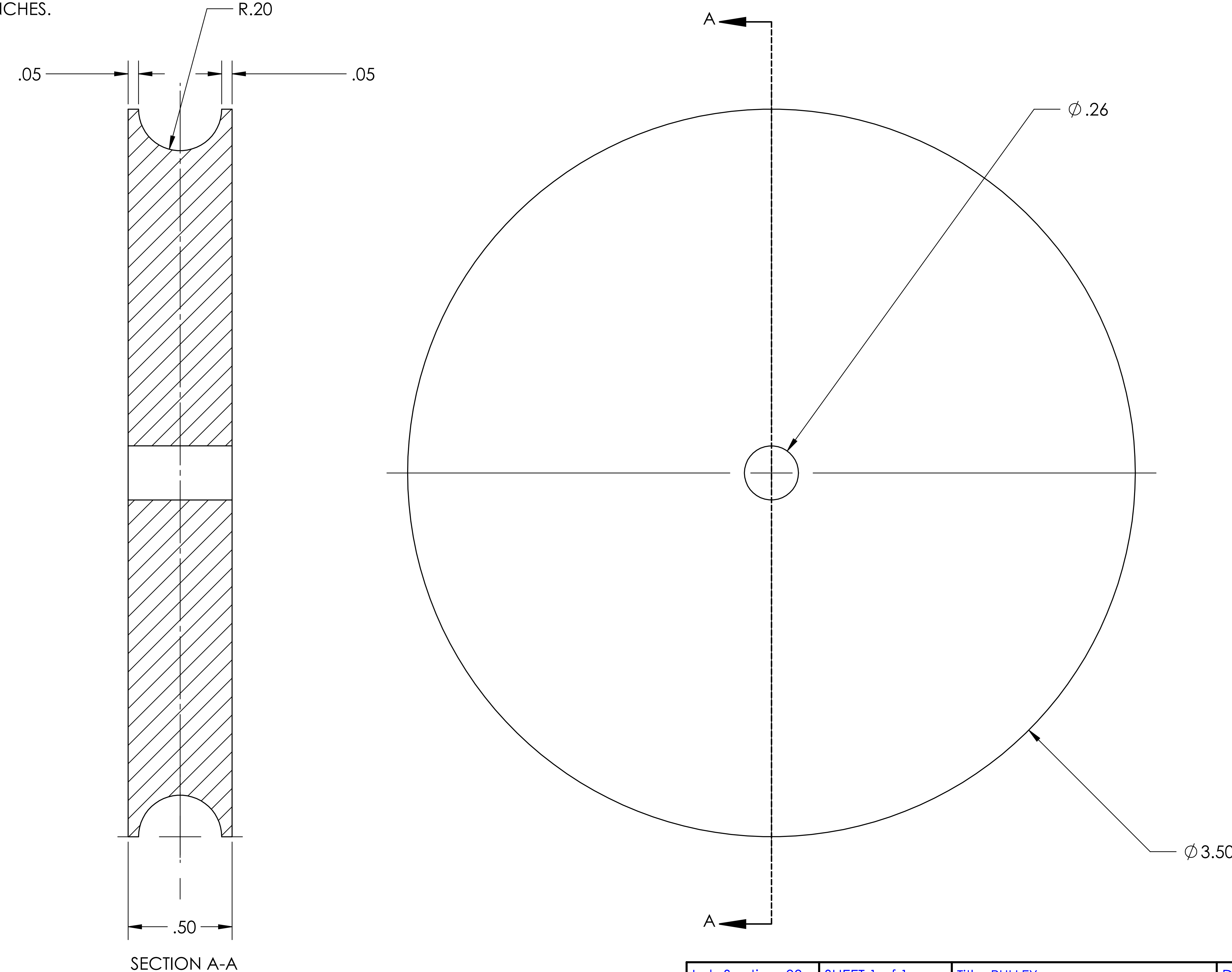
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



Lab Section: 03	SHEET 1 of 1	Title: CONNECTOR BRACKET		Drwn. By: I. DAVISON
Dwg. #: P004	Nxt Asb: R800	Date: 12/8/2015	Scale: 4:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

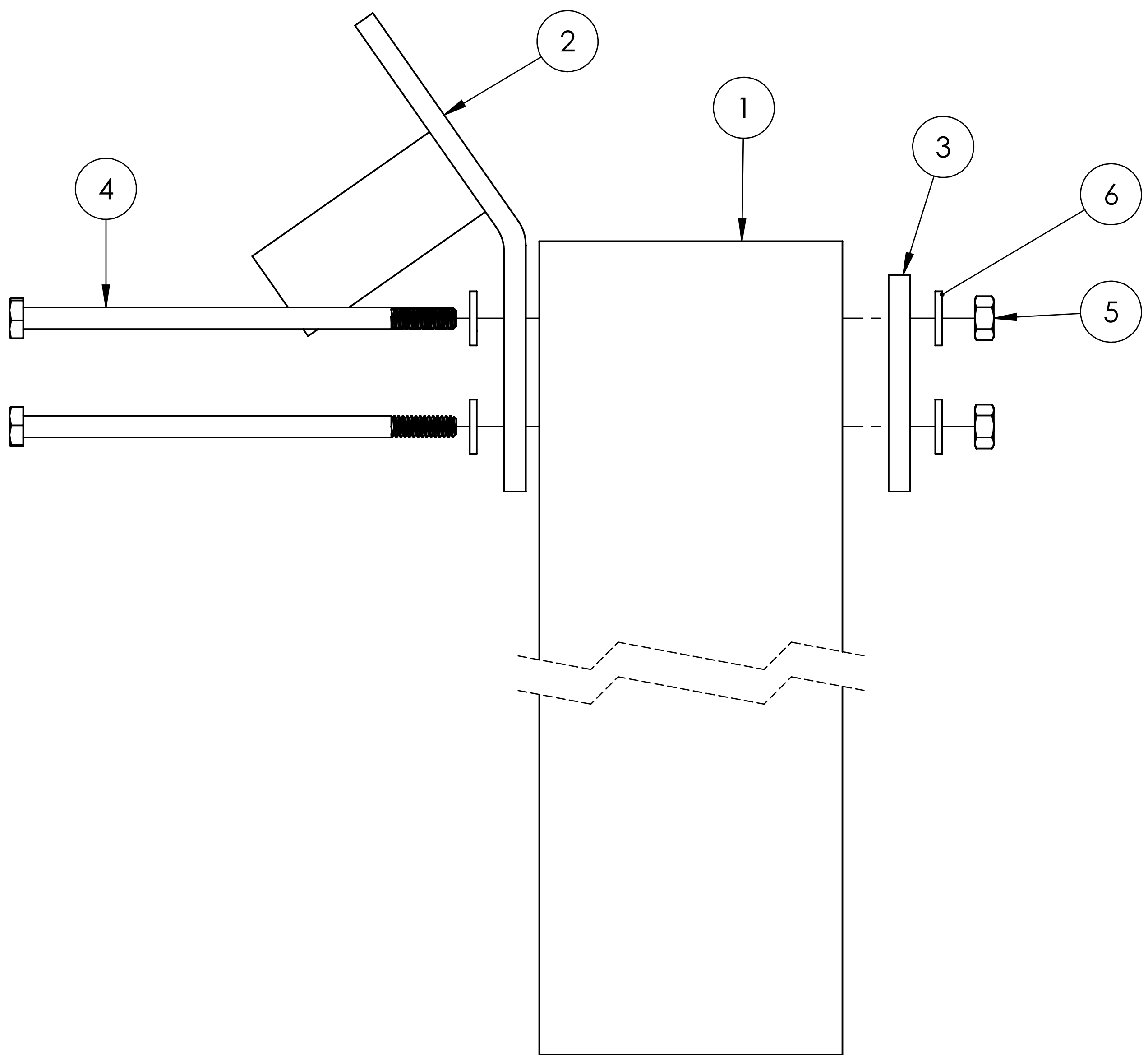
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

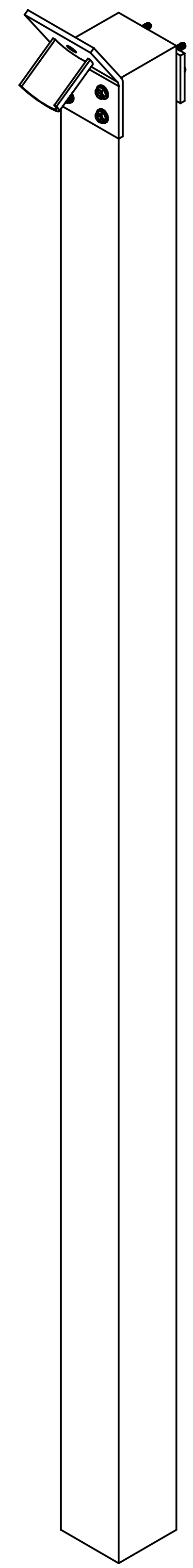


Lab Section: 03	SHEET 1 of 1	Title: PULLEY		Drwn. By: I. DAVISON
Dwg. #: R901	Nxt Asb: R500	Date: 12/03/15	Scale: 2:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



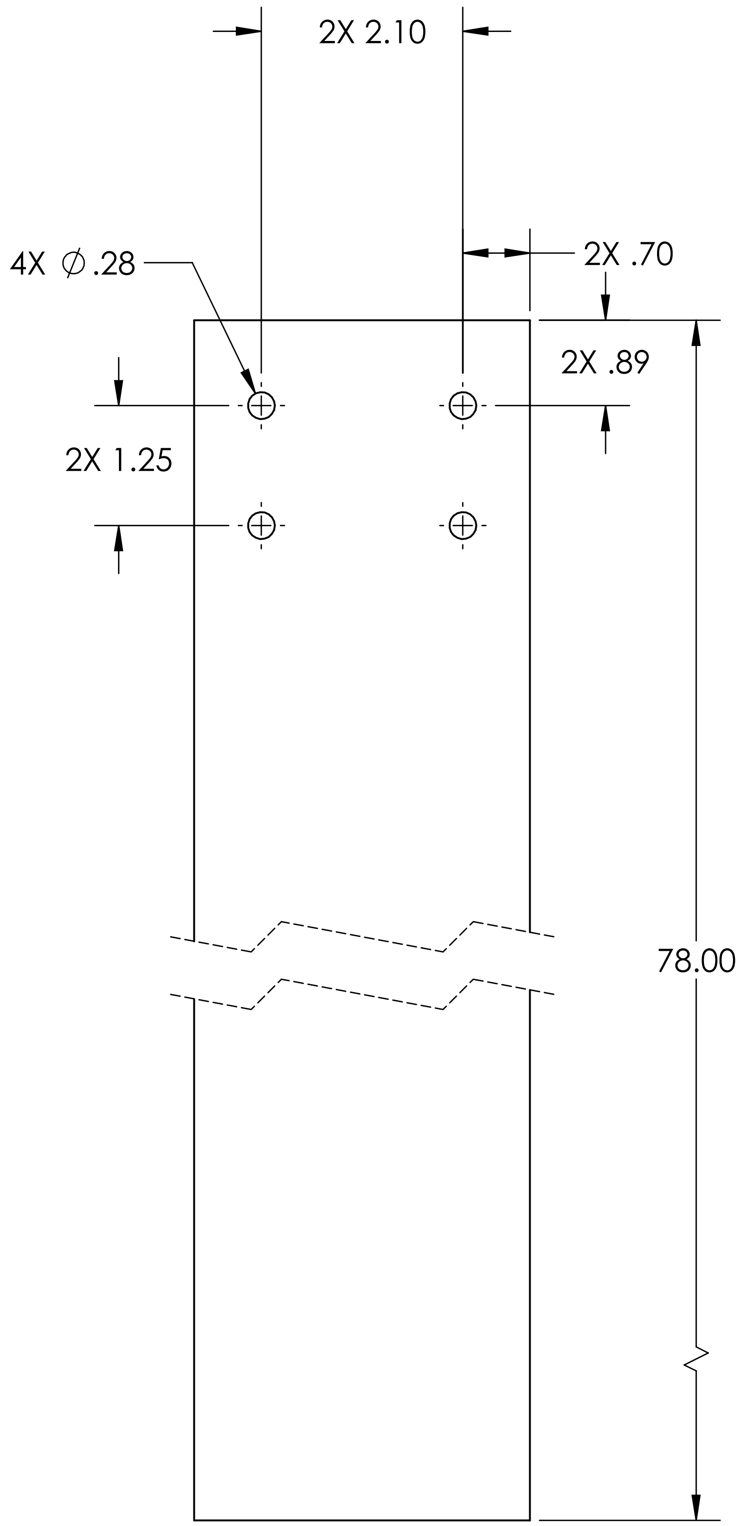


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R101	REAR UPRIGHT POST	1
2	R011	TOP BENT STEEL PLATE WITH PIPE FITTING	1
3	R009	SUPPORT BRACKET PLATE	1
4	91286A128	1/4-20 X 5 STEEL BOLT	4
5	N/A	1/4-20 NUT	4
6	N/A	WASHER FOR .25 INCH	8

Lab Section: 03	SHEET 1 of 1	Title: REAR UPRIGHT ASSEMBLY	Drwn. By: I. DAVISON
Dwg. #: R051	Nxt Asb: R000	Date: 12/03/15 / Scale: 1:2	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

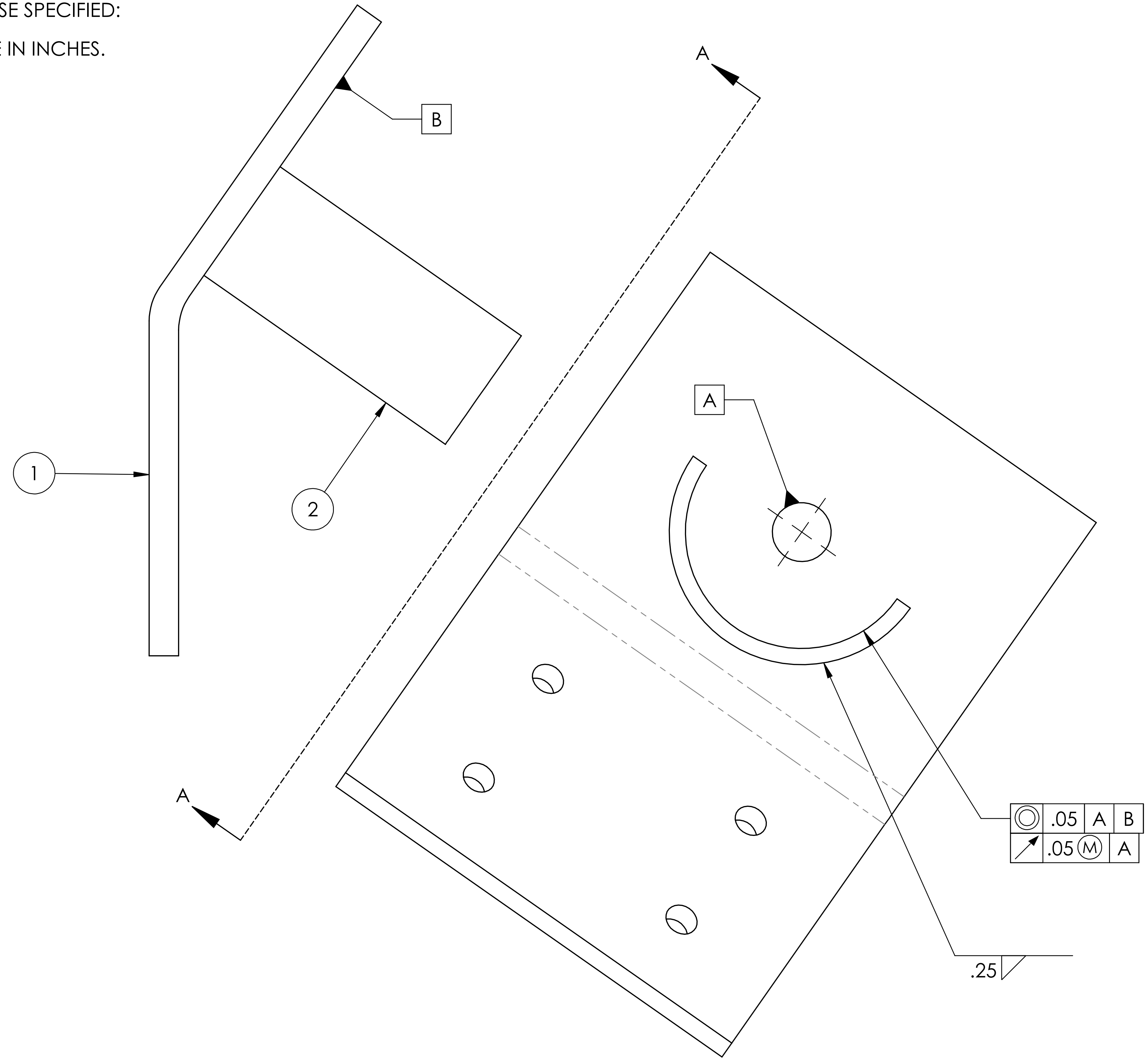


MATERIAL: PINE, 4X4 NOMINAL
FINISH: WEATHERPROOF PAINT, CAL POLY GREEN

Lab Section: 03	SHEET 1 of 1	Title: REAR UPRIGHT POST		Drwn. By: I. DAVISON
Dwg. #: R101	Nxt Asb: R051	Date: 12/03/15	Scale: 1:2	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



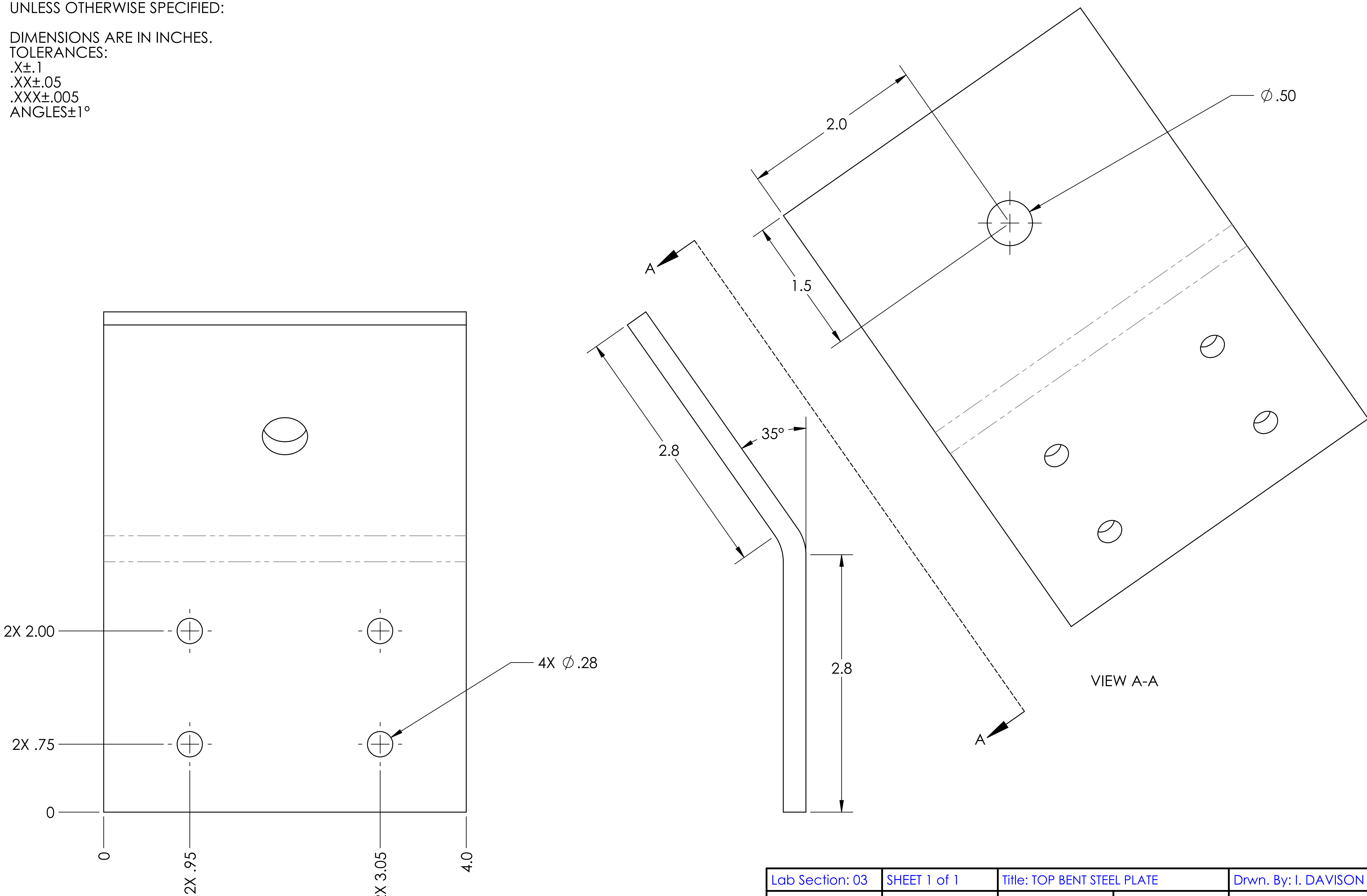
VIEW A-A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	T001	TOP BENT STEEL PLATE	1
2	T002	HALF PIPE	1

Lab Section: 03	SHEET 1 of 1	Title: TOP BENT STEEL PLATE WITH PIPE FITTING		Drwn. By: I. DAVISON
Dwg. #: R011	Nxt Asb: R051	Date: 12/03/15	Scale: 1:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

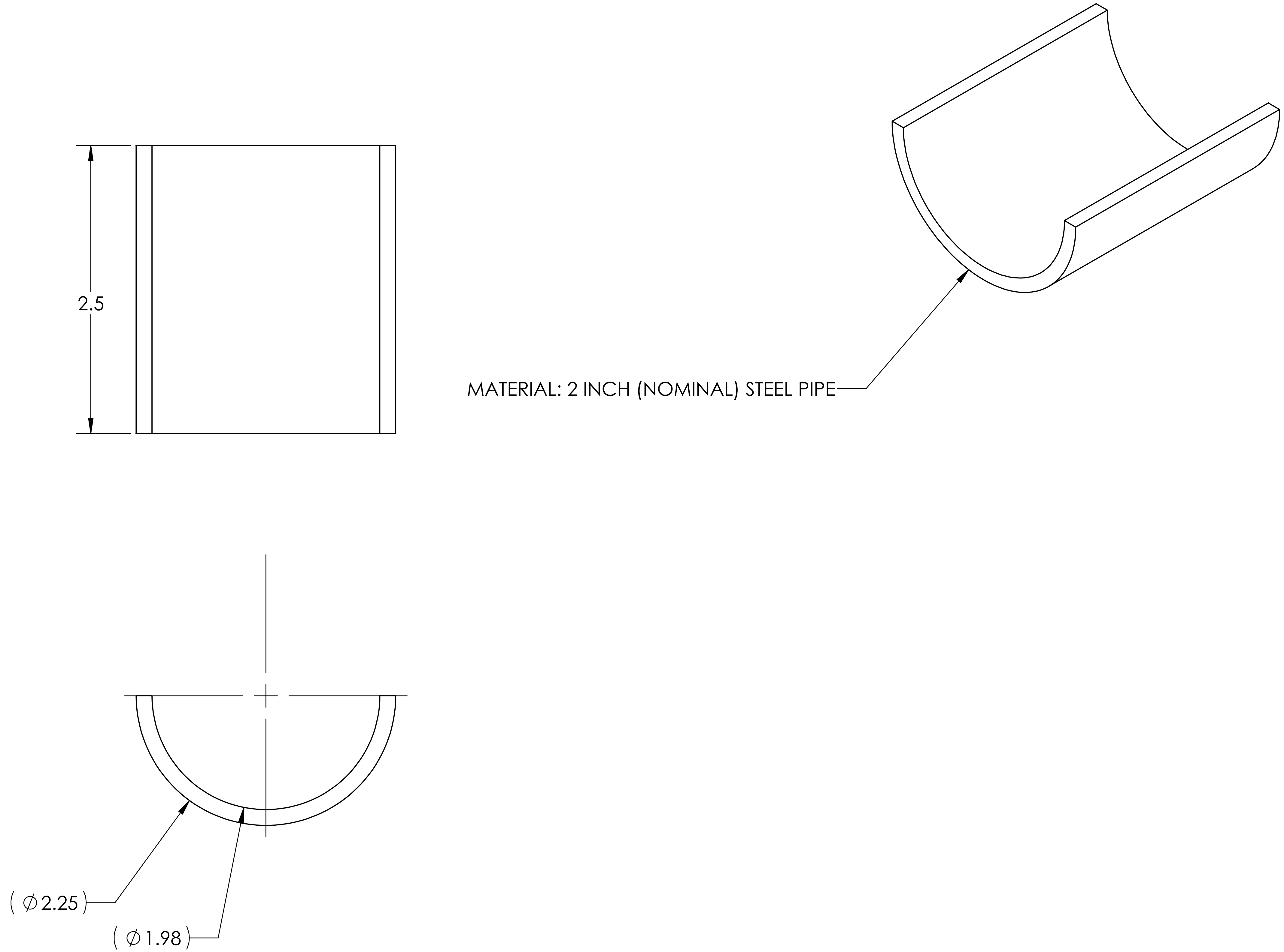
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



Lab Section: 03	SHEET 1 of 1	Title: TOP BENT STEEL PLATE		Drwn. By: I. DAVISON
Dwg. #: T001	Nxt Asb: R011	Date: 12/03/15	Scale: 1:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

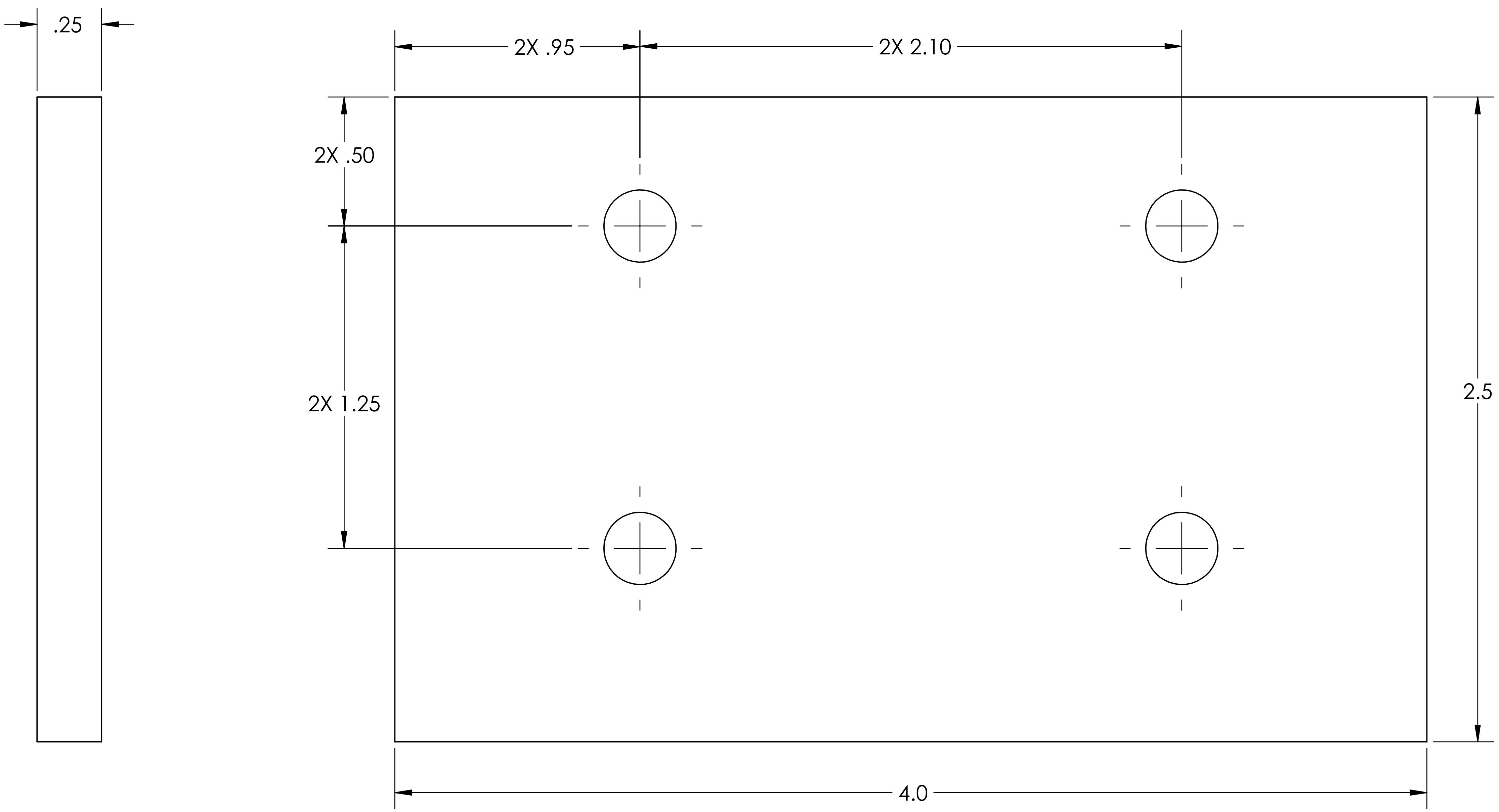
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



Lab Section: 03	SHEET 1 of 1	Title: HALF PIPE		Drwn. By: I. DAVISON
Dwg. #: T002	Nxt Asb: R011	Date: 12/8/2015	Scale: 1:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

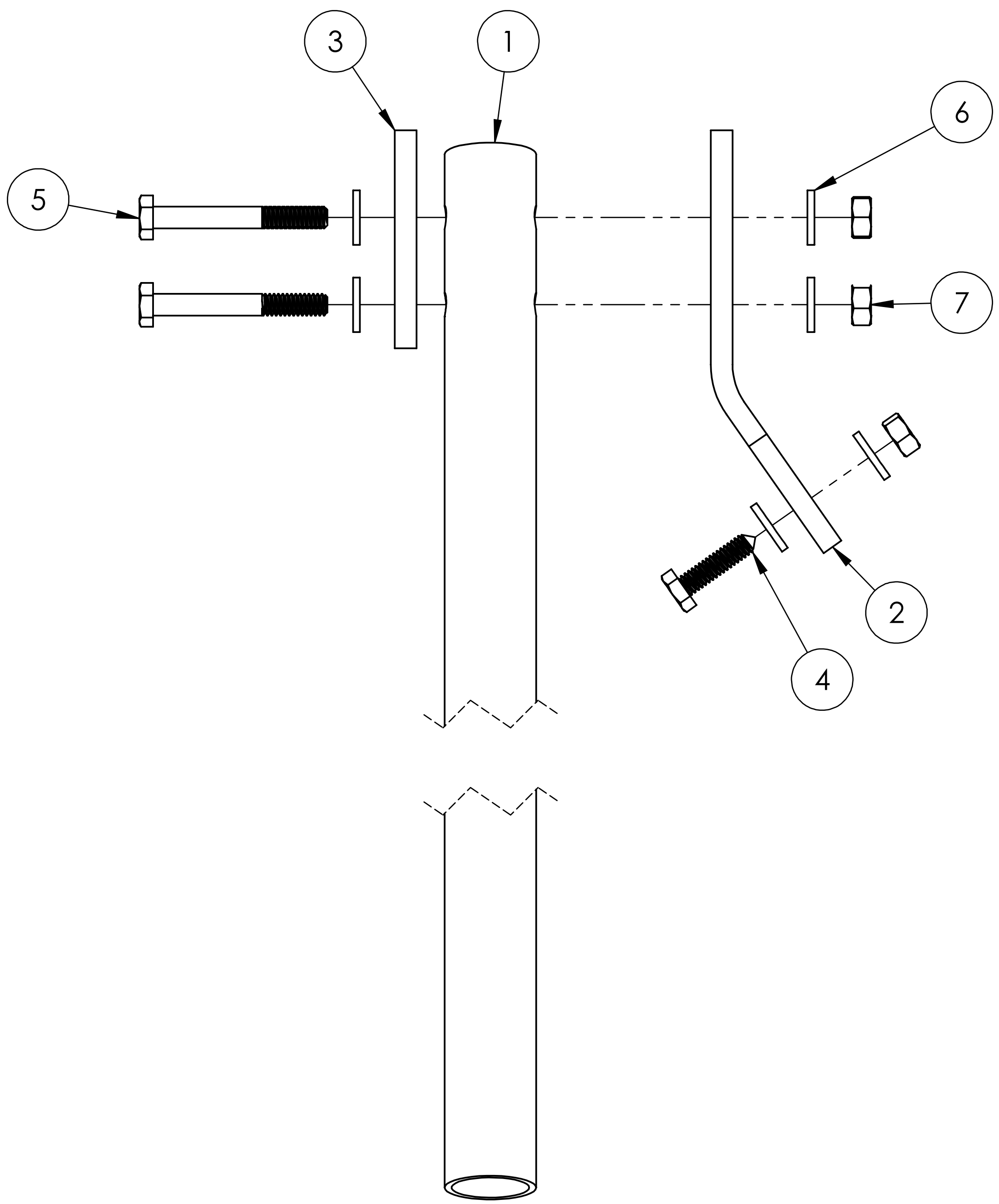


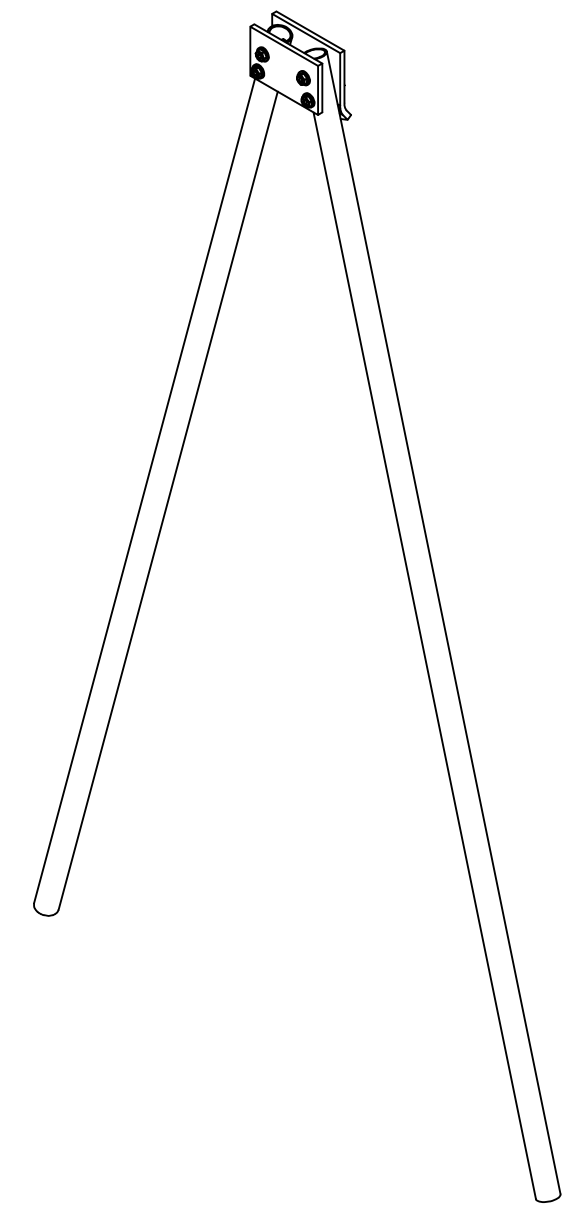
MATERIAL: MILD STEEL

Lab Section: 03	SHEET 1 of 1	Title: SUPPORT BRACKET PLATE		Drwn. By: I. DAVISON
Dwg. #: R009	Nxt Asb: R051	Date: 12/03/15	Scale: 2:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



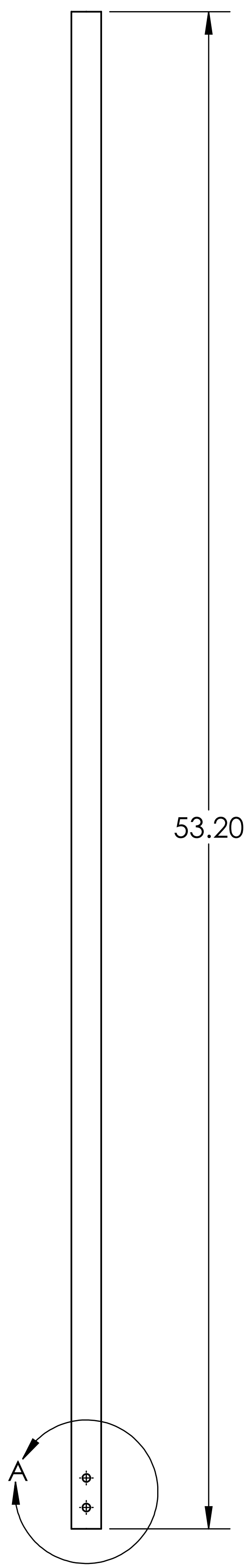


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	R007	1.5" SHORT STEEL PIPE LEG	2
2	R008	BOTTOM BENT STEEL PLATE	1
3	R010	BOTTOM BRACKET PLATE	1
4	R012	MILLED PIVOT BOLT	1
5	91286A128	1/4-20 X 2 STEEL BOLT	4
6	N/A	WASHER FOR .25 INCH	10
7	N/A	1/4-20 NUT	5

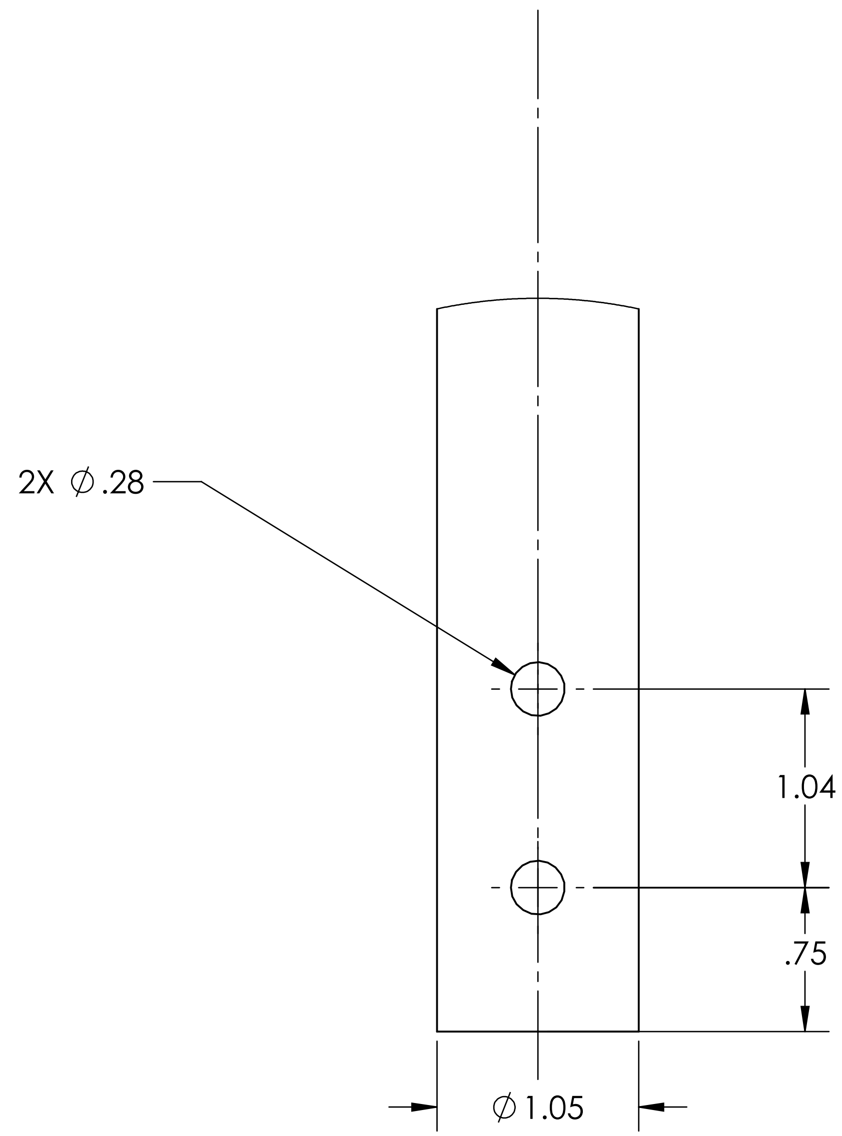
Lab Section: 03	SHEET 1 of 1	Title: FRONT UPRIGHT ASSEMBLY		Drwn. By: I. DAVISON
Dwg. #: R200	Nxt Asb: R000	Date: 12/03/15	Scale: 1:8	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



MATERIAL: 1 INCH GALVANIZED STEEL PIPE

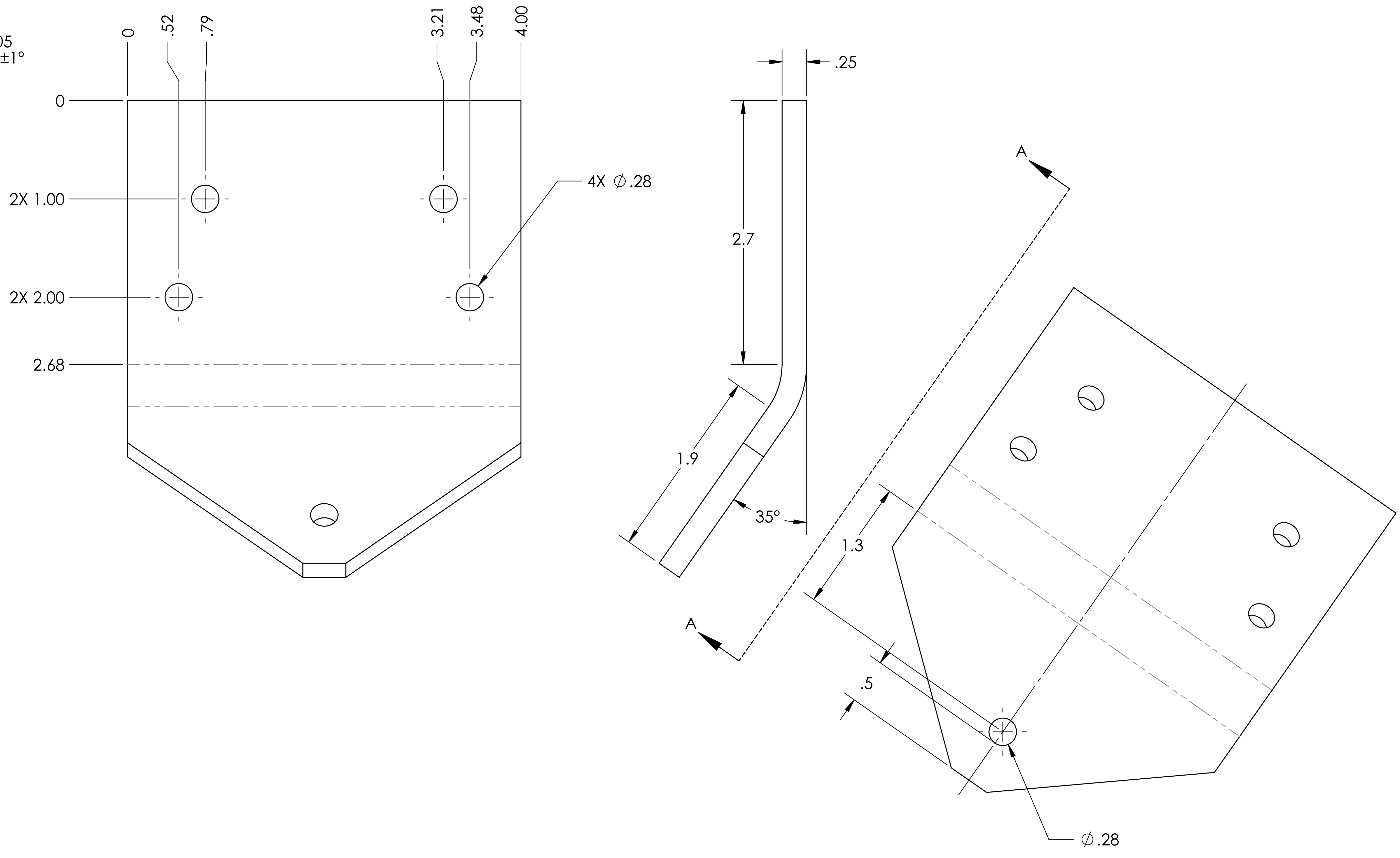


DETAIL A
SCALE 1 : 1

Lab Section: 03	SHEET 1 of 1	Title: 1.5 STEEL PIPE LEG		Drwn. By: DEVIN MAST
Dwg. #: R007	Nxt Asb: R200	Date: 12/8/2015	Scale: 1:6	Chkd. By: I. DAVISON

UNLESS OTHERWISE SPECIFIED:

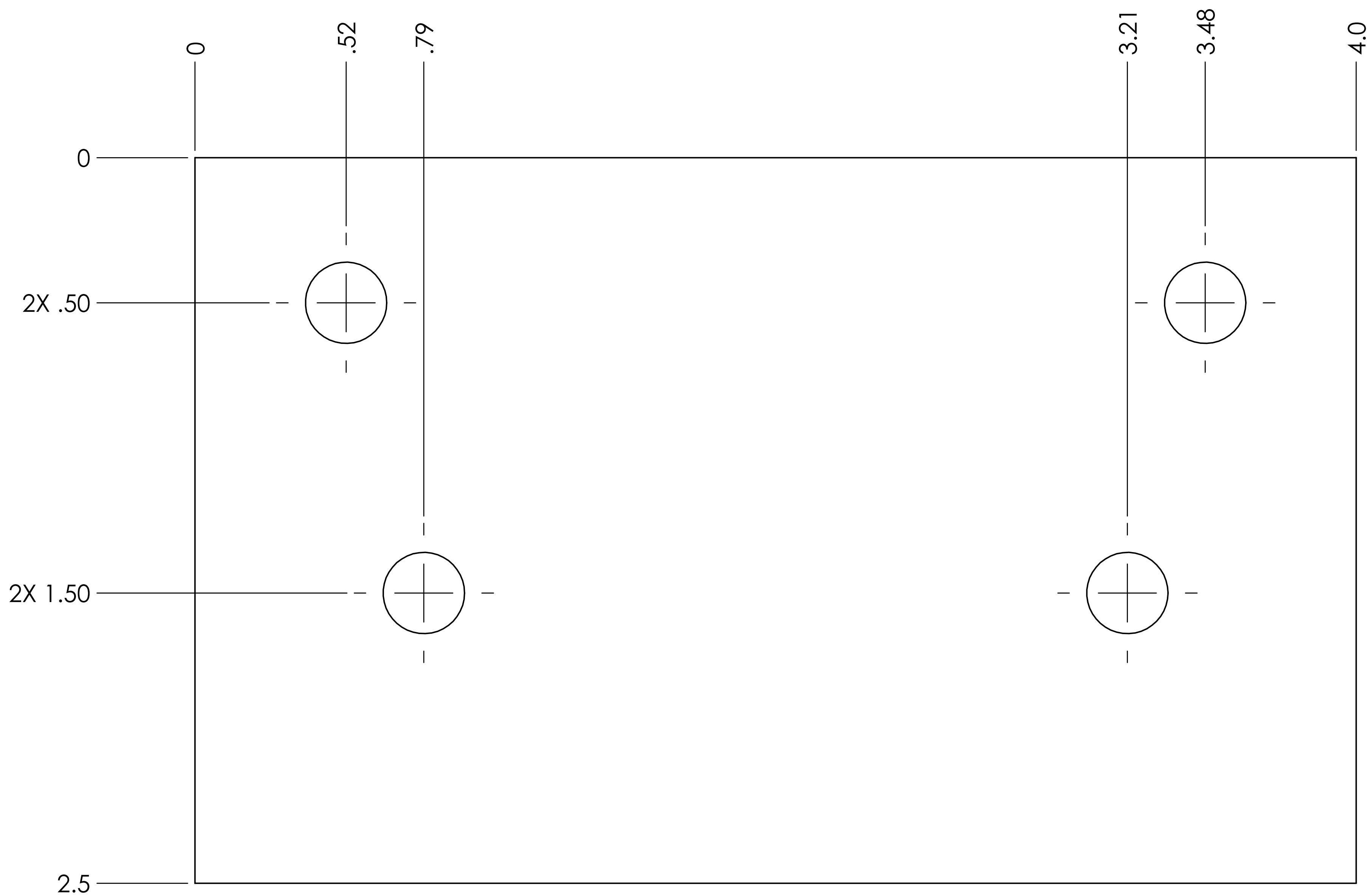
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



Lab Section: 03	SHEET 1 of 1	Title: BOTTOM BENT STEEL PLATE		Drwn. By: I. DAVISON
Dwg. #: R008	Nxt Asb: R200	Date: 12/03/15	Scale: 1:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

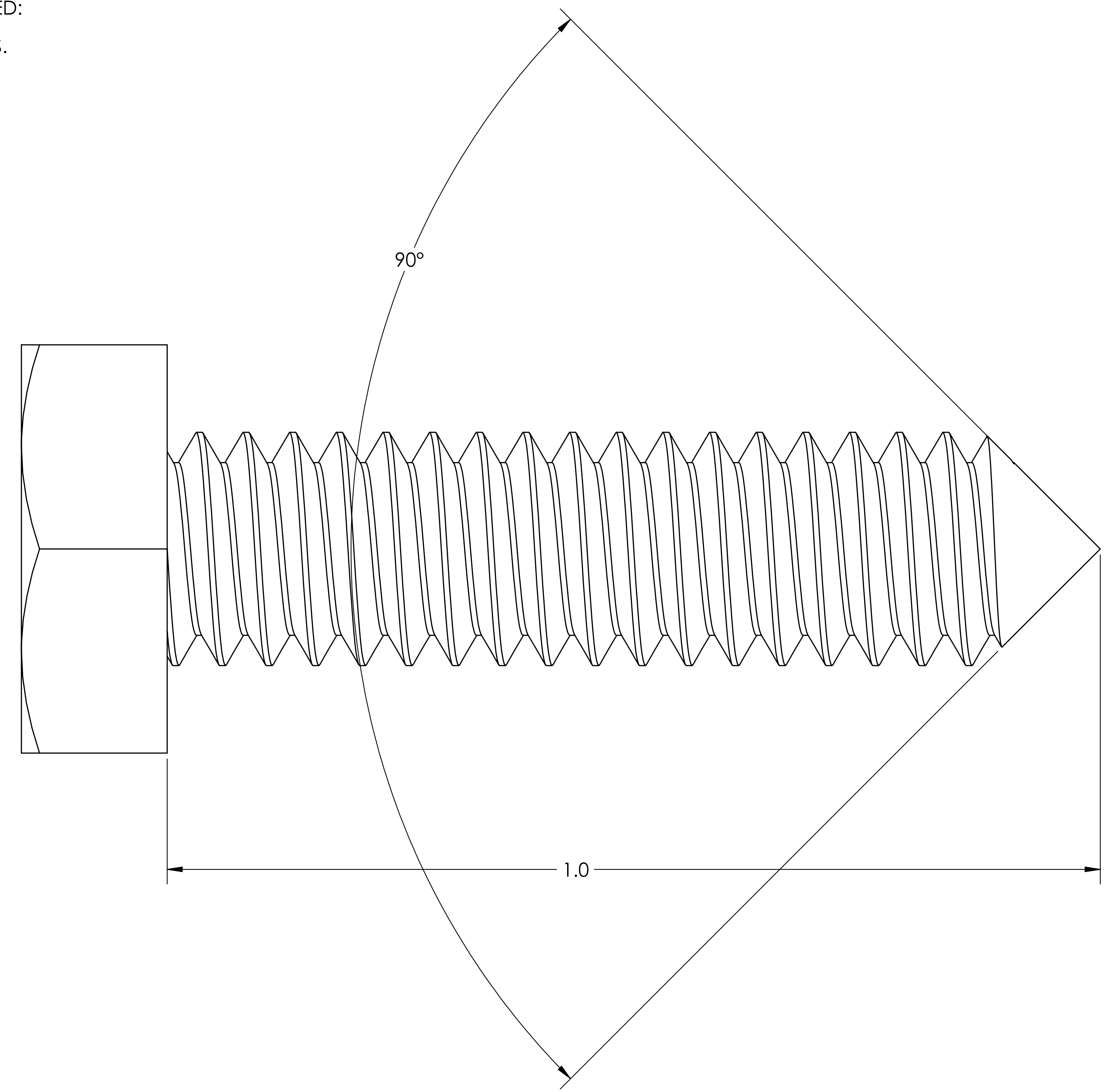


MATERIAL: 1/4 INCH SHEETMETAL, MILD STEEL

Lab Section: 03	SHEET 1 of 1	Title: BOTTOM BRACKET PLATE		Drwn. By: I. DAVISON
Dwg. #: R010	Nxt Asb: R200	Date: 12/03/15	Scale: 2:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

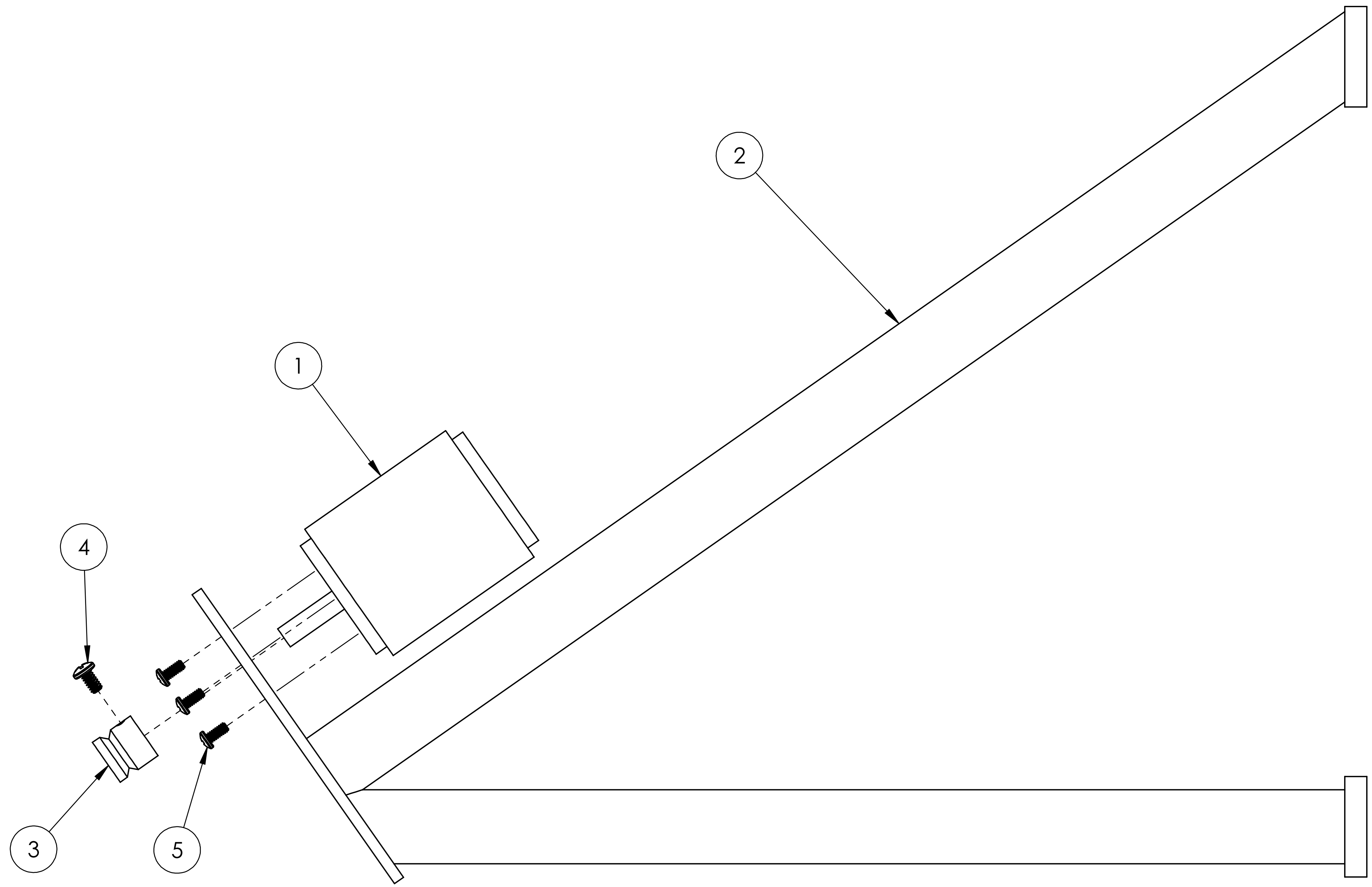


MATERIAL: 1/4-20 X 1.0 SCREW

Lab Section: 03	SHEET 1 of 1	Title: MILLED PIVOT BOLT	Drwn. By: I. DAVISON
Dwg. #: R012	Nxt Asb: R200	Date: 12/03/15 / Scale: 8:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

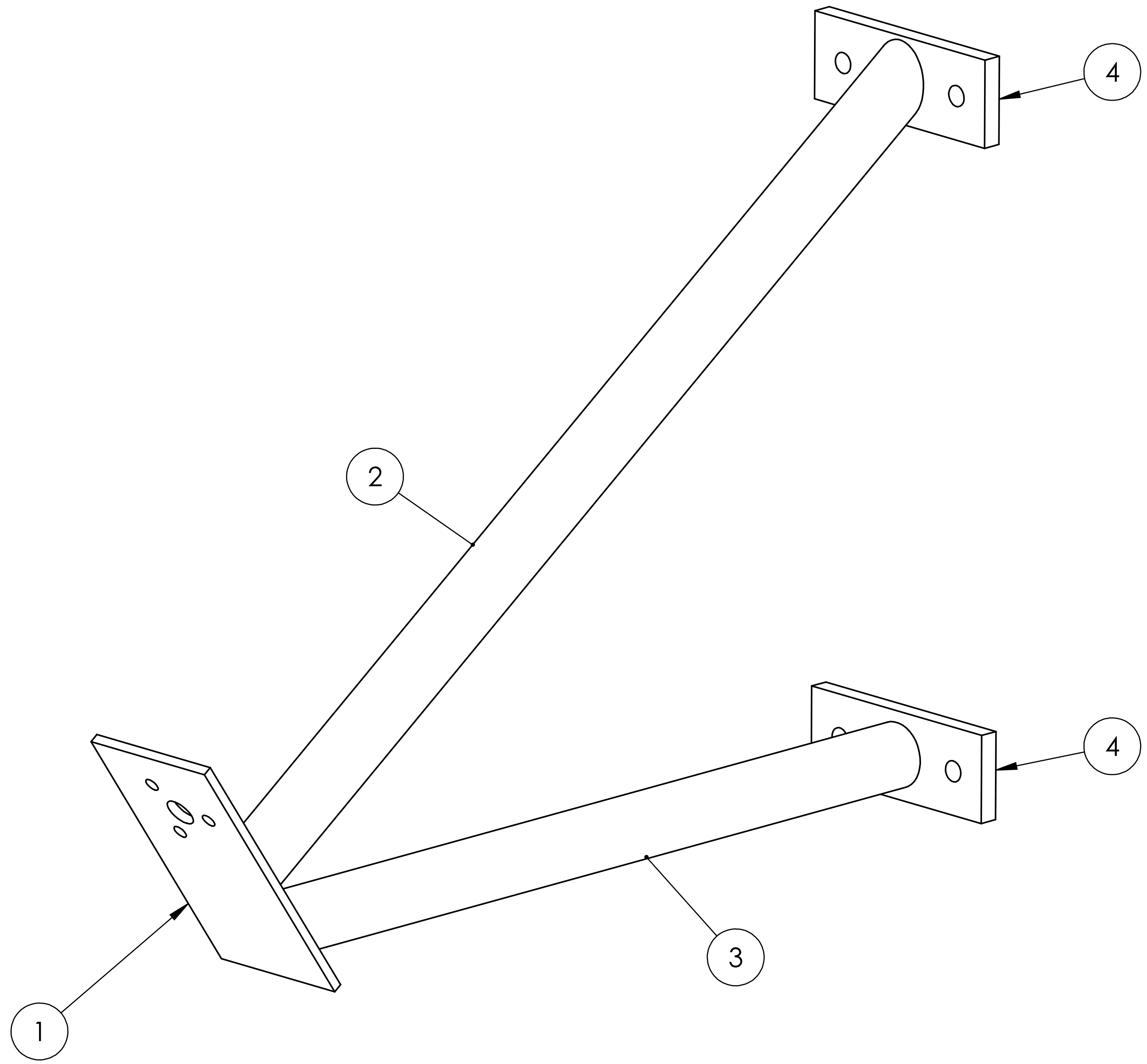
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	a12032000ux0190	12V DC 5 RPM GEARMOTOR	1
2	R020	MOTOR MOUNT	1
3	M503	MOTOR PULLEY	1
4	91400A170	#6-40 X .25 STEEL SCREW	1
5	91735A102	#4-40 X .25 MACHINE SCREW	3

Lab Section: 03	SHEET 1 of 1	Title: MOTOR MOUNT ASSEMBLY		Drwn. By: I. DAVISON
Dwg. #: M400	Nxt Asb: R000	Date: 12/03/15	Scale: 1:2	Chkd. By:

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	MOTOR MATCH PLATE	N/A
2	1	PIPE, SCH 40, .50 DIA.	14.38
3	1	PIPE, SCH 40, .50 DIA.	11.33
4	2	MOUNTING FLANGE	N/A

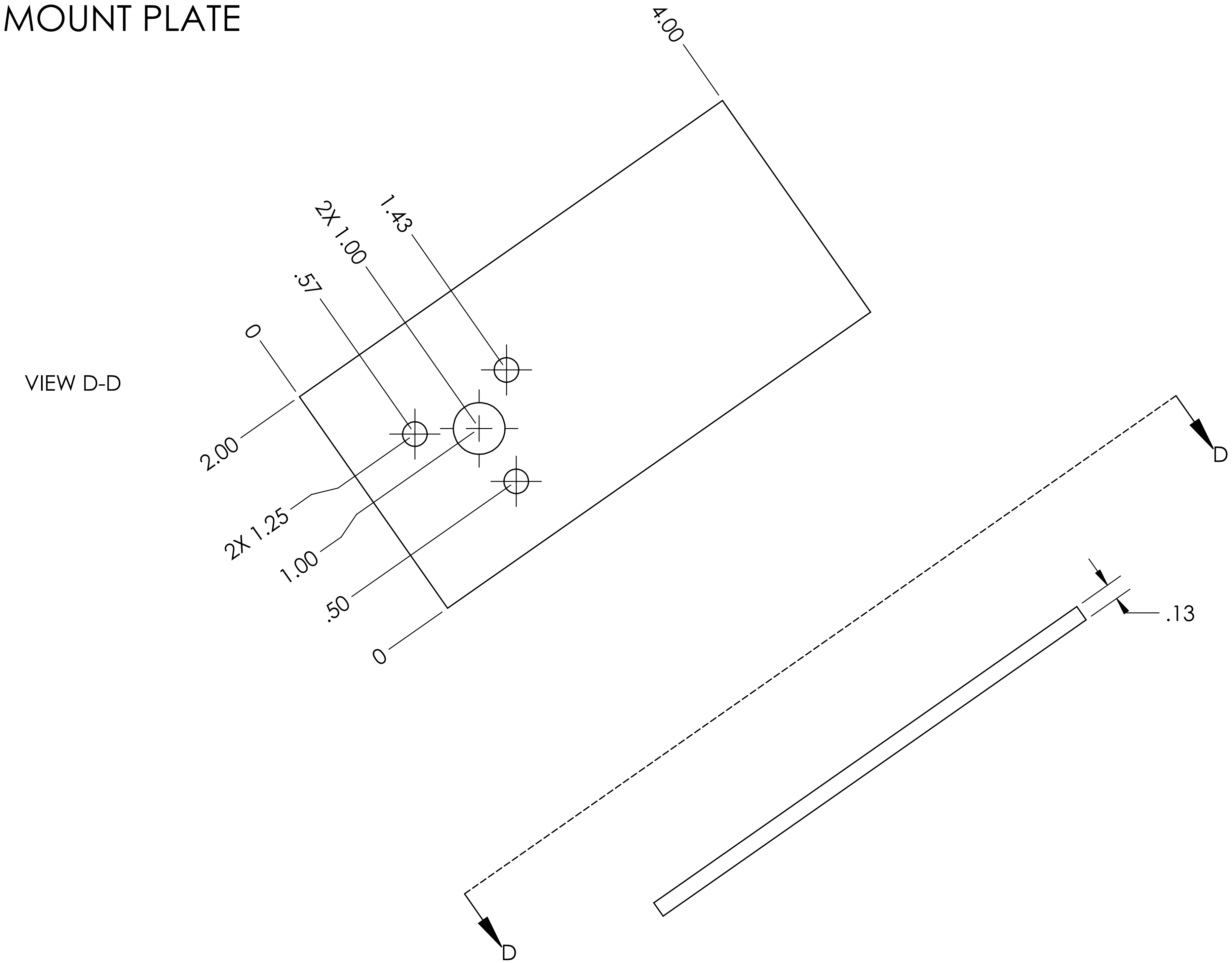


UNLESS OTHERWISE SPECIFIED:

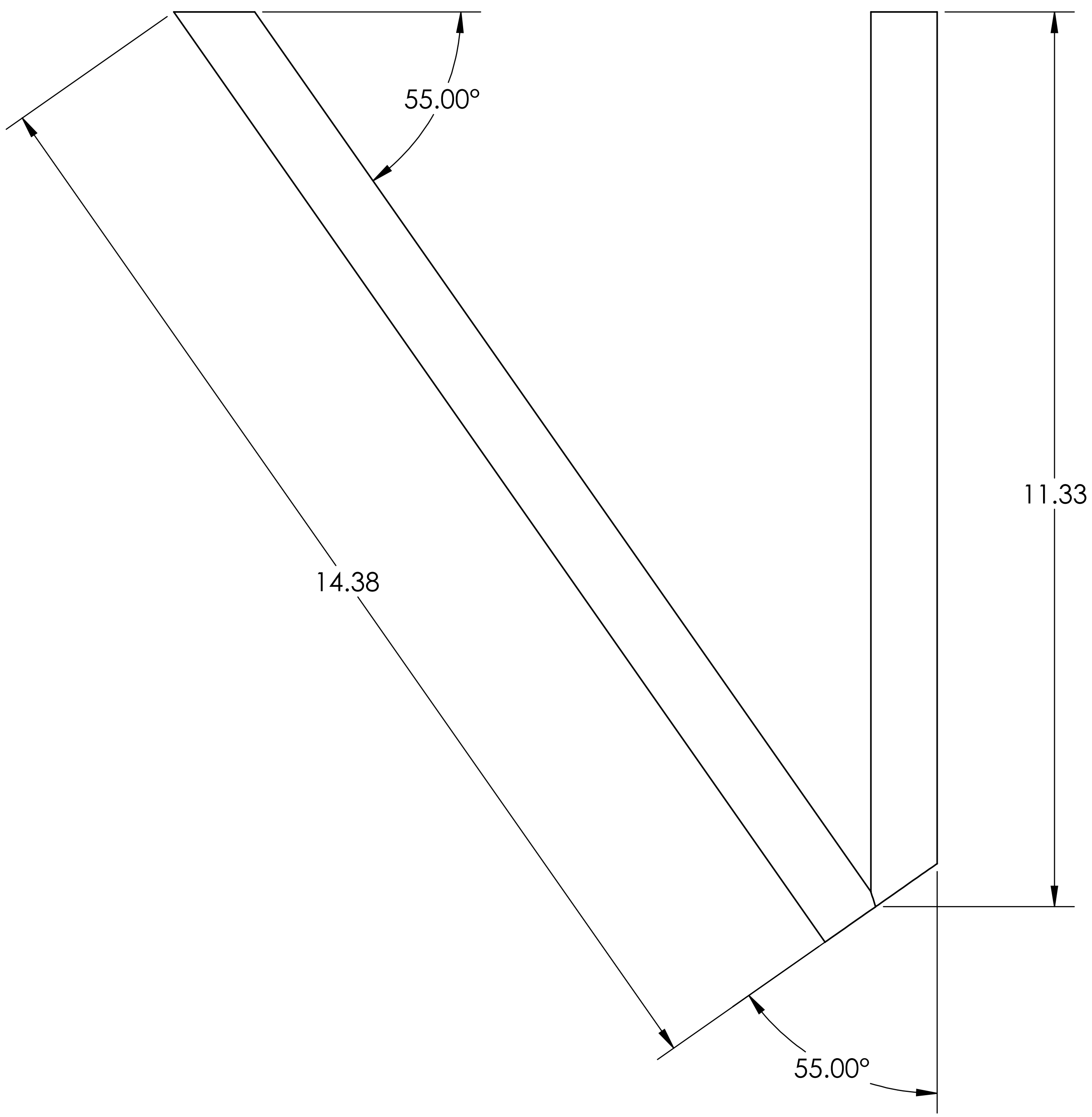
DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

Lab Section: 03	SHEET 1 of 3	Title: MOTOR MOUNT		Drwn. By: I. DAVISON
Dwg. #: R020	Nxt Asb: M400	Date: 12/03/15	Scale: 2:1	Chkd. By:

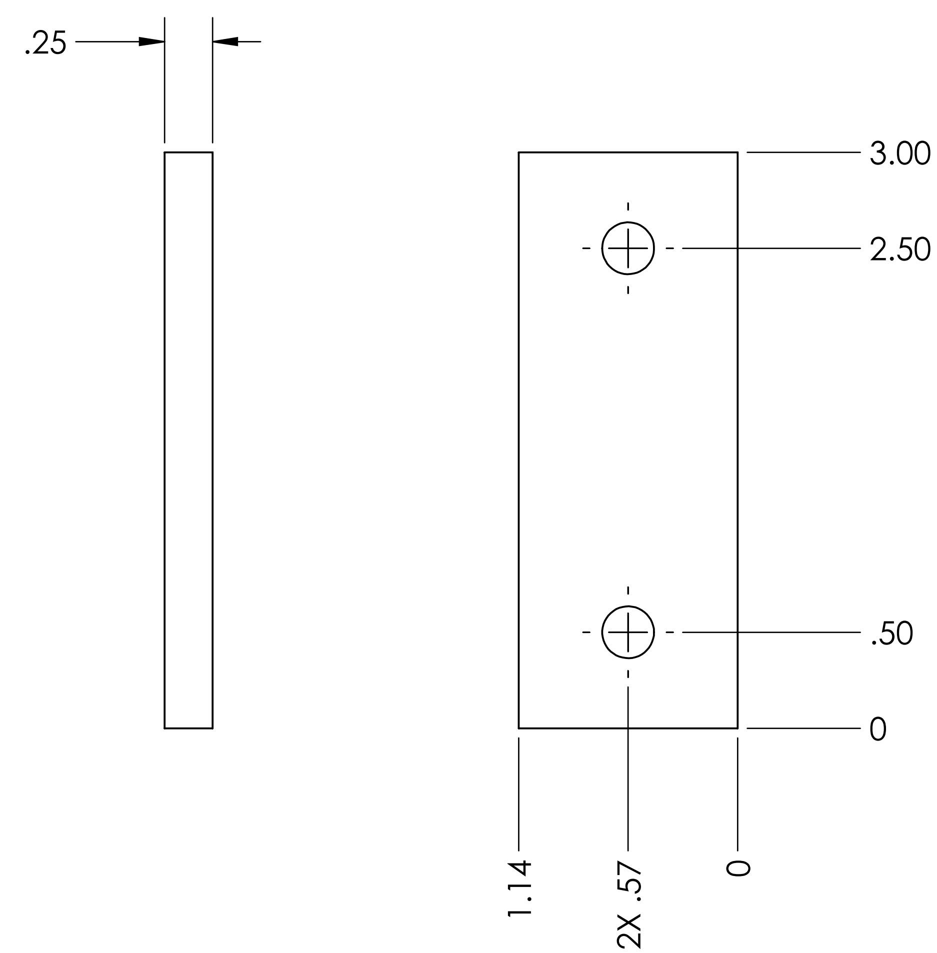
MOTOR MOUNT PLATE



Lab Section: 03	SHEET 2 of 3	Title: MOTOR MOUNT		Drwn. By: I. DAVISON
Dwg. #: R020	Nxt Asb: M400	Date: 12/03/15	Scale: 1:1	Chkd. By:



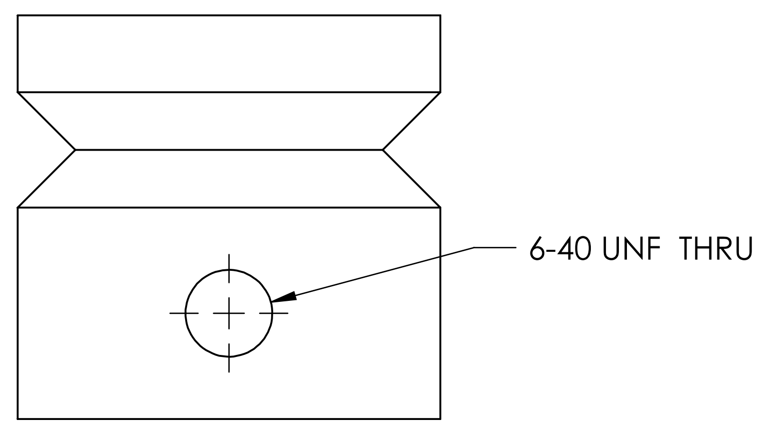
QTY.: 2

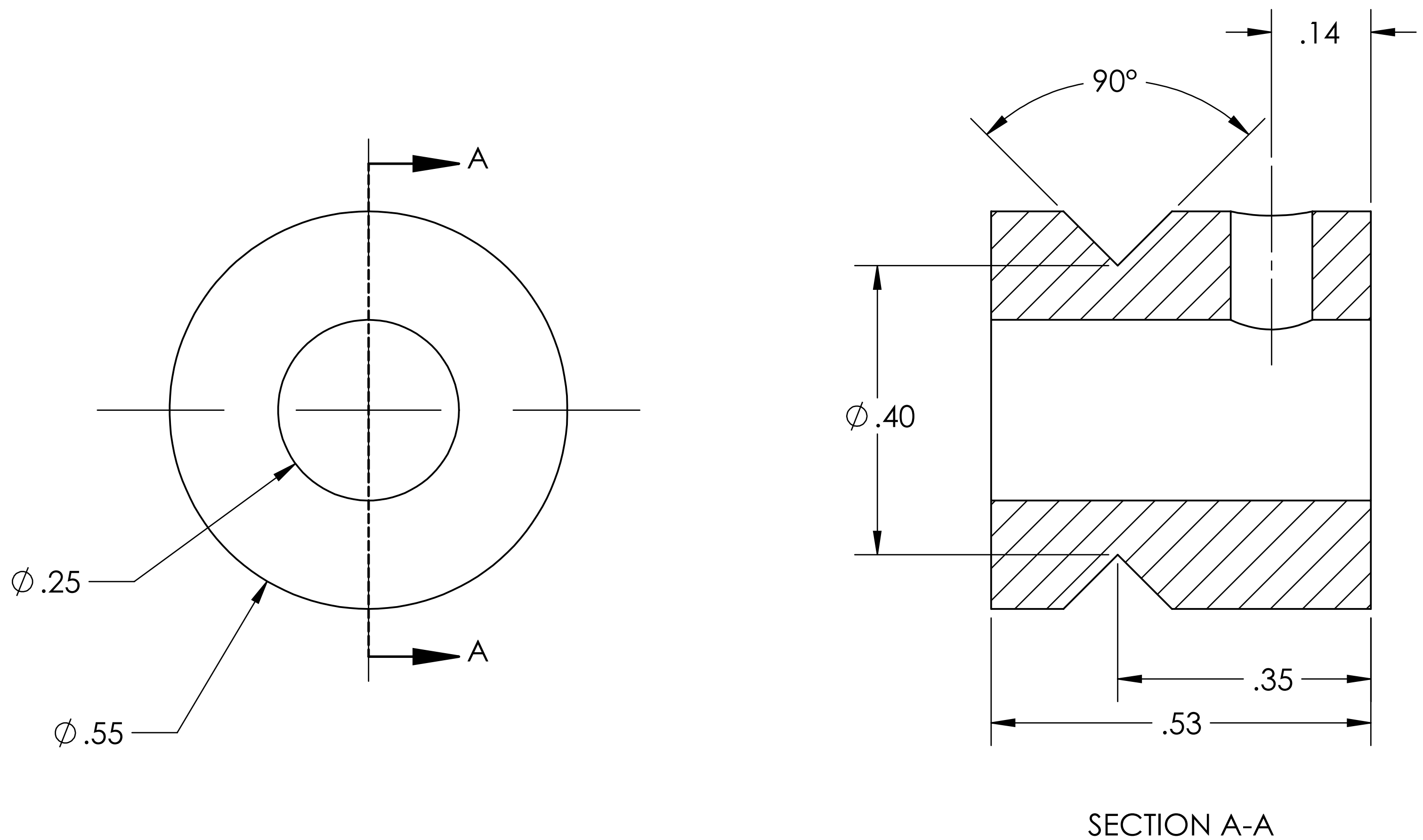


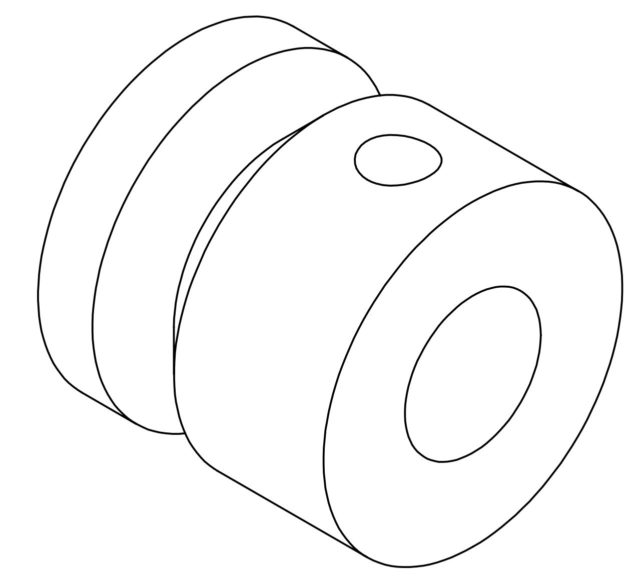
Lab Section: 03	SHEET 3 of 3	Title: MOTOR MOUNT		Drwn. By: I. DAVISON
Dwg. #: R020	Nxt Asb: M400	Date: 12/03/15	Scale: 1:2	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°





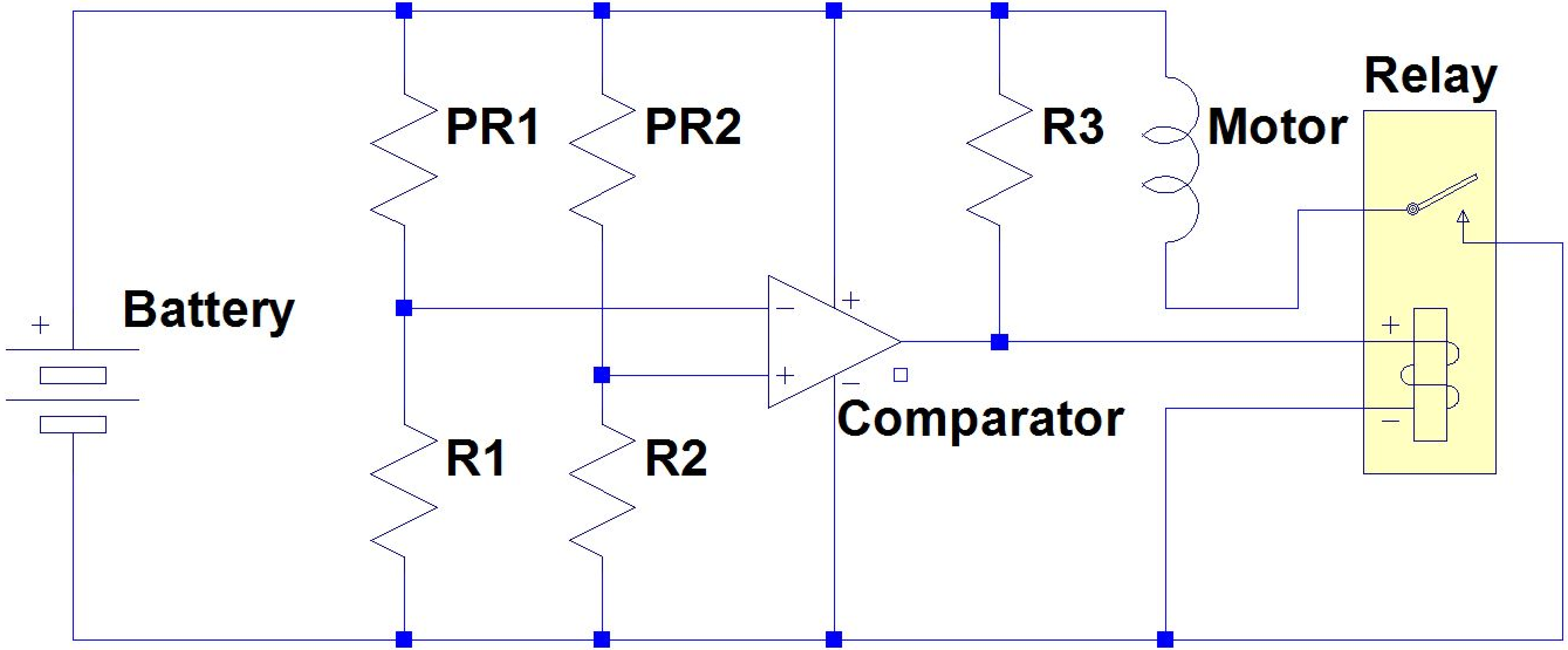


MATERIAL: DELRIN

Lab Section: 03	SHEET 1 of 1	Title: MOTOR PULLEY		Drwn. By: I. DAVISON
Dwg. #: M503	Nxt Asb: M400	Date: 12/03/15	Scale: 4:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°

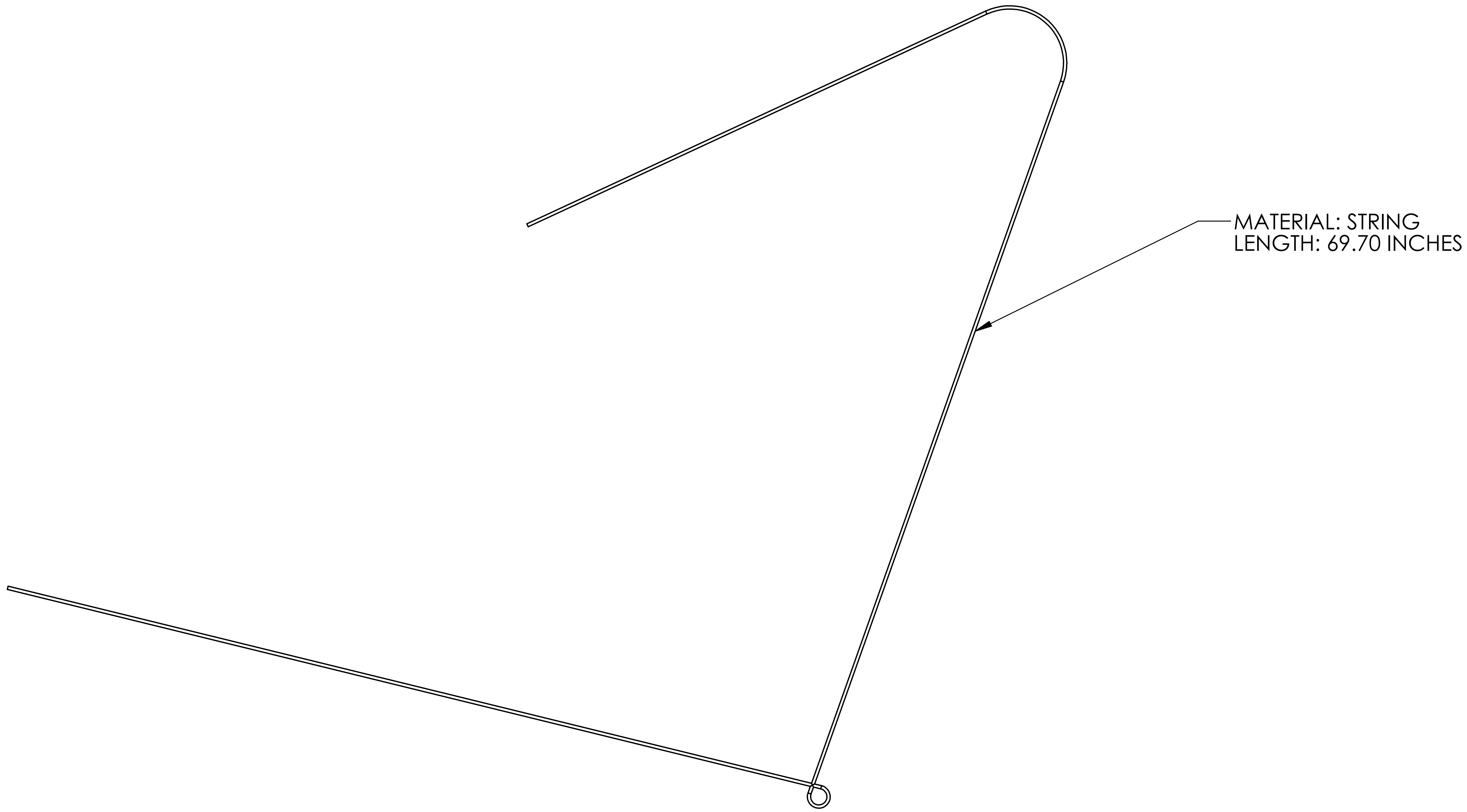


Circuit Component	Specifications
Motor	Amico a12032000ux0190
Relay	TE OUAZ-SS-112D
Comparator	LM 311
R1	1000Ω
R2	2200Ω
R3	150Ω
PR1	80Ω in direct sunlight, 600Ω in shade
PR2	80Ω in direct sunlight, 600Ω in shade

Lab Section: 03	SHEET 1 of 1	Title: TRACKING CIRCUIT		Drwn. By: I. DAVISON
Dwg. #: R700	Nxt Asb: R000	Date: 12/8/2015	Scale: 1:1	Chkd. By:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES.
TOLERANCES:
.X±.1
.XX±.05
.XXX±.005
ANGLES±1°



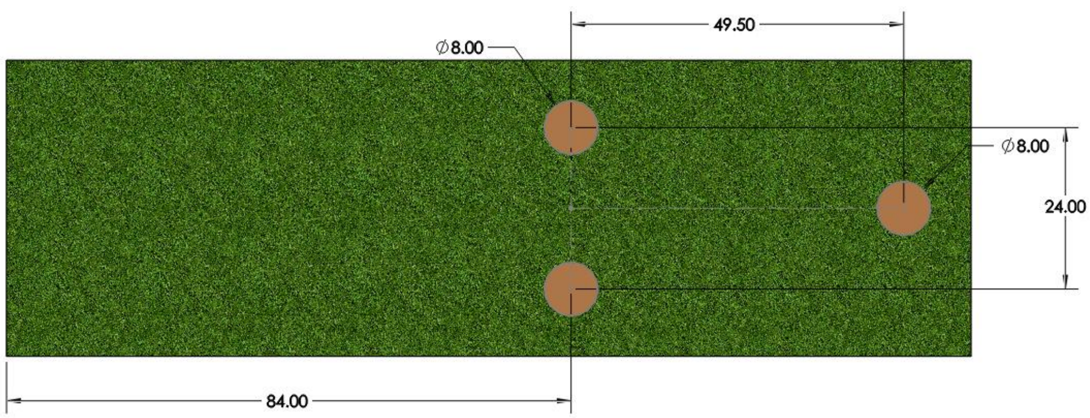
Lab Section: 03	SHEET 1 of 1	Title: STRING		Drwn. By: I. DAVISON
Dwg. #: S001	Nxt Asb: R000	Date: 12/8/2015	Scale: 1:4	Chkd. By:

Appendix K: Instructions

Device Installation
Objective:
To install the heliostat concentrator solar cooker to prepare it for cooking.

Materials:
Heliostat concentrator solar cooker
Compass
String
Gravity-based angle finder

Procedure:
14. Assemble:
    a. Rear Upright Assembly (R051)
    b. Front Upright Assembly (R200)
    c. Tracking Stage Assembly (R500)
15. First, find an area of ground 6 feet by 12 feet that is stable, flat, and that does not experience periods of shade throughout the day.
16. Use the compass and mark a line about 5 feet long on the ground to establish a north-south axis.
    a. Ensure that this line is true north-south, not magnetic north-south by correcting for magnetic declination according to your latitude and longitude. This orientation is critical for proper performance of the device.
    b. Draw this line at the north end of the free area to ensure there is a free area at least an additional 7 feet south of this line for the concentrator and kitchen setup.
17. At the south end of this line, use the compass to mark an east-west line that extends 2 feet in either direction.



18. 49.5 inches north from the east-west line, dig a hole on the north-south line about 6 inches wide and at least 20 inches deep.
19. Use this hole to secure the 4x4 post.
    a. Ensure the post is perfectly vertical.
    b. Ensure the sides of the post run north-south and east-west, and that the Top Bent Steel Plate with Pipe Fitting (R011) is on the south-facing side of the 4x4.
    c. One method to fill the hole: after placing the post, backfill with a small layer gravel, then fill in the spaces with sand, and repeat until level with the ground.
20. Dig holes centered 1 foot east and west from the intersection of the marked lines at least 8” wide and at least 20 inches deep.

21. Place R200 in the holes on the east-west line and install it vertically, ensuring the milled pivot bolt (R012) faces the 4x4.
22. Ensure the two upright assemblies are positioned to incline the tracking stage at your latitude:
    a. Connect a string to R012, then thread it through the hole in R011.
    b. Measure the inclination of the string with the gravity-based angle finder.
    c. Adjust the depth to which R200 will be buried until the inclination of the string matches your latitude.
23. With at least two people, mount the tracking stage assembly:
    a. Slide the bolt through the Top Bent Steel Plate,
    b. Place the bottom on the Pivot Bolt of the front upright assembly, and
    c. Secure the top with the 3/”-16 Locknut.
24. Attach the motor mount to the 4x4 as shown in R000.
25. Attach the string and spring to the motor mount, pulley, and .25” peg on the tracking stage assembly’s cross pipe.
26. Secure the tracking circuit to the underside of the upper instance of M004 on the tracking stage assembly.
27. As soon as the device is plugged in to the battery it is ready for use.

Instructions for Use: Let's Cook Something!

Objective:

To cook food with the power of the sun.

Materials:

Heliostat-Concentrator Solar Cooker
Cookstand
Cookware
Sunglasses
Food
Sunlight

Procedure:

1. Rotate the device so the mirrors face east (if you are in the northern hemisphere).
2. Power the tracking circuit (if your device is set up with a solar panel disregard step 1) and step back to allow the device to orient itself properly.
3. Ensure you are wearing eye protection (e.g. sunglasses) and oven mitts as you approach the hotspot.
4. Place your food filled pot or pan in the hotspot on the cooking stand.
5. Whenever you approach the device to stir your food or check its status, ensure you are wearing proper protection.