Intro to ME 128 Lab

by

Daniel Miranda

Nikhitha Byragani

Nicholas Loey

Project Advisor:

Sarah Harding

Instructor's Comments:

Instructor's Grade: ______________________________

Date: ______________________________

California Polytechnic State University

Department of Mechanical Engineering

Introduction to ME 128: Thermodynamics, Fluid Mechanics, and Heat Transfer Activity

Daniel Miranda, dmiran01@calpoly.edu
Nikhitha Byragani, nbyragan@calpoly.edu
Nicholas Loey, nloey@calpoly.edu

Sponsored by
Dr. Steffen Peuker

June 4, 2017

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Contents

1 Introduction **1**

1.1 Stakeholders . . . 1

2 Background **1**

2.1 Introduction to ME Curriculum . . . 1

2.2 ASEE Research . . . 1

2.3 Cal Poly Senior Projects . . . 4

2.4 PASCO Products . . . 5

3 Objectives **5**

3.1 Problem Statement . . . 5

3.2 Customer Requirements . . . 5

3.3 Quality of Function Development Analysis . . . 6

3.4 Engineering Specifications . . . 6

4 Idea Development **7**

4.1 Ideation . . . 7

4.2 Concepts . . . 7

4.3 Concept Refinement . . . 9

5 Final Concept Comparison **10**

5.1 Joule House . . . 10

5.2 Energy Conversion and Losses . . . 11

5.3 Recommended Choice . . . 13

5.4 Final Overall Selection . . . 13

6 Final Design **14**

6.1 Housing and Base Subsystems . . . 15

6.2 Pulley and Mass Subsystem . . . 16

6.2.1 Analysis . . . 16

6.2.2 Durability . . . 19

6.2.3 Concept Modeling . . . 20

6.3 Power Transfer Subsystem . . . 20

6.3.1 Overview . . . 20

6.3.2 Analysis . . . 21
6.3.3 Concept Modeling . . . 21
6.4 Potential Energy Conversion Subsystem . . . 23
6.4.1 Concept Modeling . . . 23
6.5 Pump Subsystem . . . 24
6.5.1 Analysis . . . 25
6.5.2 Concept Modeling . . . 27
6.6 Electrical Subsystem . . . 27
6.7 Heat Engine Subsystem . . . 27

7 Manufacturing **28**
7.1 Manufacturing Timeline . . . 28
7.2 Baseplate and Acrylic Housing . . . 29
7.3 Drivetrain . . . 31
7.4 Pump and Pump Shaft . . . 37
7.5 Mass, Winch, and Pulley . . . 38
7.6 Final Assembly . . . 39

8 Testing and Validation **41**

9 Cost Analysis **42**
9.1 Bill of Materials . . . 42
9.2 Ordering . . . 42
9.3 Final Order Specs . . . 42

10 Design and Manufacturing Improvements and Recommendations **43**

11 Conclusion **45**

12 Attachments (12) **46**

List of Figures

1 Bench top free and forced convection experiment [5]. 3
2 Jet flow inside an enclosure experimental setup [6]. 3
3 Flow over a backward facing step experimental setup [6]. 4
4 The HVAC house simulation project. This project was largely controls based, and was meant to simulate and record housing heating and cooling in various popular configurations. 4
5 A hydroelectric energy storage facility uses the same building to both pump water up a hill and pull energy from water falling down the hill. During low demand, excess grid energy is used to pump water to the upper reservoir. During peak hours, water is run down into a turbine. Not much power can be generated from a small scale version of this facility, but the concepts scale well. 8
6 Similar to the hydroelectric storage unit, this rail cart stores potential energy by running up a hill during low demand, and falling down the hill with a cable or regen brake during peak hours. This device could work to teach thermodynamic laws on in a more hands-on way than water can. 8
7 A generalized concept sketch of the house apparatus used in the Joule House experiment. Components shown would be removable, allowing students to observe fluid changes due to hardware configuration. 10
8 The hydro-powered version of the energy conversion experiment. This version uses a double-tank energy input to pull water through a turbine via gravity. 11
9 This alternative energy conversion and losses experiment uses air instead of water to power the input shaft. Not shown is the necessary gearing required to turn the input fan at a high RPM to achieve maximum airflow under human power. 12
10 The final concept sketch completed before solid modeling began. Note the full gearbox and belt drive, which were later omitted to reduce costs. 13
11 CAD model of the overall experiment. 14
12 Housing subsystem placed onto the base subsystem. 15
13 CAD model of the mass-pulley system. Attachment of mass is shown by the red line while the red circle outlines winch drum 16
14 Relationship between input mass and output RPM. 18
15 Relationship between input weight and the estimated input power supplied to the various subsystems. 19
16 The power transfer subassembly. 20
17 The dogtooth insert inside a modern racing gearbox. These parts are crucial to the design of the gearbox, as they allow for power transfer between gear reductions withing a very small footprint. . . 22
18 Potential energy conversion subsystem. 23
19 The pump subsystem. 24
20 Exploded view of the pump.The three components include the main housing, the impeller, and the housing cover. 25
21 Isolated view of the electrical subsystem, which passively converts mechanical motion into electricity. 27
22 A model temperature differential engine similar to that which will be purchased for demonstration purposes. 28
23 Baseplate of the experiment with locating rectangular through slots. 29
24 Outer acrylic housing wall. From left to right the holes are as follows: shaft hole (left), lever hole (middle), and lock-nut hole (right). 30
25 Top view of drive train with all power transmission components from mass-pulley to pump and cart subsystems. 31
26 Keyed driveshaft. 32
27 Rotating 4-jaw chuck head that can be set up on a knee mill. 32
28 First attempt at creating the dogtooth.The five cuts are clearly not centered on the part. 33
29 Second attempt at creating the dogtooth. Better centering resulted in a better cutting pattern. 34
30 Finished dogtooth gear. 35
31 Pump and ramp pulleys with dogteeth milled out. 36
32 The extrusion on the drivetrain gear was faced down to fit within the subassembly. 36
33 3D printed pump with filleted edges. 38
34 Mass-Pulley Subsystem to produce initial potential energy input 39
35 Fully assembled experiment on top of one of the HVAC tables. 40

36 One concept that utilizes the modular experimental setup, demonstrating only fluid energy transfer through a pump using a drill-driven pump and a small custom made turbine. This is essentially what the pump side of the project design covered, but broken out to create an easier to make assembly. Small experimental stations like these would be made for the other forms of energy conversion. . . . 44
A1 The Heat Engine Efficiency Lab by PASCO. This lab is rather complex mechanically, but covers all the relevant topics desired by the customer. It also contains a DAQ (data acquisition) device that specializes in thermodynamic process graphing. Sadly, the price is rather inflated, and some of the parts are rather delicate. 1
A2 The PASCO Stirling Engine catalog entry. While engaging on a visual and mental level, this product is rather single-dimensional, targeting only simple conduction and an isothermal/isochoric process. . 2
A3 The PASCO fluid flow lab, which highlights various fluid properties by changing cross sectional areas, pressures, and surfaces. This lab is rather large in size, and requires fluids in open containers that must be prepared before lab. However, it does have numerous DAQ sources, making data collection of the fluid properties easy for users. 3
A4 The catalog excerpt for the PASCO Thermal Conductivity Apparatus. This product offers a hands-on way to observe the conductive properties of various materials, but is very slow as it relies on ice melting to demonstrate heat transfer. It also requires ice to be frozen and water to be boiled, hindering setup times. 4
B1 Quality of Function Development Chart for this proposal phase, correlating customer requirements to create engineering specifications. 1
C1 Experiment ideas compared in a Pugh matrix. The insulated house was used as a datum since it is a relatively common demonstration or example used in universities, including Cal Poly. 1
C2 A concept component refinement Pugh matrix looking at the various heat transfer and HVAC component possibilities and their use to the project. 1
C3 Another concept component refinement matrix, this time looking at potential energy conversion components compared to heat transfer and HVAC components from the house idea. 2
D1 Safety checklist for the recommended double tank energy conversions and losses experiment. This checklist is subject to change if the experiment concept is modified. 1
D1 Calculations for torque output of the winch. 2
D2 Calculations for the RPM output of the winch. 3
D3 Calculations for torque output of the winch. 4
H1 Page one of the Gantt chart leading up to the current date. We have completed the design phase... . . . 2
H2 ...and are moving onto the build and testing phase (page two). 3

List of Tables

1 Engineering specifications, with their risk and compliance. 7
2 Maximum pump head as a function of initial mass. 26

Executive Summary

This report describes the development of a prototype lab experiment intended to introduce mechanical engineering students at California Polytechnic State University to concepts in the realms of thermodynamics, fluid mechanics, and heat transfer. These topics have been neglected in the introduction class for multiple reasons, but the instructing group feels it is possible to integrate a lab into the class demonstrating basic concepts from these subjects. The proposed prototype is a self-sufficient energy generating and transfer mechanism. Unfortunately, the primary project goals of being producible on-campus and for under a specified $500 per unit were not obtained with the included proposed design. Recommendations for future development, therefore, are also included.

1. Introduction

Introduction to Mechanical Engineering (ME 128) is a class targeted at first year students in the mechanical engineering department, with the intent of briefly exposing students to each of the major components of the Mechanical Engineering coursework and potential career opportunities. Aside from an HVAC concentration introductory lab, this class has neglected to include a specific experiment focused on the subjects of thermodynamics, fluids, or heat transfer, and these topics represent a significant amount of the ME curriculum. This report describes a proposed solution, the process of developing the design, and also includes any educational documents required for the sustainability of the activity.

1.1 Stakeholders

The sponsor of this senior project is Dr. Steffen Peuker. During his time as an instructor, he has noticed that the current Introduction to ME course lacks completeness in content related to thermodynamics, fluid mechanics, and heat transfer. He, along with the other ME professors involved in ME 128, have called for a team to create a new experiment, which will replace the current spring lab.

The customers for this project are the future mechanical engineering students who will use the experiment. It is assumed that they have very little to no experience in dealing with these concepts, therefore it will be important that the designed experiment covers a contemporary and simple experiment that they can understand.

2. Background

The team conducted extensive research in order to fully understand the proposed project and define a customer need. This research included reviewing current material in the Introduction to Mechanical Engineering class, finding effective experiments at other schools, and looking at commercial products.

2.1 Introduction to ME Curriculum

The Introduction to Mechanical Engineering class, ME 128, is the first major-related course that students take at Cal Poly. It is a hands-on class that gives an overview of what mechanical engineers do at Cal Poly and in the workplace. ME 128 provides this overview through a series of interactive lab experiments that students complete in groups of four. The current labs include the disassembly and reassembly of a drill and lawn mower motor, programming a robot, analyzing an air conditioner, and measuring the spring constant of different springs. While these labs do a good job of introducing freshman students to mechanical design, mechatronics, and HVAC, they fail to introduce the students to thermodynamics, fluid mechanics, and heat transfer.

This is a problem since these topics are considered a core part of mechanical engineering and can be found in roughly 40% of the undergraduate curriculum at Cal Poly. On top of that, many students come in with interests in thermodynamics, fluid mechanics, and heat transfer but do not know how their interests apply to their major. A solution to this problem would be the creation of an introductory experiment, similar to the labs currently in ME 128, that introduces these missing topics.

2.2 ASEE Research

To understand how engineering educators are dealing with introducing these topics, references can be drawn from articles published in ASEE, the American Society for Engineering Education. Numerous professors have reported on hundreds of experimental education environments, which aim to improve academic practices or, more importantly, approach a topic from a new angle. To understand difficulties and practices in introducing thermodynamics and fluids, papers mainly authored by Dr. Michael J. Prince of Bucknell University were found to be the most relatable.

In one of his papers, Dr. Prince cites the four most commonly misconceived topics in this area as: "(1) temperature vs. energy, (2) temperature vs. perceptions of hot and cold, (3) factors that affect the rate vs. amount of heat transferred and (4) the effect of surface properties on thermal radiation" [2]. These are familiar concepts to most engineering academia, but for incoming students properties such as these can be difficult to grasp or modify

existing misconceptions. Prince proposes that by using a hands-on laboratory based experiment, students better understand the concepts behind the fundamentals of thermodynamics-based classes. In follow-up reports, he notes that universities that adopted the proposed curriculum without allowing students to get hands on experience (the professor does the experiment as a demonstration instead) saw little to no change in the perceptions in students on the concepts covered [2].

To understand how other universities are achieving similar goals, either with or without Dr. Prince's advice, ASEE papers revolving around specific experiments were pulled and referenced. Many of these experiments are or were designated for a traditional single-topic class, not an introductory class; however the ideas and concepts behind each experiment have the potential to be combined and modified to meet the ME 128 requirements.

One paper, authored by Dr. Katharyn E. K. Nottis, proposes multiple experiments separated into activities that exemplify common thermodynamic properties. Each of these activities has a write-up broken down into three phases: "written prediction (I), an action (II, either experiment or simulation), and written post-processing (III)" [3]. This is necessary, Nottis explains, as many students "too easily dismiss the results as 'Oh, sure, I thought that would happen," without a predictory and post-process phase. While Dr. Nottis' process is seemingly ideal for ME 128, the actual activities proposed in her paper do not reflect the general style of Learn-by-Doing and weekly topic coverage. The experiments, ranging from entropy to enthalpy to Carnot engines, are round-robin style activities with short write-ups, not group-centered lab activities with a formal lab write-up as is traditional with ME 128.

Another paper, by Dr. Adrienne Minerick, recommends the use of a Desktop Experiment Module (DEMo) to teach students. The DEMo system illustrates conduction of various materials, thermal energy generation, thermal contact resistance, heat dissipation and convection across surfaces through multiple desk size experiments. According to Dr. Minerick, learning is achieved because "1) each student can closely examine and manipulate the apparatus, 2) student teams can progress through experiment discovery at their own learning pace, and 3) all learning styles are stimulated" [4]. Even though the DEMo experiments follow Cal Poly's Learn-by-Doing philosophy, they overlap with heat transfer experiments in later courses which is not desired.

Timothy C. Scott's paper describes a bench top experiment that demonstrates the concepts of free and forced convection [5]. His experiment setup, which can be found in Figure 1, is notable due to its low cost allowing multiple units to be built so that students could work in small groups. The low cost aspect of Dr. Scott's experiment would be desirable since students in ME 128 work in group of four throughout the quarter. However, his experiment looks aesthetically lacking and does not match the quality of the current ME 128 experiments.

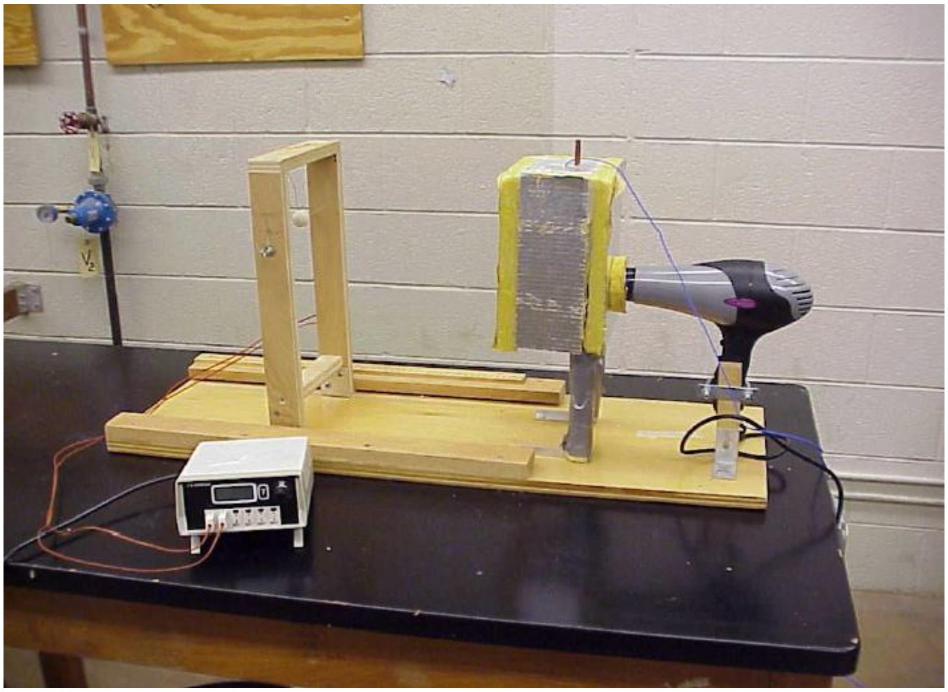


Figure 1. Bench top free and forced convection experiment [5].

In regards to fluid mechanics, Dr. Afshin Goharzardeh's paper provides an overview of two experiments that investigate fluid flow [6]. These experiments use Particle Image Velocimetry (PIV) to capture the dynamics of a jet flow inside a cylindrical enclosure and single phase flow over a backwards facing step (see Figures 2 and 3). Unlike some of the previous experiments mentioned, the cameras required to implement PIV data collection are extremely expensive and would not be a feasible option for small groups. Due to this and the complex nature of the topic itself for Freshman, Dr. Goharzadeh's experiments were considered not suitable for ME 128.

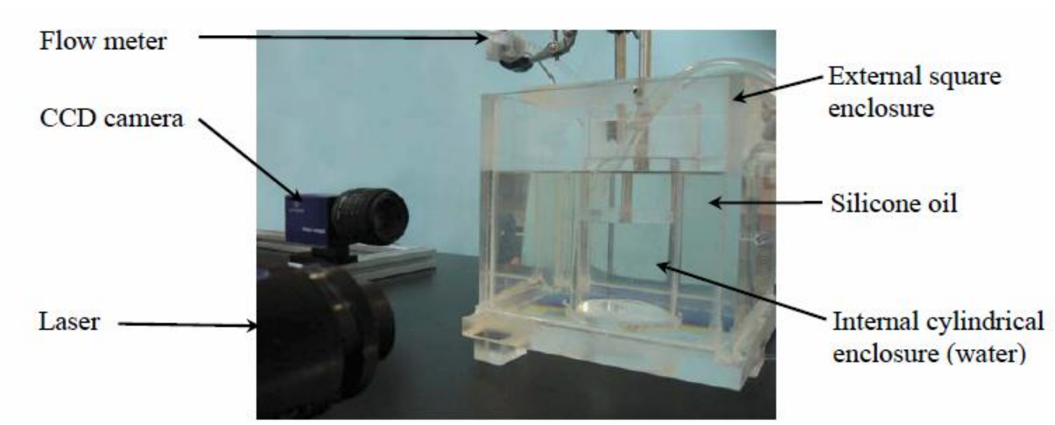


Figure 2. Jet flow inside an enclosure experimental setup [6].

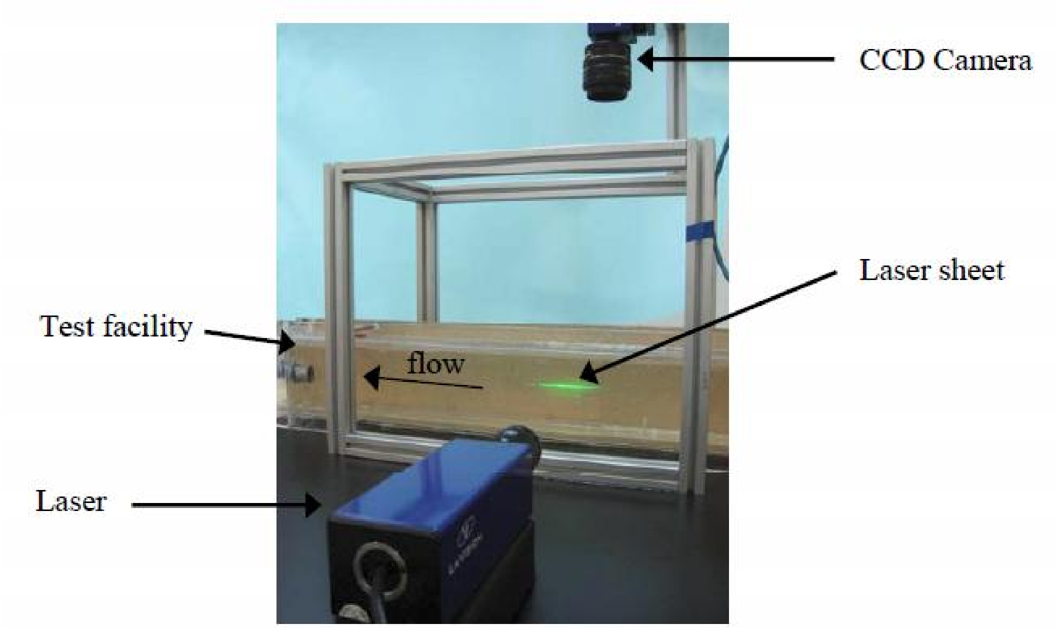


Figure 3. Flow over a backward facing step experimental setup [6].

Reading through the ASEE articles offered the team valuable insight on what methods and experiments professors from other universities have used to teach thermodynamics, fluids, and heat transfer. However, all of the researched methods proved to be either too difficult, too specialized, or too expensive for the ME 128 class. Thus, the team turned to researching commercial educational products in hopes of finding better scoped experiments.

2.3 Cal Poly Senior Projects

In an attempt to find more relatable experiments, previous Cal Poly senior projects were researched. The most notable project was a lab experiment created in 2015 for the Fundamentals of HVAC class. In the experiment, students analyze the thermal response of a building under various heating and cooling loads. The apparatus, shown in Figure 4, consists of a scaled-down model of a building, its control system, and various data acquisition tools [8].

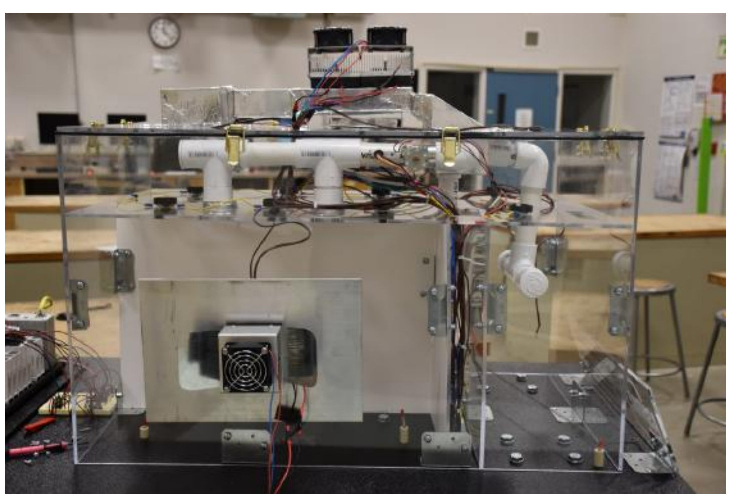


Figure 4. The HVAC house simulation project. This project was largely controls based, and was meant to simulate and record housing heating and cooling in various popular configurations.

This experiment is great since it is a straightforward model of a real world problem, but the total cost is roughly $5,000 which is way over the budget given. However, most of the cost can be attributed to the advanced control and data acquisition systems. Overall, this experiment would be an effective way to demonstrate heat transfer concepts to incoming freshman if a more cost effective and simplified solution is developed.

2.4 PASCO Products

The main (if not only) commercial competitor in this area, which provides mass-manufactured lab experiments, is PASCO engineering [7]. PASCO provides numerous modular products that cover a wide variety of mechanical engineering concepts. Their relevant thermodynamics, fluid dynamics, and heat transfer lab products are located in Attachment A. Figure A1 shows the most complex and encompassing lab experiment, the Heat Engine Efficiency lab. This experiment uses a hot and cold water bath to expand and contract air within an enclosed chamber, causing a piston-cylinder to do work on a mass. While this experiment is a fantastic way to demonstrate isobaric cycles, p-V diagrams, convection, conduction, and fluid statics, the total price for one unit is well over $1,000. Buying six of these is well outside of the given budget. Additionally, the equipment needed is very bulky and not user friendly, requiring numerous parts to be set up each time the experiment is to be performed.

PASCO has other well-produced products that are smaller and cheaper, but do not cover as many topics as the heat engine. Figures A2 , A3, and A4 show some of these products. The Stirling Engine is a single apparatus that demonstrates fluid work and changes in temperature causing an isochoric system to expand or contract. The Fluid Flow experiment demonstrates flow rates across different cross sectional areas, as well as drag and reactive changes in pressure. The Thermal Conductivity Apparatus demonstrates the concept of a thermal circuit for conduction through various solid materials by melting ice over sample squares. All of these products are either too short in interaction time, cover too few topics to validate a lab report, or are too expensive for their academic value to Cal Poly. This sentiment is valid for most of PASCO's products: While generally "cool," the cost of these experiments is highly inflated, the content is not dense enough, and there are too many additional product required to make one product fully functional as a lab. A better solution can be tailor-made here, at Cal Poly, for a much lower cost.

3. Objectives

Based on the team's research, a problem statement was created to clearly define the need for an introductory thermodynamic, fluids, and heat transfer experiment. Additionally, input from the team's sponsor, adviser, and customer was used to create a list of requirements and specifications for the project.

3.1 Problem Statement

To reiterate, current students in the Introduction to Mechanical Engineering class have no introduction to thermodynamics and fluid mechanics. These topics represent a significant amount of both future coursework and are a critical component of engineering problems in the workplace. A new experiment must be designed to excite, engage, and stimulate students with a contemporary problem. This experiment must be manufactured by the Cal Poly machine shops and should be relatively low cost compared to on-the-market options.

3.2 Customer Requirements

Aside from the main project sponsor's requirements, the mechanical engineering professors who traditionally teach the introductory course have all submitted their own requirements and desires for this project. These ideas have been solidified into the requirements presented in this section.

The most important aspect of the final product is its durability and reproducibility. The experimental apparatus will be in the hands of 24+ students for multiple labs a week, every fall quarter. These students are both curious and unacquainted with lab equipment handling, so the apparatus must account for this. Since there are six stations in the classroom, an additional five apparatus must be produced following the design documents from the final project report. This must be done in-house at the Cal Poly machine shops, and with relative ease.

The educational value and "fun-factor" of the experiment succeed these requirements. Being an

introductory class, each and every one of the labs should engage and excite the incoming students, encouraging them to pursue each of the covered subjects. The ideal way to do this is to mimic an issue or concept commonly seen in industry. By doing this, the lab introduces the students to not just the upcoming curriculum, but a possible career path. However, if the lab fulfills this goal, but is boring and uninteresting, this project will have not fulfilled its purpose.

The final customer requirements involve the lab's academic quality-of-life. The final project should include an introductory presentation and a lab report guide for the professor to present to the students before and after the experiment, respectively. The presentation should outline the concepts behind the upcoming experiment, and introduce multiple applications of the concepts in the engineering workplace. The lab report guide can have multiple forms, such as a short document of requirements, or an empty data table which can be investigated with supplemental questions.

It must be gradable, meaning that the results should be easy to follow and predictable each time the experiment is performed. Finally, the experiment must be easy to set-up by the professor, and should not over encumber both the storage area and the lab tables.

3.3 Quality of Function Development Analysis

To generate these engineering specifications, the quality function deployment method was applied to the given customer requirements. This method allows the project team to materialize high quality engineering specifications and gauge their importance in the final product and any prototypes. From these generated specifications, correlations can be formed and levels of importance or focus can be developed. It also allows the project to compare itself to already existing related products, further solidifying the scope and definition of the final engineering requirements. Specifications can be drawn out onto a separate table and their risks can be assessed.

The QFD chart for this project is included in Attachment B. The goal of having each engineering specification correlating with at least one customer requirement in some aspect was achieved, with each specification having a quantifiable target. Ideally, the specifications generated are the most concentrated and important ones, however they may change with further input from the sponsor. This QFD iteration is the first of multiple, as the process is applicable to each phase of the project, up into manufacturing. These future iterations will be appended as the project progresses.

3.4 Engineering Specifications

The final engineering specifications generated from the QFD are listed in Table 1.

Interestingly but appropriately, the most critical specifications seen by the team are educationally based. Not only are the times required for each phase of the lab relatively important, but the content of the lab should be valuable. This means that there should be a distinct number of topics covered, and that they should all be easily observable, recordable, and presentable.

The manufactured apparatus for the lab is constrained by human abilities and the pre-existing lab stations used for the class, which are found in Building 13, Room 124. The height, width, and length of the apparatus must not exceed the maximum safe capabilities of the lab tables. Additionally, the weight of the apparatus must not exceed that of a medium parcel, so the lab instructor or students can easily transport them from storage to the lab tables. Since there is no power available at or near these tables, the apparatus should not utilize external power.

Total costs for this project should not exceed $500. This cost includes the price for one experimental apparatus, any supplemental lab equipment that is shared by the class but is required for the experiment to operate, and any prototype material. This project budget can be modified if outside funds are acquired, but all successive iterations of at least the experimental apparatus must cost less than $500. Costs can be curbed by keeping manufacturing in-house, so the entirety of the project must be manufactured by either the Mustang '60 or Aero Hangar shops.

Each lab experiment should last more than five years of normal operation, enduring over 40 uses per year during the fall quarter. During this entire span of operation, it must maintain safety standards seen by all Cal Poly ME lab

equipment. There should be no sharp edges that can expose themselves over time, nor any live wires or moving parts that are easily accessible.

Table 1. Engineering specifications, with their risk and compliance.

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk*	Compliance†
1	Materials Cost	$ 500	Max	M	A
2	Manufacturability at Cal Poly	100%	Min	L	A, T
3	Weight	15 *lb*	±5	L	A, I
4	Height	2′	Max	L	A, I
5	Width	2′	Max	L	A, I
6	Length	5′	Max	L	A, I
7	Safety	100%	Min	L	A, T, I
8	Max Uses	40/year	Min	L	A, T
9	Quantifiable Data Points	2	Min	L	A, I, S
10	Cords	0	Max	M	A
11	Lifetime	5 yrs	Min	L	A, T
12	Experimental Time	2 hrs	Max	L	T
13	Presentation Time	.5 hrs	Max	L	T
14	Report Making Time	.5 hrs	Min	L	T
15	Concepts Covered	3	Min	L	A, T

∗: Medium Risk(M) and Low Risk (L) of feasibility
†: Verification through Analysis(A), Testing(T), Inspection(I), Similarity to Existing Designs(S)

All of these requirements are summarized in Table 1. This table describes the constraints, risks, and validation methods for each specification. Note that almost all of them are low risk goals, with the only possible issues arising from the need for more funds or power. The funding could overrun the $500 cap due to the desire for more high-tech analysis instruments, but this can be remedied if MESFAC funds are allocated for the project. The need for power is of mild concern since heat transfer without fire or electricity is rather slow or requires a material with high heat capacity, impacting rapid experimental repeatability. Even with these mild risks, the end product as defined by the customer is a definite possibility in terms of engineering.

4. Idea Development

With the requirements and specifications locked in, idea generation could begin, with experiment concepts undergoing testing and comparison against the requirements. From this ideation, a refined final experimental concept could be molded.

4.1 Ideation

The team performed multiple ideation sessions based on the techniques learned in class. The first session focused on brainstorming contemporary problems related to thermodynamics, fluid mechanics, and heat transfer. Some of the proposed problems included keeping a train or car engine cool, insulating an average household, measuring work done by a piston, and simulating thermocline in a water tank. From this session, the team discovered that almost all contemporary problems would require a significant amount of simplification so that incoming students would be able to understand them. Additionally, these problems would have to be scaled-down is size in order to fit within the required footprint.

4.2 Concepts

The first experiment concept was the simulation of a hydroelectric energy plant, seen in Figure 5, by having water flow from tanks at different heights. This two tank experiment revolves around the contemporary problem of storing energy during low demand so that it can be used during high demand. The experiment itself introduces

incoming students to the first law of thermodynamics and fluid flow. Ideally, this experiment builds on students basic knowledge of potential and kinetic energy while introducing dynamic concepts of pipe flow. Students collect data to analyze efficiency in the system and determine where sources of losses could be found.

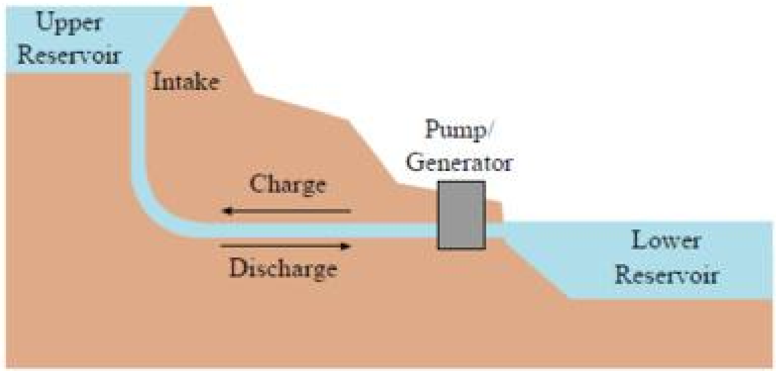


Figure 5. A hydroelectric energy storage facility uses the same building to both pump water up a hill and pull energy from water falling down the hill. During low demand, excess grid energy is used to pump water to the upper reservoir. During peak hours, water is run down into a turbine. Not much power can be generated from a small scale version of this facility, but the concepts scale well.

For the next concept, a different method of energy transfer was considered. This experiment concept would use a cart on an incline to power an attached wind turbine. As seen in Figure 6 this system models an Advanced Rail Energy Storage (ARES) facility which uses elevated carts to provided additional energy during peak use. Again, students learn about the first law of thermodynamics and build on their knowledge of potential and kinetic energy. This experiment aims to stimulate interest in future thermodynamic classes by demonstrating one use of turbine work. Data similar to the hydroelectric experiment would be recorded and analyzed.

Figure 6. Similar to the hydroelectric storage unit, this rail cart stores potential energy by running up a hill during low demand, and falling down the hill with a cable or regen brake during peak hours. This device could work to teach thermodynamic laws on in a more hands-on way than water can.

The team created a modified concept of the HVAC senior project mentioned in Section 2.3. The experiment apparatus would be similar to the one in the report, except that the advanced controls system would be removed and the walls of the modified house would have interchangeable material. The reasoning for this is interchangeable material would give students a hands on introduction to two modes of heat transfer: conduction and convection. Students would record data such as change in temperature and compare how different materials affect that measurement.

During this process, students would also be introduced to material properties, such as thermal conductivity and thermal resistivity, and the necessary equations to find them.

4.3 Concept Refinement

Although the ideas created went through judgment during the ideation that tested them against larger customer requirements, the process of choosing the final project requires a more defined approach. To select an idea as the seed for the project design, a quantitative weighing technique called a Pugh matrix was used. Pugh matrices weigh concepts with respect to a set of criterion defined by the customer requirements and engineering specifications. To simplify later analysis, each concept is weighed against a datum as either better, worse, or the same in terms of the criteria in question.

To refine the concept pool, an initial Pugh matrix was used to challenge each project concept from ideation against the others, seen in Figure C1.

The two top contenders were the downhill cart with wind turbine attachment and the double tank fluid flow energy experiment. These two perform higher than the datum in most categories, but lack in experiment flexibility and measurement variety. The downhill cart fairs worse, as it does not have much report worthy material aside from frictional losses and turbine efficiency. Both experiments have the potential to cost the same or more than an insulated house experiment.

The other designs ranked poorly compared to these two. Radiator efficiency scored third highest against the datum, but did poorly in the educational sector since it provides no good base knowledge for students to branch off from. The data center convection cooling experiment, as expected, scored similarly to the datum. It only differs in the number of data points available to measure and complexity of the assembly due to the need for forced air convection. The worst scoring concept was the wave generator. While interesting on paper, everything but the educational content, laboratory recycle time, and data availability were worse than the datum.

With the outcome of the analysis uncertain, a second round of Pugh matrices focused on experimental components were created. To do this, the top concepts, as well as the datum, were reconfigured and blended. Since the data center ventilation and insulated house experiments were so similar, they could be easily combined. The result of this combination is similar to the HVAC building senior project from Section 2.3. The double tank fluid flow experiment could be used to power the turbine in the potential energy experiment, pulling the cart up the hill.

The double tank fluid flow experiment matrix analyzed the moving car, the incline, the pump impeller, and piping. To keep the comparison similar to the previous matrix, the insulated wall was also used as the datum. Overall, the results showed that the components of the two tank system were almost indistinguishable to the components of the house system. The biggest variations occurred when comparing the relatability and the cleanliness of the components. It was found that the car on an incline scored better than the insulated wall in relatability since students could see what was physically happening in the system. On the other hand, the piping in the two tank system scored worse in cleanliness since the system uses water instead of air.

Using these Pugh matrix results, a final complete system could be conceptualized and presented as a potential project solution.

5. Final Concept Comparison

The final two overarching concepts, while both within the scope of the project, are very different in character. While the project is currently leaning towards one over the other, the numbers from the Pugh matrix demand that both be given equal light before a final decision is made.

5.1 Joule House

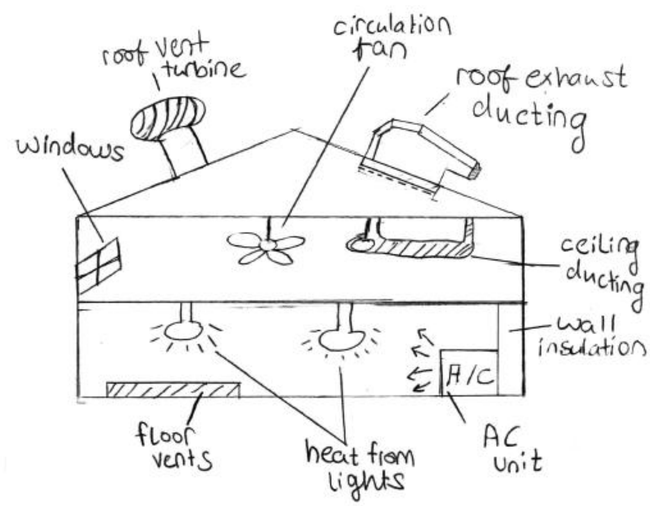


Figure 7. A generalized concept sketch of the house apparatus used in the Joule House experiment. Components shown would be removable, allowing students to observe fluid changes due to hardware configuration.

The Joule House experiment introduces incoming freshman to heat transfer, fluid flow, and basic HVAC components. This experiment is capable of demonstrating the concepts of convection, conduction, radiation, and incompressible flow using common components such as ducting, windows, wall insulation, and venting. The experimental apparatus would be a scaled-down model of a house, similar to the senior project presented in Section 2.3.

In order to focus students on one subject at a time, the house would be modular, so that the experimental components of the house (i.e. walls, duct size, windows, etc.) would be interchangeable. This modularity would also allow students to see how changing components effects different engineering parameters like air velocity, temperature change, thermal conductivity, and thermal resistance. Additionally, it would promote an iterative, inquiry based experiment, where students predict the effect of the change, observe the change as it physically occurs, and analyze what actually happened.

Specific component modules in this experiment are insulated walls and windows, venting through horizontal multi-level surfaces, ducting placement along a thermocline, and radiation from surrounding surfaces. Most all of these use a warm object in the center of the room, simulating heat-generating objects inside of an enclosure (such as a human, computer, or appliance). By changing certain component configurations, either one at a time or in various combinations, the student can predict and observe changes in the object and it's surrounding's energy state. These observations can be made through infrared temperature measurements, or in a more visually appealing manner with a thermal imaging camera.

Lecture material for this class would introduce the three modes of heat transfer, general HVAC practices and principles, and how they are applied and measured in construction. Efficiency, energy from heat, and fluid density could also be glossed over as introductory interesting points in coursework. The introductory lecture should also include report writing guidelines to help guide students through the experiment with the mindset of recording their observations.

5.2 Energy Conversion and Losses

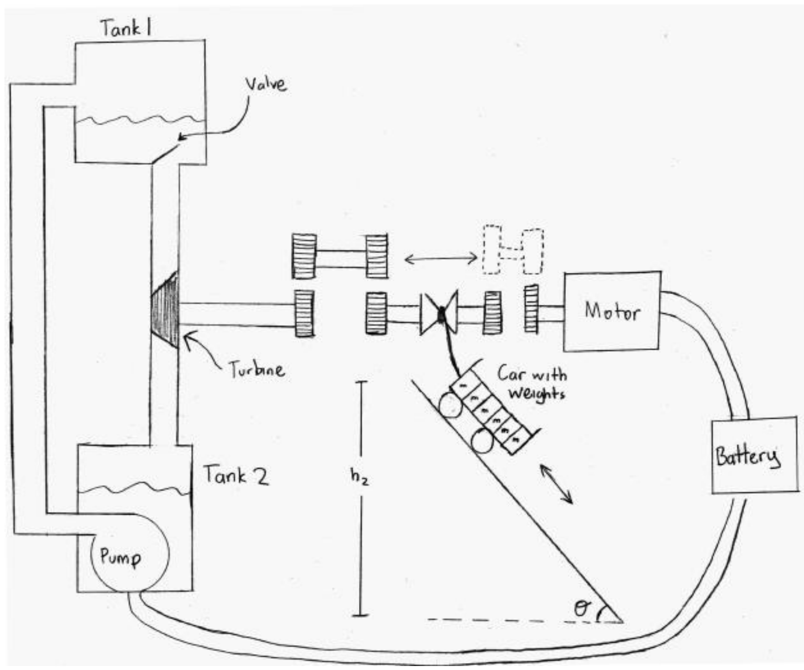


Figure 8. The hydro-powered version of the energy conversion experiment. This version uses a double-tank energy input to pull water through a turbine via gravity.

The energy conversion and losses experiment would function as a scaled-down model of an energy storage plant. The experiment could work in two possible ways: by having fluid flow from an upper tank to a lower tank, or by having air from a high speed fan move through a pipe, with both methods turning a turbine. With the gears in the first position, the rotation of the turbine shaft would turn a pulley which moves a small weighted car up an incline. The gears would then be switched to a second position connecting the pulley shaft to a generator shaft, releasing the car into a gravity-assisted fall. The rotation of the generator shaft would then power a device that could measure the energy output of the generator. For the water powered system, this could be done by powering a pump to pump water back to the input tank, where the change in volume can be measured. In the air powered system, a lamp, kill-a-watt, or fan can be used to measure energy output. A picture of the described apparatus can be seen in 8, with the air-type system shown in Figure 9.

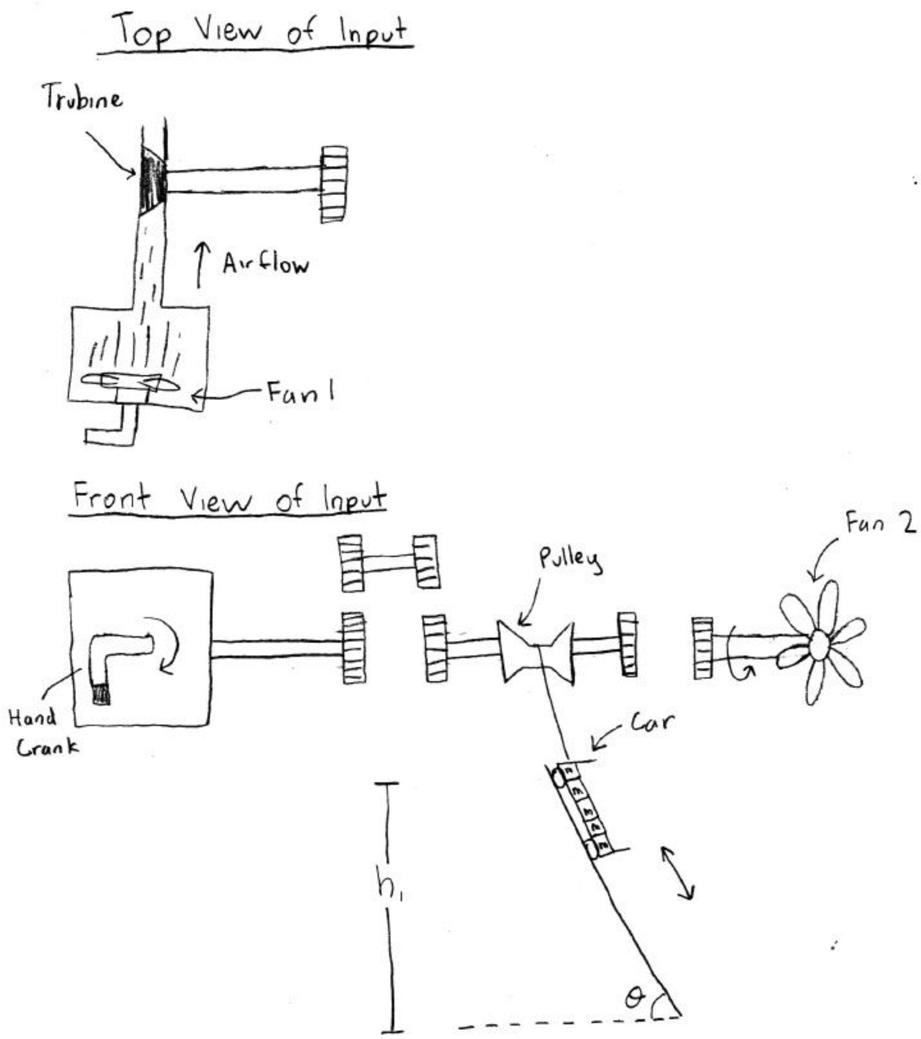


Figure 9. This alternative energy conversion and losses experiment uses air instead of water to power the input shaft. Not shown is the necessary gearing required to turn the input fan at a high RPM to achieve maximum airflow under human power.

This experiment introduces students to the first and second law of thermodynamics, conservation of mass, and pipe flow. By measuring energy at multiple points, students can estimate and observe energy loss through a simple mechanical system. Using the first law of thermodynamics and basic energy equations, students can predict the ideal energy transfer without losses. Then, using various velocities, masses, and power measurements, students can measure actual energy loss as power is transmitted through the system. If possible, students can try to rig up a "potential energy machine" by connecting the input fluid flow to the output fluid flow (or by letting water continue to pump if water is used). By doing this, students can inquire about and observe the second law of thermodynamics in a physical example. By observing fluid flow at the input and output (through pressure or velocity), advanced students can answer questions on fluid losses and laminar pipe flow.

The introductory lecture would introduce the first two laws of thermodynamics, and provide students with enough background to start the experiment. It may also introduce report writing guidelines, to ensure that the instructor does not need to rush the end of the period. The concluding lecture can consist of examples of systems who see problems similar to those in the lab constantly, and can discuss hydroelectric storage options which use energy storage and conversion to supply high demand energy periods.

5.3 Recommended Choice

While these two choices for the experimental concept are conceptualized and can be manufactured with relative ease, a final decision had to be made. The team recommended the pursuance of the energy conversion and losses experiment. The main reason for this choice is the tangibility of the experiment; the student changes multiple physical variables throughout the experiment, directly observing the consequences of the choices, allowing for open questions in the lab manual. In contrast, the house experiment uses solely air as its dependent variable generating material, which is not visible, even in a thermal imaging camera. While less modular than the house experiment, the energy conversion experiment's single iteration loop can help students focus on the concepts being covered rather than the procedure of the experiment. It also anchors onto high school level physics concepts that are expanded upon in college, while the house experiment introduces mostly brand new law, equations, and theory.

5.4 Final Overall Selection

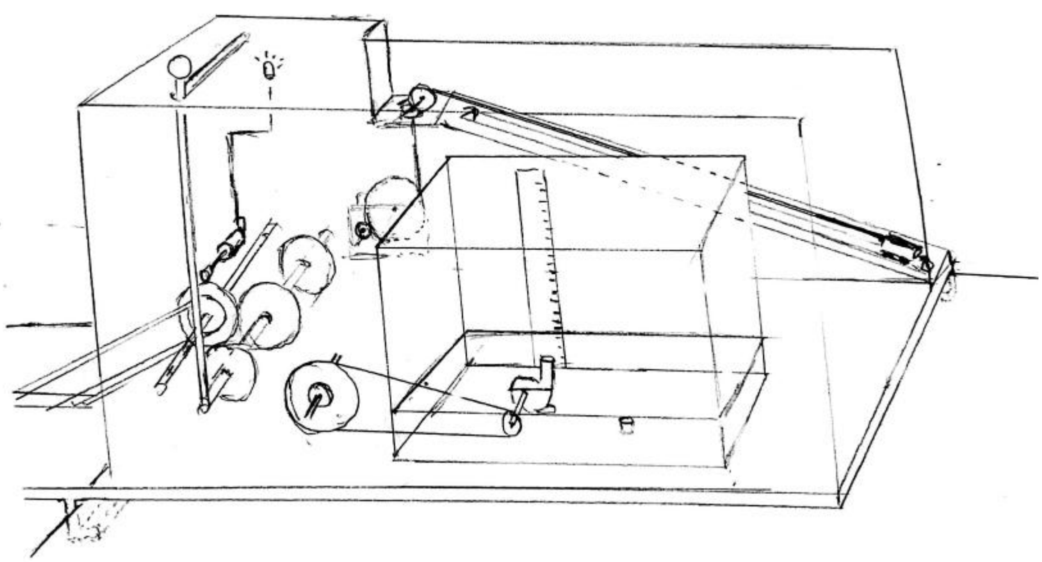


Figure 10. The final concept sketch completed before solid modeling began. Note the full gearbox and belt drive, which were later omitted to reduce costs.

While the team decided to go with the overall energy conversion theme, a few changes had to be made to ensure that the experiment would work properly. Instead of having the fluid fall to power a closed loop system, a mass would be dropped to power three separate subsystems. The final proposed system, sketched in Figure 10 is explained in detail in the following section.

6. Final Design

The final design of the experiment introduces incoming students to the conservation of energy. It does this by converting potential energy to kinetic energy, rotational energy, and electrical energy. The experiment starts by dropping a mass at a specific height to turn a shaft. The rotational motion of the shaft is then transfered through a series of gears and pulleys to either pull the cart up the ramp, turn the pump impeller, or power the light bulb. The final design of the experiment can be seen in Figure 11.

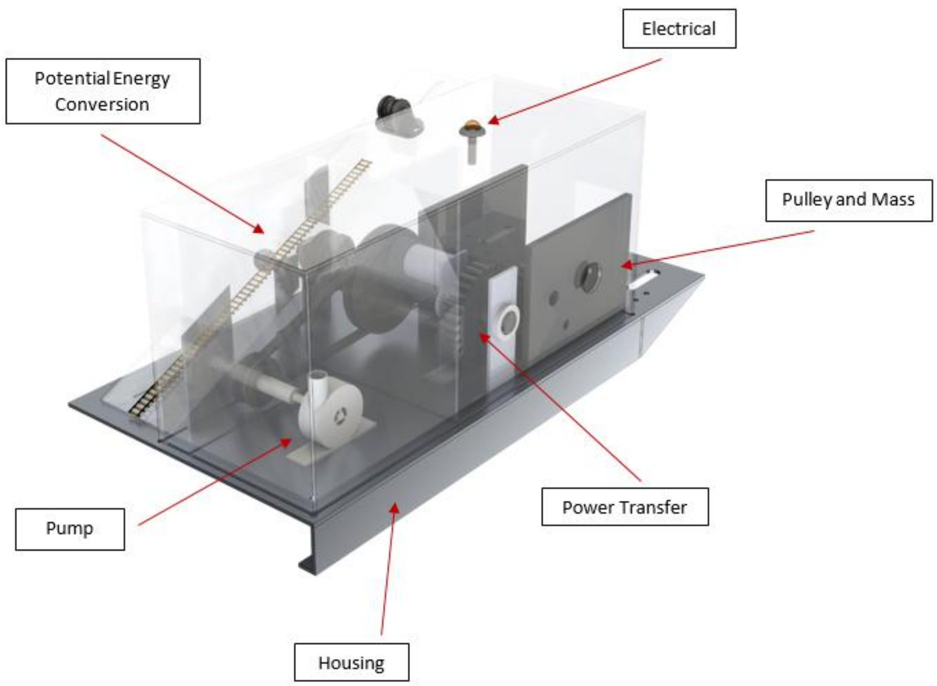


Figure 11. CAD model of the overall experiment.

As seen from above, the experiment includes six subsystems: housing, pulley and mass, power transfer, potential energy conversion, pump, and electrical. Additionally, the experiment includes a heat engine subsystem that is not pictured. A detailed description of each subsystem can be found in the following sections.

6.1 Housing and Base Subsystems

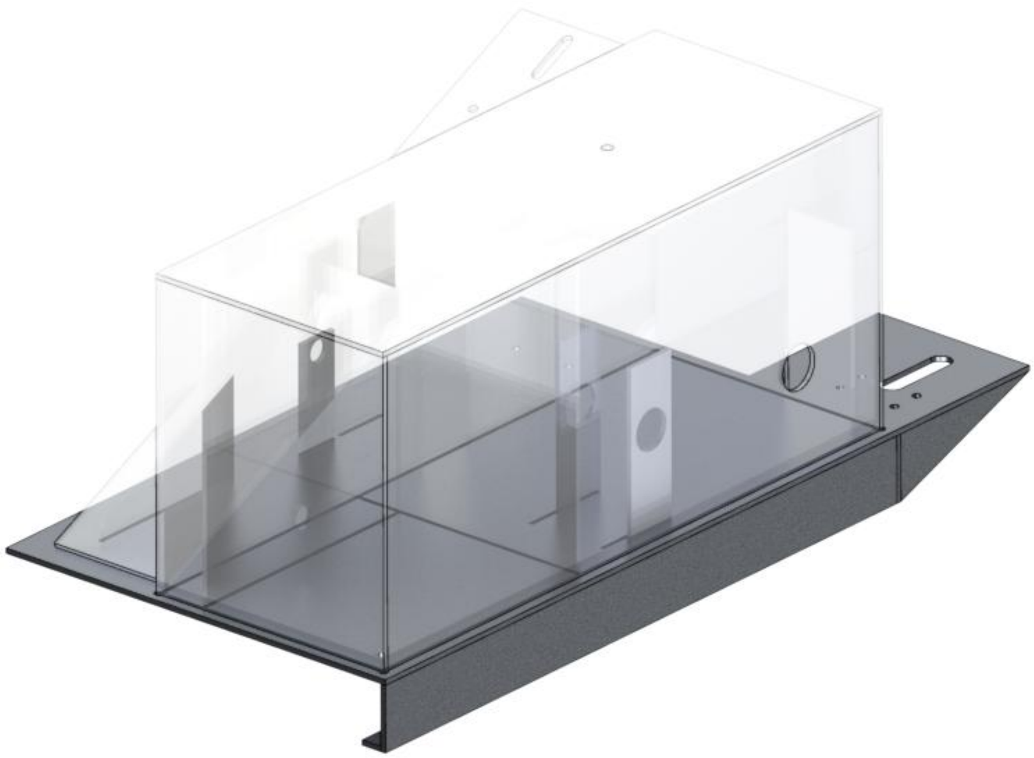


Figure 12. Housing subsystem placed onto the base subsystem.

The base and housing subsystems, while separate on paper, are closely related. Both act together to create a safe and fun tool for students to utilize without contributing much to the actual engineering being observed.

The base subsystem is constructed completely with 0.125" thick 6061-T6 sheet metal. High strength aluminum was chosen for its durability and weight, which are important for constant handling and storage. The main plate is a CNC-slotted for precision location of the housing walls and other components. Holes for the pulleys, winch, and oil drain screw are also machined on. Welded to the base are cleats which allow the system to rest on the edge of a table in a manner that restricts it from tipping when a large mass is dropped. These cleats are attached using a TIG fillet weld.

One edge of the base hangs off the side to allow the pulley-mass system to drop its mass off the side of the table. This cantilever section has the potential to deflect, however since it is so close to the anchored base at 0.95", the shear stresses experienced by the aluminum plate are minimal. With a 30lb weight, the maximum deflection seen by the plate would by under 0.001". This is the only loading concern with this subsystem.

The housing subsystem, which consists of any walls and most supports, is made entirely out of sheet acrylic. This material was chosen over the main competitor, polycarbonate, due to its manufacturability and material properties, and over metals for its transparency and weight. Additionally, acrylic is one of the cheapest options for this subassembly.

It is important that the walls remain as transparent as possible so data and observations can be recorded by students for many years. Polycarbonate yellows after some time, while acrylic does not. Polycarbonate also has the ability to become toxic under some circumstances, while acrylic remains inert.

Acrylic can be cut on the laser cutters at Mustang ’60, an important factor in respects to meeting our customer requirement of complete in-house manufacturing. Polycarbonate does not break cleanly when cut by a laser, and must be deburred imprecisely, which also mars the surface transparency.

All like sides of the walls will be cemented using acrylic glue, which chemically reacts with the acrylic to melt the edges and create a permanent, airtight bond. To attach to metals, a silicon caulking will be used. Note that this method forbids any lifting of the system from the walls, which will be included in a warning on the final device.

If necessary, a hinged door can be added to the lid, allowing for maintenance of the pump. This can be added with ease, however it would compromise the airtightness of the pump system. If maintenance is required, it is recommended that the acrylic be pried from the base since there is already an opening allowing access to the gear system.

6.2 Pulley and Mass Subsystem

The power input for the experiment is falling weights. For the weight to transmit their gravitational potential energy a pulley and winch system must be used. For this there is a range of different sized weights, which fall at the same height. The vertical falling motion is converted to rotary motion through a winch system as can be seen in Figure 13.

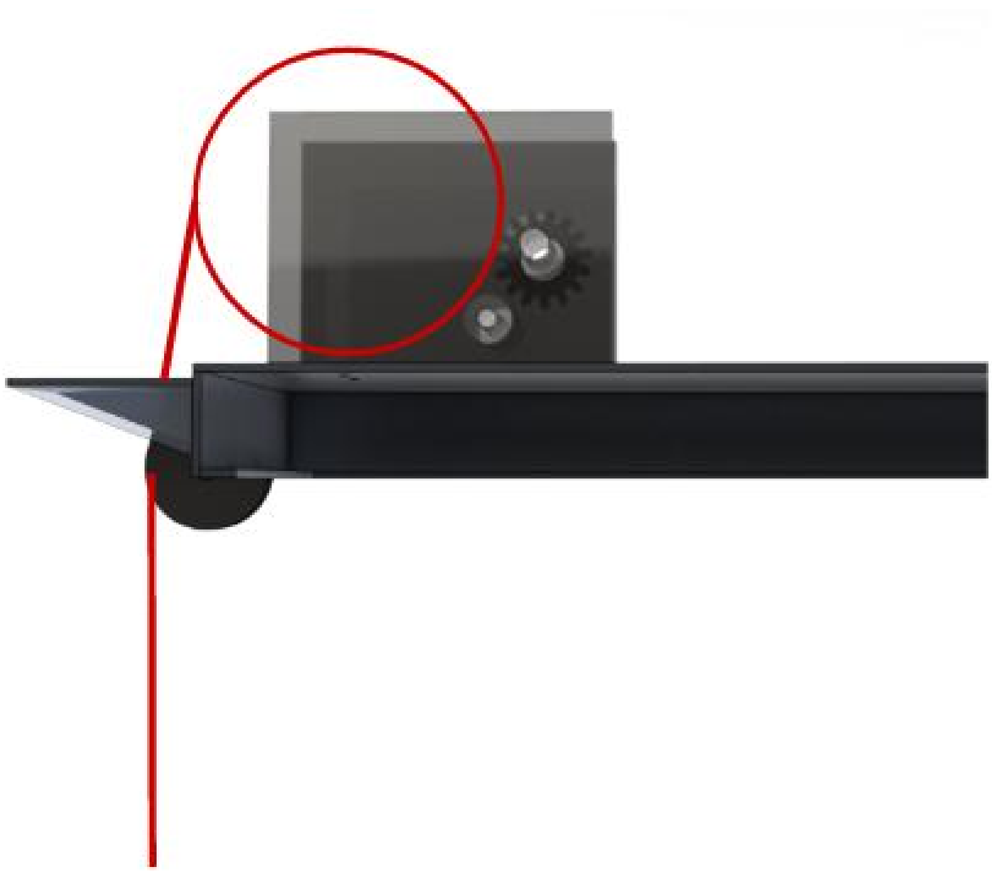


Figure 13. CAD model of the mass-pulley system. Attachment of mass is shown by the red line while the red circle outlines winch drum

6.2.1 Analysis

The main analysis that needed to be completed was to see if enough energy was produced from the falling mass to power the three subsystems. Basic dynamics was performed to get the output rpm of the winch gear that would go into the power transmission system. The main values that were needed to do this analysis were the drum diameter and the gear ratio between the drum and the output shaft. The following set of equations show how the output rpm was derived from the falling weight.

First, knowing that the force on the drum is just the weight of the mass which is given by :

$$f = m\, a_g \tag{1}$$

Where:
m = input mass
a_g = acceleration due to gravity
f = force of mass on drum

Putting that value into the equation for torque

$$T = f\, r_D \tag{2}$$

Where :
T= Torque on drum
r_D = radius of drum

$$I_x = \frac{m_D\, r_D^2}{2} \tag{3}$$

Where:
I_x = moment of inertia of drum
m_D = mass of drum

From using the calculated valued above to find angular acceleration

$$\alpha = \frac{\mathrm{T}}{I_x} \tag{4}$$

Where:

From there finding the tangential acceleration using :

$$a_{tD} = \alpha\, r_D \tag{5}$$

Where:
a_{tD} = tangential acceleration on winch drum
α= rotational acceleration

Rearranging the kinematic equation of motion, the time of the fall can be estimated :

$$t = \sqrt[2]{\frac{2\,\mathrm{h}}{a_{tD}}} \tag{6}$$

Where:
h = height of falling mass

The number rotations made in each fall is simply found out by:

$$N = \frac{h}{2\,\pi\,r_D} \tag{7}$$

Where:
N = no. of revolutions

Finally the angular velocity of the drum can be found by :

$$\omega_D = \frac{N}{t}\,\frac{60s}{1min} \tag{8}$$

Where:
ω_D = angular speed of the drum

The final output to the shaft that will connect to the power transmission is simply found using the gear ratios :

$$rpm_{os} = \omega_D\,R \tag{9}$$

Where:
R = gear ratio
rpm_{os}= output speed of the mass-pulley system

From the above derivation, Figure 14 was plotted to show a relationship between the input mass that falls and the output rpm. With that relationship, the minimum mass required to power the system was be found. Additionally, the negative concavity of the graph showed that increasing the mass had diminishing return on rpm, thus giving the team an upper limit for mass.

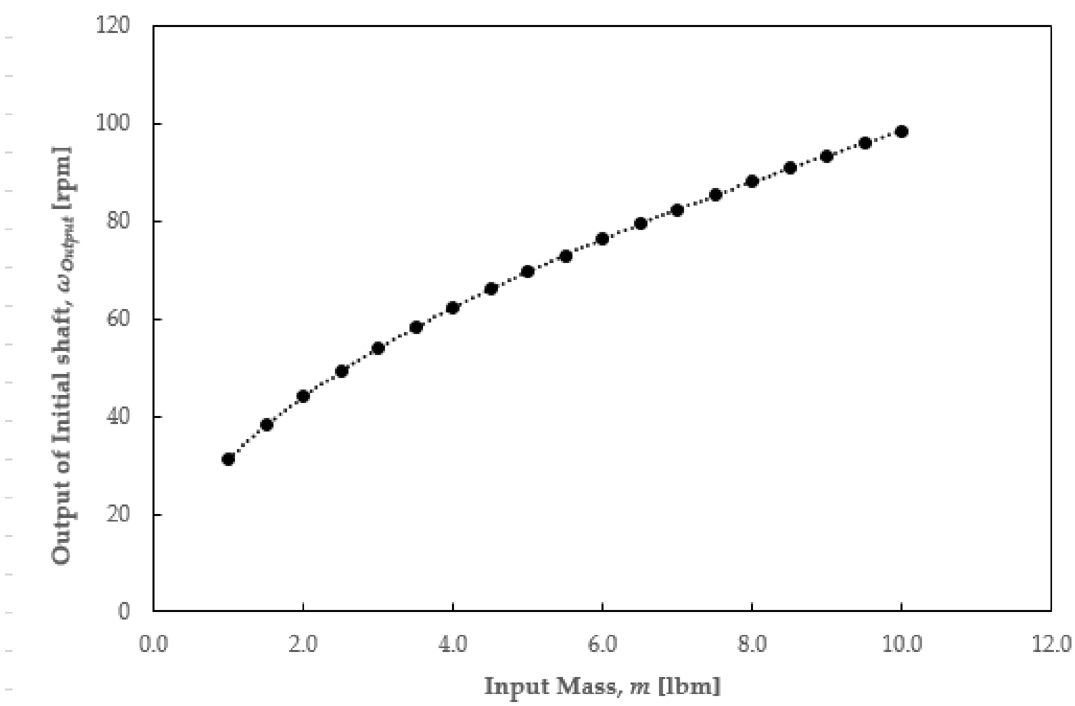


Figure 14. Relationship between input mass and output RPM.

Using excel to curve fit the data points with a power fit, an equation to relate input mass to output rpm is found to be :

$$rpm_{os} = 31.148\, m^{0.5} \tag{10}$$

The tachometer that will be purchased has a minimum reading of 50 rpm. With Equation 10 the minimum input mass required for that speed is around 2.5 lbs.

The final estimated input power (in Watts) to the various energy converting subsystems is found by :

$$P_{in} = \frac{rpm_{os}\, T}{R} \frac{745.7}{33000} \tag{11}$$

The relationship between estimated input power and the initial mass that is dropped can be seen below in figure 15 .

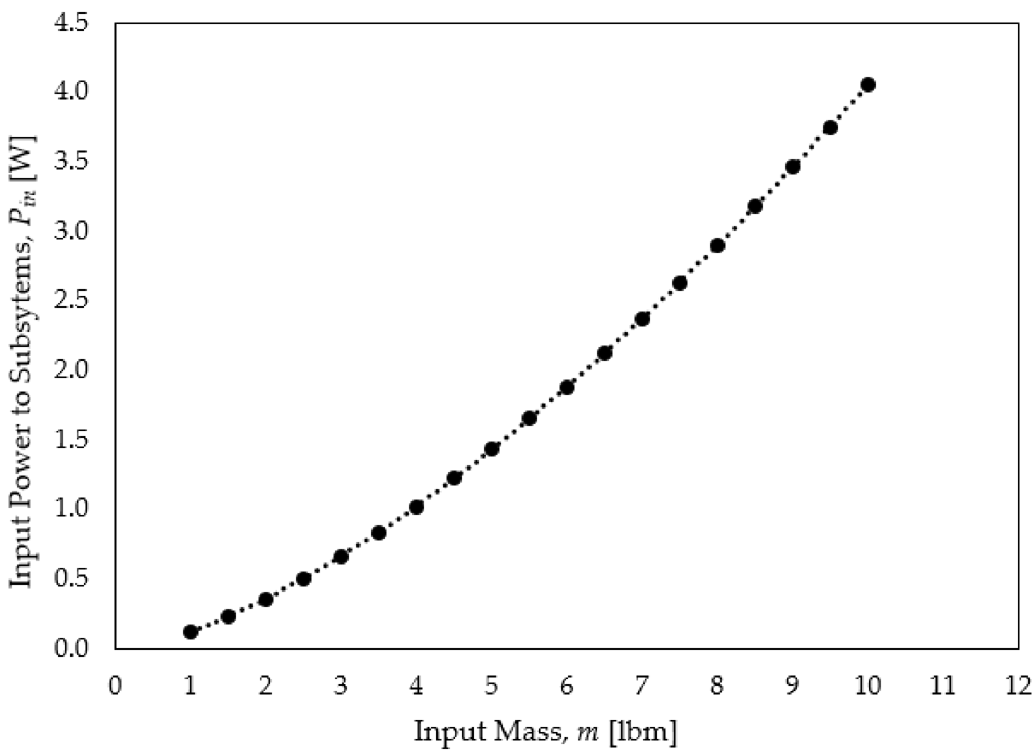


Figure 15. Relationship between input weight and the estimated input power supplied to the various subsystems.

Using excel to fit a trend line to these data points the equation that will relate this parameters can be seen below in Equation 12 :

$$P_{in} = 0.1283\, m^{1.5} \tag{12}$$

6.2.2 Durability

The winch is designed for a load capacity of 350 lbs (lowest size available) , however the maximum weight that the experiment will have is 10 lbs. This experiment would only be used 50 hours per year, so no significant lifetime calculations needed to be calculated. The gears on the winch will be adequately lubricated and should not undergo

any major wear. The only component of the mass-pulley system that will need maintenance is the rope for the winch. However, this is standard stock 3/16" Nylon rope which is cheap and can be easily replaced. Once students notice any fraying the professor can simply swap out the rope. This rope is rated to hold a 36lb load which is around 300% heavier than the expected maximum mass of 10 lbs.

6.2.3 Concept Modeling

Students can imagine the falling mass as a gravitational power source such as a hydroelectric dam, a counterweight on an elevator, or even a pile driver. All of these systems store energy by leaving it in a higher elevation energy state. This energy is then released and captured using some other mechanism. The mass in question does not have to be solid, nor does it have to be attached by a rope. Roller coasters, for example, constantly use potential energy to self propel. Certain gliders can power their electrical systems by falling towards the earth against the resistance of the air, spinning bladed turbines to generate shaft power. These are some of the examples that can be covered in the introduction presentation when discussing energy engineering applications.

6.3 Power Transfer Subsystem

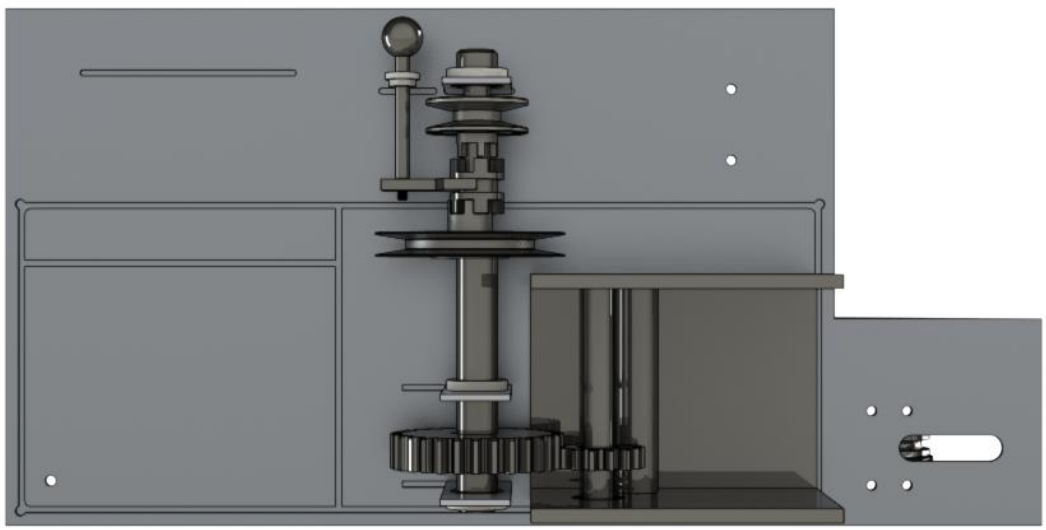


Figure 16. The power transfer subassembly.

The heart of the assembly is the power transfer system, which acts as a pseudo gearbox that transfers rotational motion from the winch to the other three subsystems in the box. The goal of this system is to transfer power while introducing losses through multiple types of rotary components including gears, dogteeth, and pulleys.

6.3.1 Overview

Power transfer is the largest subsystem, and is easiest to outline by following the path of the transmitted forces. The winch has a gear on the main spindle, which turns a pinion attached to the handle assembly. There is a clearance behind this winch assembly that allows a 32-tooth gear to be hooked up to the winch pinion. This gear has a keyway, which allows it to permanently attach itself to a steel shaft. The shaft is supported by delrin bushings glued to acrylic supports.

This steel shaft is only keyed to the gear and a special dogtooth gear. This gear, which rotates with the shaft, has coarse teeth which require little precision to engage with any mating gears. This makes it easier for students to engage the different systems and reduces the amount of moving parts of the subassembly. The lever for this shifter is attached by a steel fork, which slides over the shifter. The lever and fork are supported by an acrylic mount with a delrin bushing.

To connect to the two systems, pulleys have been recycled from the old ME 128 lawnmower racers lab. These pulleys have a large cast iron outcropping with a set screw hole, which can be machined with teeth fairly easily, allowing for easy engagement with the opposing dogteeth. These pulleys will be allowed to spin freely on the shaft until engaged by the shifter. From these two, pulley power will be transfered by either rotational motion or spooling of wire.

6.3.2 Analysis

The use of dogteeth not only makes manufacturing easier but reduces the worry of gear tooth stresses. Initial revisions of the subassembly used four different gears, the one input gear and three other gears used in a traditional shifter fashion along a translating shaft. This system, however, proved to have significant losses at the designed operating conditions. While a gear reduction would have been interesting for students to investigate, the chances of the final system not working as intended was too high. Thus, a direct power system works much better for us, and still allows students to perform a gear calculation on the input gearing (if so desired).

For the input, the gearing has a 32-tooth gear on the winch going into a 10-tooth pinion. When an additional 32-tooth gear is attached as the shaft input gear, the 10-tooth pinion becomes an idler gear, resulting in a 1:1 gear ratio. Students should be able to calculate and observe this fact by monitoring the speed of the gears as a mass falls, and by performing gear calculations which were introduced during the drills lab. Another added benefit of the 1:1 system is the direct relationship between the height of the mass dropped and the travel distance of the cart. Ideally they would be the same, but the weight of the cart may sometimes forbid this from occurring.

The input gear, made of hardened steel, is overbuilt for the system. AGMA calculations proved to be rather helpless, since most calculation constants expect much higher speeds and loads. Even for the maximum expected torque with a mild shock loading factor added, the shear factor of safety is well above the acceptable limit. For the gears on the winch, the manufacturer specifications rate them to lift at least 300 pounds vertically, more than enough for this system's needs.

The pulleys are made of zinc cast-iron, with the teeth of the dogtooth section measuring about 3/8" in thickness. Assuming the teeth are cantilever beams with a point load on the end, the overall bending stresses are negligible. If frictional wear from engagement shreds the teeth, the dogtooth design would have no issues engaging. If wear becomes serious, a manufactured replacement is recommended.

6.3.3 Concept Modeling

By integrating multiple forms of rotary power transmission components, this system helps exemplify the many ways that rotary power is handled in numerous applications. The gear system calls back to the drills lab, and shows how gears can be power sources without requiring manual turning. The v-belt system demonstrates a simple accessory system used commonly in large machine parts where gearing does not fit, and where costs do not allow for a more complex system. Students can also be introduced to belts which are off-axis, attached to multiple pulleys (like in a modern car engine), or in lightweight designs in the place of a chain and sprocket.

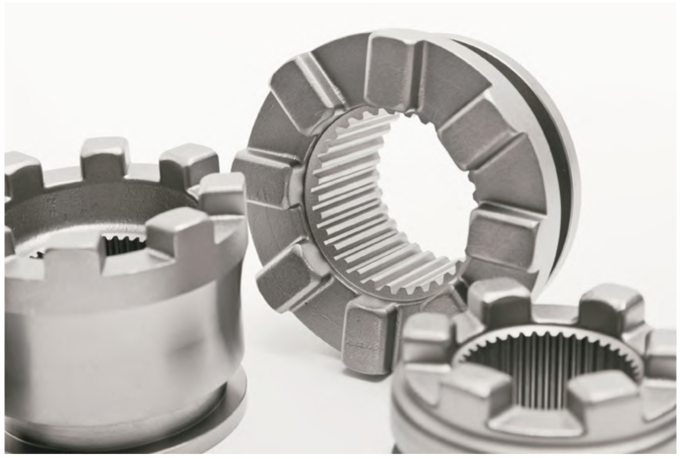


Figure 17. The dogtooth insert inside a modern racing gearbox. These parts are crucial to the design of the gearbox, as they allow for power transfer between gear reductions withing a very small footprint.

The dogtooth system introduces students to a common but rarely seen component inside modern day gearboxes. This critical component has allowed the design of a manual transmission to reduce its footprint significantly since the early days of automobiles. As seen in Figure 17, they are used in multiple locations with multiple shifting forks. By showing a very simple model of the dogtooth system, students can add a new tool in their design toolbox for use in future projects.

This system is also important in that is creates the losses that students must analyze. These types of losses exist in powertrain systems everywhere, and are remedied many different ways (bearings, bushings, face width, tooth count, etc). Some of these methods and applications can be covered in the intro presentation. Conceptualizing and observing these types of losses, be it directly through this system or through comparison of other connected systems, is crucial to understanding the first and second law of thermodynamics and the idea of a non-reversible process.

6.4 Potential Energy Conversion Subsystem

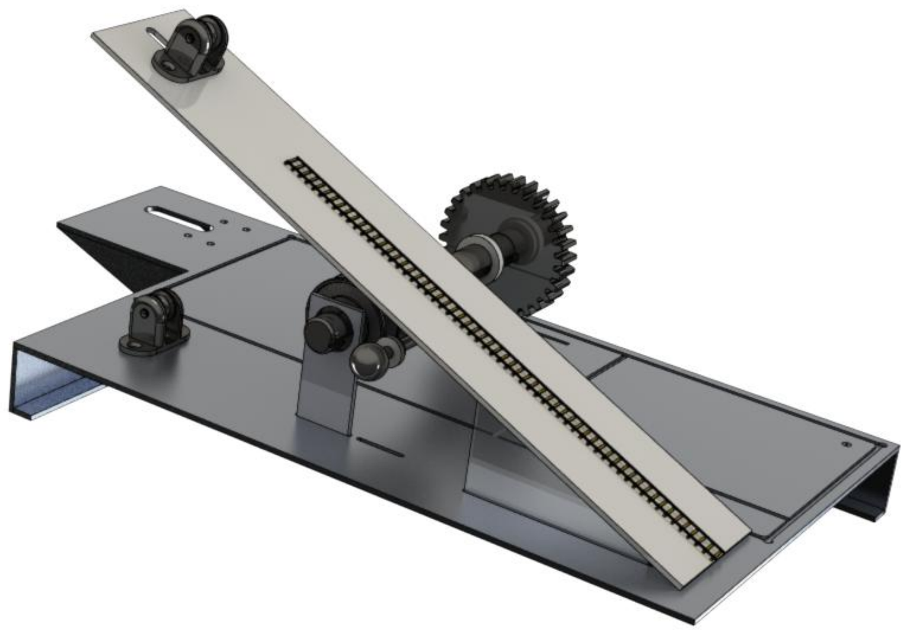


Figure 18. Potential energy conversion subsystem.

The potential energy conversion subsystem is the simplest energy conversion subsystem to understand in the experiment. Similar to the power transfer system, it introduces freshman to losses that occur from static and kinetic friction of rolling objects. When the system is engaged with the power transfer shaft, the pulley underneath the ramp gets spooled, thus pulling the cart up the track.

Both the ramp and ramp base will be cut to size from .118" thick acrylic sheet. The ramp base will be located with a slot on the housing and bonded with an acrylic bonding agent. The ramp will then be bonded on to the ramp base at a 25°angle. The ramp will also be slotted towards the top to fit the 1/8" braided rope. Additionally, horizontal pulleys will be mounted on both the housing and ramp with 3/16" fasteners. The track will be purchased online as Code 80 Flextrack and glued onto the ramp. A standard Atlas boxcar was selected as the cart for the subsystem. Due to the difficulty to calculate the exact losses in the power transfer system, it was decided that the mass of the cart would be determined through testing.

Through this subsystem, students would observe that the cart can never move up the ramp on its own. They would also see that the max height of the cart would never reach the height of the initial mass. Students can then compare the efficiency of the PE change to the efficiency of the rpm and determine what causes those differences if any.

6.4.1 Concept Modeling

Although the conversion from potential energy to potential energy may seem pointless to the students, the first and second law of thermodynamics are easiest to demonstrate here. While the students are observing the first law, they can also see how the flow of energy could be reciprocated for practical use and real world applications. As mentioned in section 4.2 with the concept of the advanced rail energy storage, the idea of a cart (in this case a train car) running up the hill storing potential energy, can easily be related to the experimental model with the weighted toy car. The basic concept of storing potential energy (at a loss) can also be seen in the hydro storage plants seen in various high demand areas around the world.

6.5 Pump Subsystem

The pump subsystem aims to introduce students to the concept of fluid energy as well as show them what a miniature centrifugal pump looks like. It consists of the large pulley, the pump pulley, the pump shaft, the pump, and SAE 10W oil that submerges the pump. Additionally, a steel ruler will be attached to the back wall of the pump housing to measure head height. A picture of the subsystem without oil and the housing can be seen in Figure 19 below.

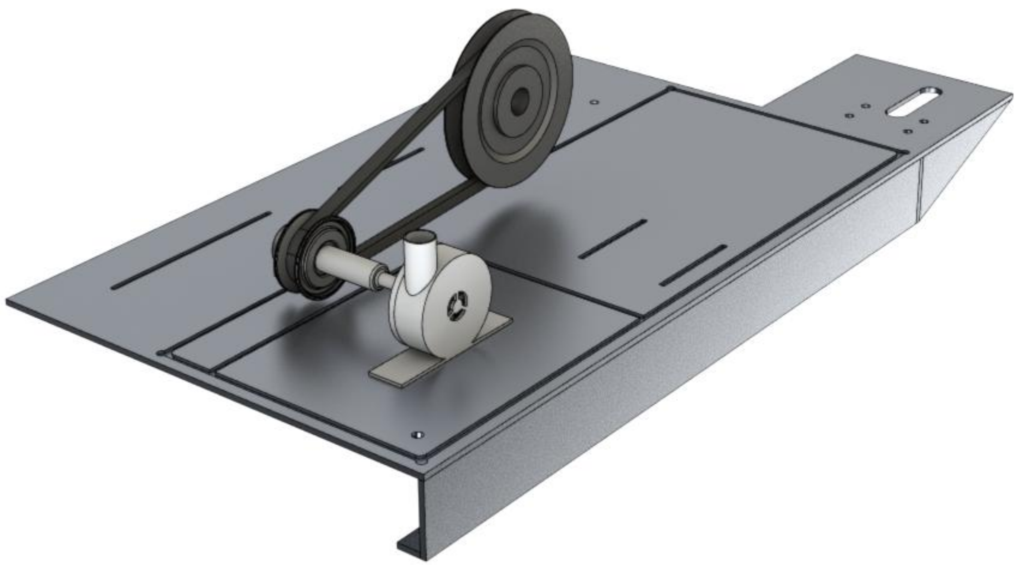


Figure 19. The pump subsystem.

When the system is engaged, the large pulley turns the smaller pump pulley which is connected to the pump shaft. The shaft then turns the impeller which produces head. The large pulley will have a diameter of 3.5" while the pump pulley will have a diameter of 1" giving a ratio of 3.5:1. The pump shaft will be connected to the pump pulley by using a set screw and will be stepped down from .5" diameter to .25". This end will be glued into the pump impeller. A detailed breakdown of the pump and its components can be seen in Figure 20.

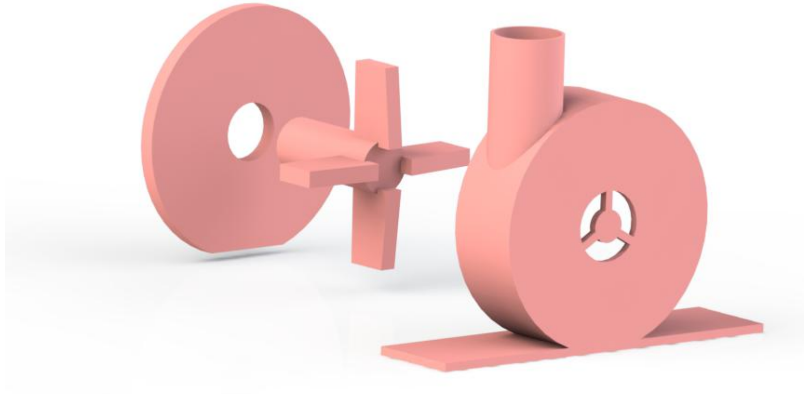


Figure 20. Exploded view of the pump.The three components include the main housing, the impeller, and the housing cover.

As seen from above, the pump consists of three main components: the main housing, the impeller, and the housing cover. In order to get an initial estimate of the pump size, a 2.25"x2.625"x3" Little Giant 1-EUAA-MD aquarium pump was borrowed from Dr. Andrew Kean and referenced. During disassembly of the Little Giant, it was found that there was no easy way to attach the impeller shaft to the stepped down pump shaft. It was also found that most standard aquarium pumps operated though use of an electromagnetic motor which increased the overall size of the pump. With this information, it was decided that the best course of action would be to 3D print a pump similar to the Little Giant but with an easily accessible impeller shaft and smaller dimensions. The final dimensions of the pump are 1.88" long, .75" wide, and 2.38" tall.

The pump was then analyzed to ensure that the falling mass would produce enough head for students to measure. The following equations detail the process used.

6.5.1 Analysis

First, starting with Bernoulli's Equation of motion when the fluid is at rest at state 1 and at the maximum height at state 2:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 - h_{pump} + h_L \tag{13}$$

Where:
P_1 = Pressure at state 1
P_2 = Pressure at state 2
V_1 = Velocity at state 1
V_2 = Velocity at state 2
z_1 = Height at state 1
z_2 = Height at state 2
h_{pump} = Head created by the pump
h_L = Head loss
ρ = Density of SAE 10W oil
g = gravity

For both states, the fluid is at atmospheric pressure and the velocity is at zero while the fluid height at state 1 is

zero. This leaves:

$$z_2 = h_{pump} - h_L \tag{14}$$

Recall that h_{pump} is equal to:

$$h_{pump} = \frac{\dot{W}_{shaft}}{\dot{m}_{fluid}\, g} \tag{15}$$

Where:
W_{shaft} = Work of the shaft
m_{fluid} = mass of the SAE 10W oil

Finally this leaves:

$$z_2 = \frac{\dot{W}_{shaft}}{\dot{m}_{fluid}\, g} - h_L \tag{16}$$

For these calculations, it was assumed that the mass of the SAE 10W oil is equal to its density times the volume in the pump. It was also assumed that the head loss term could be dropped due to head losses being hard to quantify at low rpms. Instead, that loss was lumped into the overall inefficiencies of the power transfer through the system. A conservative value of 40% efficiency was used. The minimum head height was calculated to be 0.8 inches while the maximum head height was calculated to be 7.5 inches. Table 2 below shows the relationship between input mass and the height of pump head.

Table 2. Maximum pump head as a function of initial mass.

Mass (lbm)	Pump Head (in)
1.0	0.8
1.5	1.1
2.0	1.5
2.5	1.9
3.0	2.3
3.5	2.6
4.0	3.0
4.5	3.4
5.0	3.8
5.5	4.2
6.0	4.5
6.5	4.9
7.0	5.3
7.5	5.7
8.0	6.0
8.5	6.4
9.0	6.8
9.5	7.2
10.0	7.5

Using the steel ruler mentioned previously, students will be able to record head height for various masses. Then by using the simplified version of Bernoulli's (Equation 16), students can compare how much head the initial power of the mass falling before going through the power transfer subsystem to the actual head measured. Students would identify potential areas of loss in the system.

6.5.2 Concept Modeling

While the pump subsystem may seem very simplified, it has multiple real world applications that can be mentioned to students after the experiment is completed. Professors can describe this subsystem as part of an hydroelectric storage facility that takes cheap or unused energy and stores it for later. In this scenario, the falling mass would be imagined as the unused energy source and the resulting head would be the stored energy. Professors could then tell the students to imagine what would happen if all the pumped oil was saved in a higher reservoir and the system was ran in reverse. This would spark an open discussion on efficiency and feasibility of real world storage plants.

Another topic for discussion would be the similarities and differences between the different types of pumps. Most students coming into college with a basic understanding of a positive displacement pumps, such as a bike pump, but lack knowledge of centrifugal pumps and their uses. This topic could be covered by a quick lecture at the start of class or through pictures found in the students experiment manual.

6.6 Electrical Subsystem

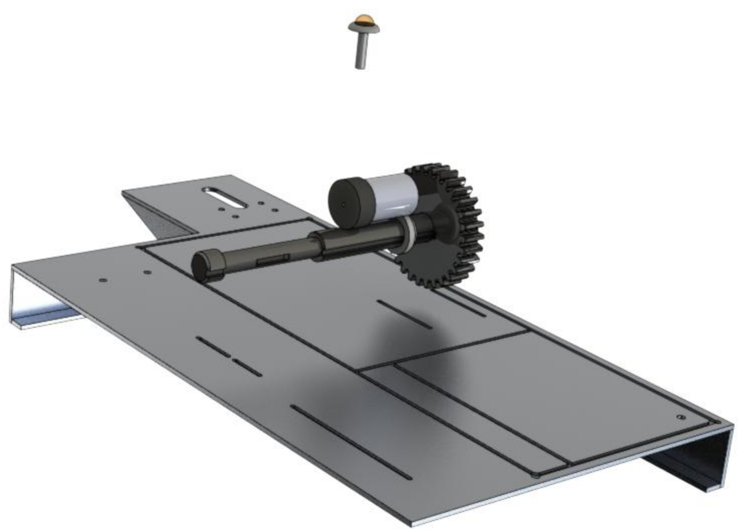


Figure 21. Isolated view of the electrical subsystem, which passively converts mechanical motion into electricity.

The LED light indicator is based off a simple rotating generator. Using a 12V laboratory motor placed in parallel with the main power transfer shaft, a small amount of current can be produced to power a low-wattage LED placed on the lid of the housing.

The design of this system is relatively passive and isolated. The motor chosen offers almost no magnetic resistance, and the LED has a high efficiency, requiring less than 1 Watt. These factors combined turn on the light whenever the shaft is rotating at any of the designed operating speeds.

If available, students can use an ammeter to measure current and voltage passing through the wires as the shaft turns. From these, power can be calculated and compared to the input shaft's power.

6.7 Heat Engine Subsystem

This subsystem is not part of the designed assembly, but is a deliverable required to meet the customer requirements for this specific design. To encompass the complete range of energy types, heat must also be covered in some form. Since the designed assembly cannot create heat energy in any form that is engaging or interesting (frictional wear), a more igniting example can be integrated into the lab.

Figure 22. A model temperature differential engine similar to that which will be purchased for demonstration purposes.

To demonstrate the conversion of stored energy into heat and mechanical energy, a small model alcohol burning engine will be purchased online. These small engines are relatively cheap compared to lower differential engines, such as the Sterling engine. One or two engines will be placed on the back table of the room, where the lecturer will call up groups one by one, showing how the engine works and how the energy input creates a thermodynamic cycle within the piston-cylinder system.

To help students quantify how much energy is being produced, a tachometer will be attached to the flywheel of the engine, reading RPMs of the engine. From this value, students can compare the power of the heat system to the main system and its various energy outputs.

To ensure the engine is operated in a safe manner, students will be forbidden from contacting any part of the engine. This rule will be enforced by a small blast shield, or piece of sheet acrylic. The lecturer can reach from the side and demonstrate the kick start required to start the engine oscillations, and then allow the students to take measurements.

Alcohol, if spilled onto the wooden table surfaces, combusts at a generally low temperature, giving anybody around a good amount of time to extinguish the flame before the table itself combusts (if it does combust at all). The multiple layers of errant hot glue strands on the tables should also protect them from any fire hazards.

7. Manufacturing

7.1 Manufacturing Timeline

As required by the customer, all manufacturing was done in-house by either the team or by a member of the Cal Poly Shop staff. A visual guide of the original plan is available as a Gantt Chart in Attachment H. However, due to many setbacks and delays, the original timing was not achieved. The biggest issue that the team faced was not finding a shop technician who was available to CNC the baseplate slots at the end of winter/start of spring quarter. This caused a chain of delays as the team had to find alternative methods to manufacture the baseplate correctly. The team took steps to limit the delay as mush as possible by focusing on manufacturing all of the other components

while the baseplate issue was being resolved. This helped considerably but the team was still unable to make up all of the lost time. The failure to get the baseplate slots CNC'd also created many problems during the assembly of the experiment since the slots were a critical feature for location and fit of the remaining components. These problems, along with the complexity of the initial experiment design lead to the team barely being able to complete the manufacturing in time.

7.2 Baseplate and Acrylic Housing

The first component that was planned to be manufactured was the baseplate. Initially, the team wanted CNC-cut slots and holes for precision placement. It was estimated that CAM work and consultation would have taken approximately 30 minutes from when the shop tech received the CAD file. Machine setup would have taken another 30 minutes, followed by the operation itself, which was estimated to take 20-30 minutes. All of this would have resulted in a manufacturing time of roughly 1.5 to 2 hours.

However, since the team was not able to find someone to CNC the baseplate in an appropriate amount of time, other measures had to be taken. After consulting with the IT department, the team decided to cut the baseplate on the IT Department's waterjet machine. The plate design was modified to make the locating slots go through the material since the waterjet does not regulate depth. This resulted in the cuts creating a path with tabs as seen in Figure 23.Using the waterjet was beneficial as the CNC operation would have caused chatter in the material as it cut a long thin strip. Additionally, the vice on the IT department's CNC machines were too small for the baseplate to fit. Unfortunately, a mishap during the cutting caused one of the slots to become slightly misaligned, which made it harder to fit the acrylic housing in.

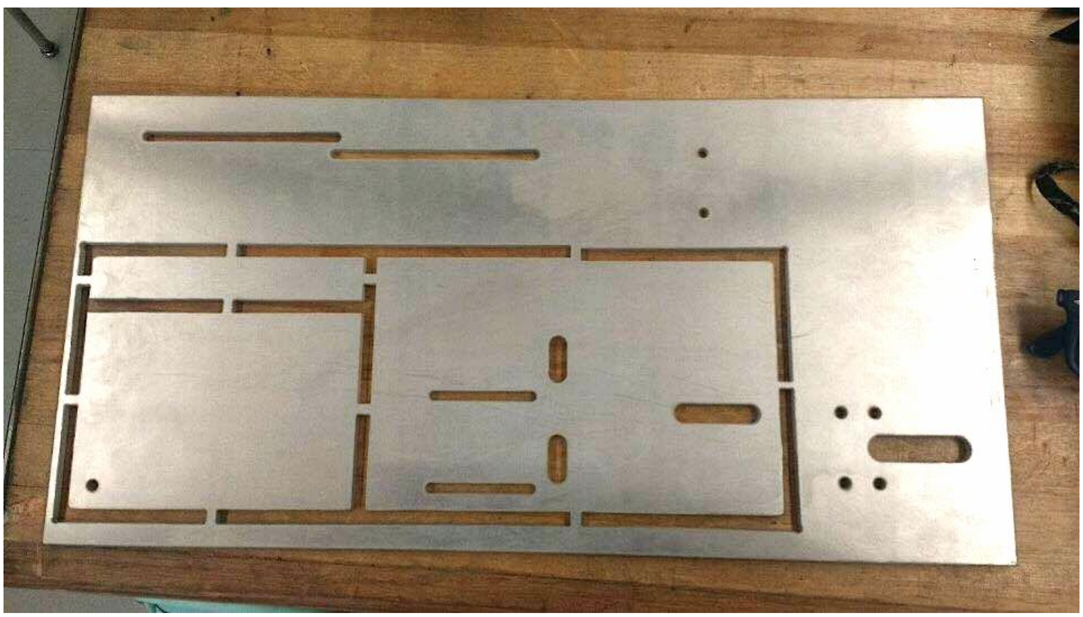


Figure 23. Baseplate of the experiment with locating rectangular through slots.

After the baseplate was cut, the gussets and cleats needed to be cut from the stock aluminum sheet. This could have been done on the vertical bandsaw and then sanded to a nice finish. However, after some consultation with the mustang 60 shop techs, it was found to be easier to simply just waterjet all the smaller pieces too. The gussets, cleats, ramp support, and bushing holders were all waterjet to achieve a precise cut.

The actual cutting time required to waterjet all the aluminum components was relatively short. However, the IT Department lab, where the waterjet is located, is only open for a few hours a week and can become very crowded. This will not be a a problem in the future as a new (or refurbished) waterjet is said to be opened in the near future for the ME department.

The acrylic housing was primarily manufactured on a laser-cutter in the M60 shop. In order to use the laser-cutter, an appointment had to be set up in the M60 office beforehand. Preparation to use the laser-cutter was key since the operation window was limited to only 3 hours. First, a DXF file of the desired cut lines was created in Adobe Illustrator and placed on a USB drive. Then, the 24"x2" acrylic sheet was cut on the table saw into a 18"x24" piece and a 6"x24" piece since the laser-cutter bed is 18"x36". With these two steps complete, the acrylic was ready to be cut on the laser-cutter.

The laser-cutter was able to cut all of the housing pieces successfully except one, which was the outer housing cover (pictured in Figure 24). For this piece, the cutter was unable to fully cut out the lever and lock-nut holes that helped locate the winch lever. The easiest method to fix this was to use a hole saw to remove the remaining material. However, more complications with the holes followed.

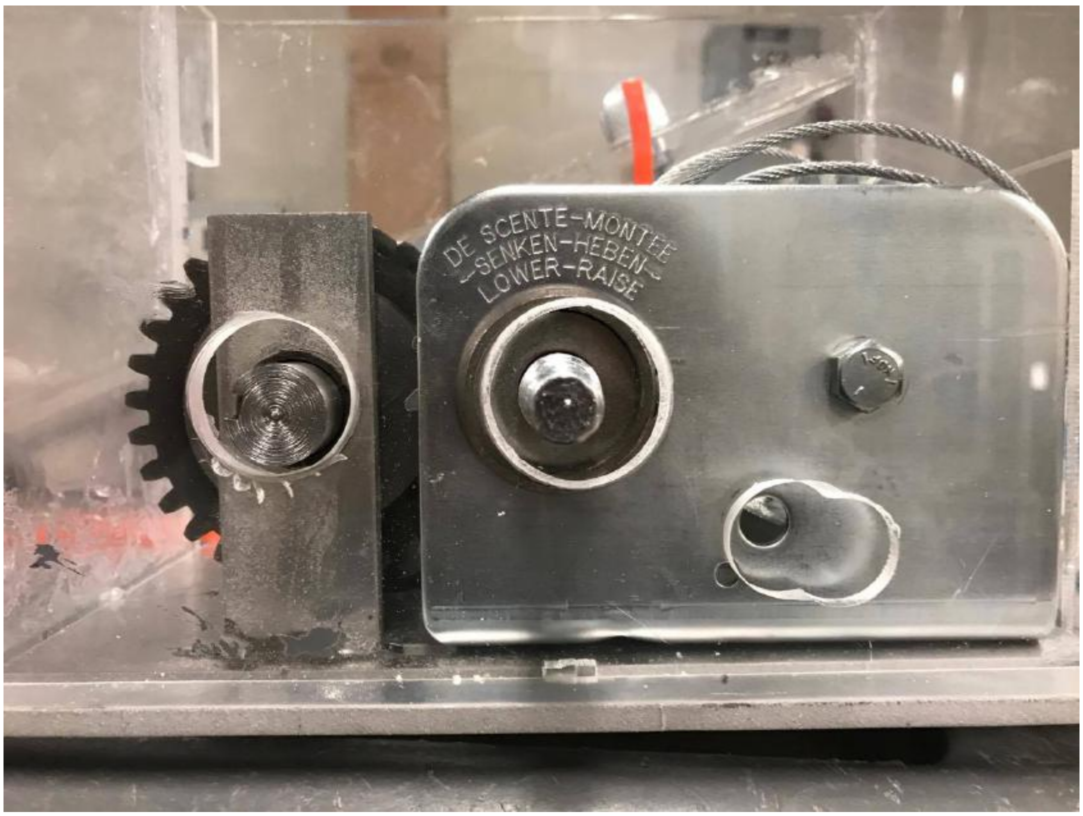


Figure 24. Outer acrylic housing wall. From left to right the holes are as follows: shaft hole (left), lever hole (middle), and lock-nut hole (right).

After placing the winch on the baseplate, it turned out that the lever hole and lock-nut hole were not correctly located on the acrylic. The team tried to fix this issue by widening the lever hole with the largest stepped drill bit possible but the lever was still unable to fit. The lock-nut hole was able to be re-drilled and was able to fit the nut but the winch lock was eventually removed (reasoning behind this decision is found in Section 7.5). Furthermore, the team used a hole saw to create an additional hole that allowed the driveshaft to be inserted easier during assembly.

The final acrylic operations arose from the baseplate being cut out on the waterjet instead of CNC'd. Locating tabs had to be cut into the bottom of the acrylic so that the housing pieces could fit into the baseplate. These tabs were simple to make and were done on the wood bandsaw in the shops. The pieces of the acrylic housing were also slightly over-sized, so the edges were sanded down on the belt sander until proper fit was achieved.

7.3 Drivetrain

The manufacturing of the drivetrain was mainly completed through the use of manual machines in the shop. These machines include the lathe, mill, and drill press. The following paragraphs contain a detailed description of the processes required to manufacture all the components necessary to assemble the drivetrain. A picture of the fully assembled drivetrain can be seen in Figure 25.

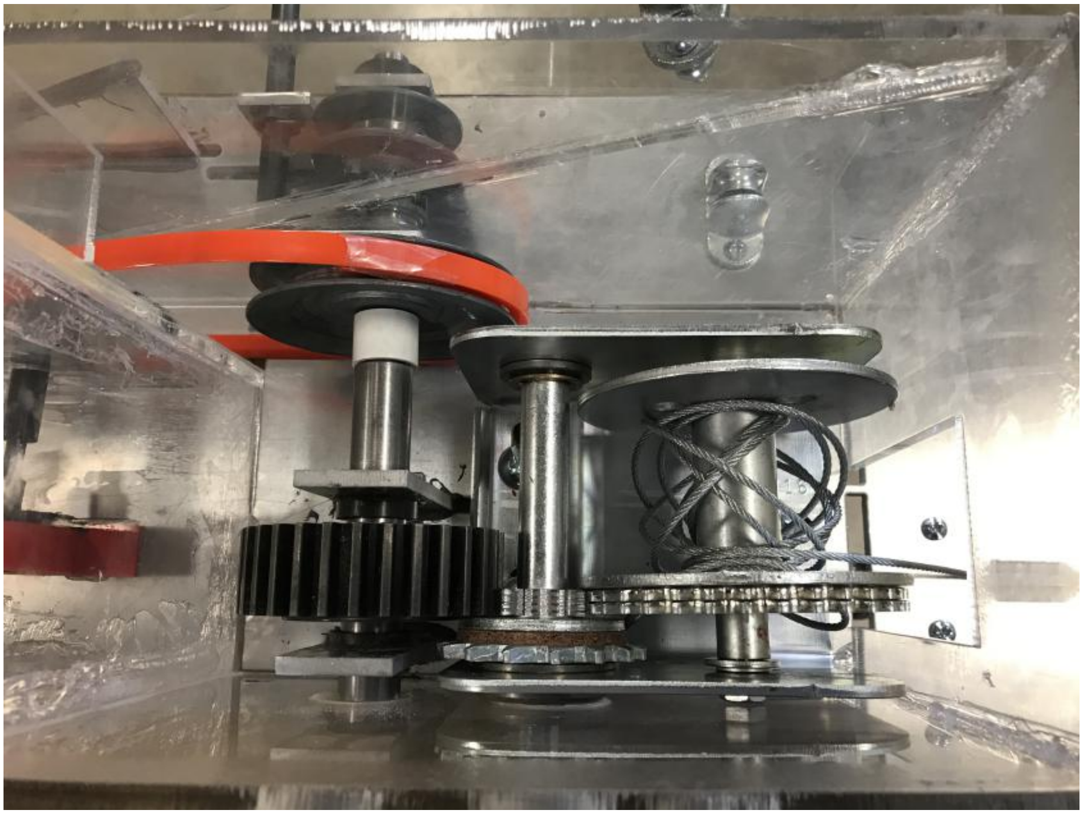


Figure 25. Top view of drive train with all power transmission components from mass-pulley to pump and cart subsystems.

The driveshaft was manufactured first due to its critical role in locating all the other components in the system. To start, a 3/4" diameter 1045 carbon steel keyed shaft was faced to length on the manual mill. Part of the shaft was then turned down to 1/2" diameter in order to fit the pulleys and dogtooth gear. Due to the keyway causing an interrupted cut, both the facing and turning processes required a slower spindle speed. Once the lathe operations were complete, a keyway was milled into the 1/2" diameter portion of the shaft. This was achieved by securing the shaft on the vise with a v-block and a scrap piece of wood underneath. To create the 3/16" keyway a 1/8" endmill was used. The milled keyway ended up being slightly small so a Dremel was used to widen the slot to allow the key to fit. Finally, the entire shaft was sanded down to allow for all the the components to fit with some clearance. The driveshaft can be seen pictured in Figure 25.

Figure 26. Keyed driveshaft.

The most difficult manufacturing operation was creating the dogtooth gear correctly. In order to prep for the final part, two practice pieces were cut out of 1" diameter 1018 carbon steel round bar stock on the steel chop saw. A rotating 4-jaw chuck head, pictured below, was then set up on the knee mill to allow the part to rotate 360 degrees.

Figure 27. Rotating 4-jaw chuck head that can be set up on a knee mill.

A bore finder was used in order to center both the chuck head and part in relation to the spindle on the mill. This process was very tedious since the bore finder needed to be used twice while setting up. First, the chuck head had to be centered along the x and y axes by checking the inner diameter of the 4-jaw opening. Then, the part was be centered in the 4-jaws by checking the outer diameter of the part and adjusting the x and y axes accordingly. Once the part was centered, five cuts were made with a 5/16" endmill 72 degrees apart. The first attempt can be seen in Figure 28.

Figure 28. First attempt at creating the dogtooth.The five cuts are clearly not centered on the part.

As seen from above, the first attempt at creating the dogtooth was extremely poor. It turned out that the part was not completely centered in the 4-jaws which severely disoriented the part as it rotated during the operation. This problem stemmed from the part being placed off-center in the 4-jaw chuck when it was initially clamped which made it harder to center. To correct for this, the part was placed as close to the center before being clamped in the chuck in order to reduce the error at the start. Furthermore, after each rotation, the endmill was brought down over the part to check that it was still centered. These changes yielded much better results as evidenced by the second attempt pictured in Figure 28.

Figure 29. Second attempt at creating the dogtooth. Better centering resulted in a better cutting pattern.

With the trial runs completed, the final part was ready to be made. The leftover round stock was placed on a lathe and then faced to ensure that the edge was flat. A 1/8" deep groove was then cut into the part using an 1/8" parting tool. The groove was widened to roughly 1/4" using the standard facing and turning tools available. Next, a 1/2" hole was drilled a little over an inch deep. Following that, the piece was cut to length (1") using a parting tool and the milling operations described previously were performed on both ends. Finally, a keyway was milled out between two of the dogteeth using an 1/8" endmill for the initial cut and a 1/16" endmill to reduce rounded corners. The finished dogtooth can be see in Figure 30.

Figure 30. Finished dogtooth gear.

After the dogtooth was completed, the 2" pulley and 3.5" pulley corresponding to the ramp and pump subsystems respectively, were manufactured next. These pulleys, which were handed down by the ME Department, came with a setscrew extrusion that was to be modified into dogteeth. The manufacturing process was almost identical to the creation of the dogtooth gear except no lathe work was necessary. The pulleys were again placed in the 4-jaw chuck and centered using the bore finder method explained above. Like the dogtooth, the pulleys were cut five times 72 degrees apart. However, a smaller 3/16" was used. The pulleys can be seen in Figure 31.

Figure 31. Pump and ramp pulleys with dogteeth milled out.

One change that cannot be seen in the pictures above was that the setscrew dogtooth was was completely removed. This was because the area around the setscrew was thicker than the other four dogteeth and caused major fit problems with the dogtooth gear. The justification for removing the setscrew dogtooth completely was that the setscrew hole already impacted the structural strength of the tooth, the other four teeth provided enough engagement to the gear, and that there was no easier alternative to make all of the components fit.

Figure 32. The extrusion on the drivetrain gear was faced down to fit within the subassembly.

Another important part of the drivetrain system was the large gear (pictured in Figure 32) that would serve to transmit the rotary motion of the winch to the subsystems. It was bought to mesh with the smaller gear in the winch. The gear however, had a keyway extrusion that needed to be removed. At first this seemed like a challenge since the gear was made out of hardened steel, but, after consultation with shop techs it could easily be faced down on a lathe using a carbide tip.

The bushing supports were made using the rectangular pieces of aluminum cut from the waterjet. The two busing supports that supported the large gear were already the correct length, but the shifter bushing support and the pulley bushing support were not. These two supports were cut on the vertical bandsaw then filed so that the driveshaft and shifter would be correctly aligned. The holes in the bushing supports were drilled on the drill press. These holes had to be drilled in incrementally increasing steps as the finished hole size was 11/16".

The four bushings were created out of 1" diameter PTFE delrin rod. These bushings were easily made on the lathe since delrin is very easy to cut. Each bushing was created with the same four steps. First, the rod was faced to create a flat surface. Next, the rod was turned down to the desired diameter. Then, a hole was drilled into the rod. Finally, the rod was parted to length.

One of the components that was planned to be manufactured outside of ME Department shops was the shifter fork. Ideally, the shifter fork would have been waterjet in the IT Department at the same time as the other aluminum parts but was not done so. This lead to a time conflict since the waterjet was extremely busy towards the end of the quarter. This resulted in the shifter fork being cut to shape out of scrap aluminum on the vertical bandsaw and filed. A 1/4-20 tapped hole was then added so that the shifter knob could be screwed on. Alternatively, the shifter fork could have be manufactured on the plasma cutter in the hangar. The shifter fork took about 45 minutes of machining time to complete.

7.4 Pump and Pump Shaft

The pump shaft was made out of the same 1" PTFE delrin rod used for the bushings. First, the rod was roughly cut on the miter saw. That piece was then faced to length on the lathe. Additionally, the shaft was turned down to 1/2" diameter and stepped down to 1/4" diameter halfway through. Some extra sanding was done on both halves of the shaft to allow for a clearance fit with the pump impeller and pump pulley.

The pump itself was 3D printed in Building 13's Stratasys 3D printer under Larry Coolidge's supervision. Unlike some of the other 3D printing stations on campus, such as Innovation Sandbox, an appointment must be set up with Larry in advance in order to use the printer. Larry suggested some minor design modifications during the 3D printing appointment to make the pump stronger and easier to manufacture. His suggestion was to add fillets to some of the sharp corners which the team abided by. Once the changes were made, the pump's position in the printer bed was set on the computer and the job was run. Larry handled the dissolution of the support media and had the pump ready for pickup after 2 days. However, the total required time was influenced by other components that were being printed simultaneously. For this job alone, the three pump components would have taken roughly 12 hours plus the time required to dissolve the support material. The final manufactured pump can be seen in Figure 33 below.

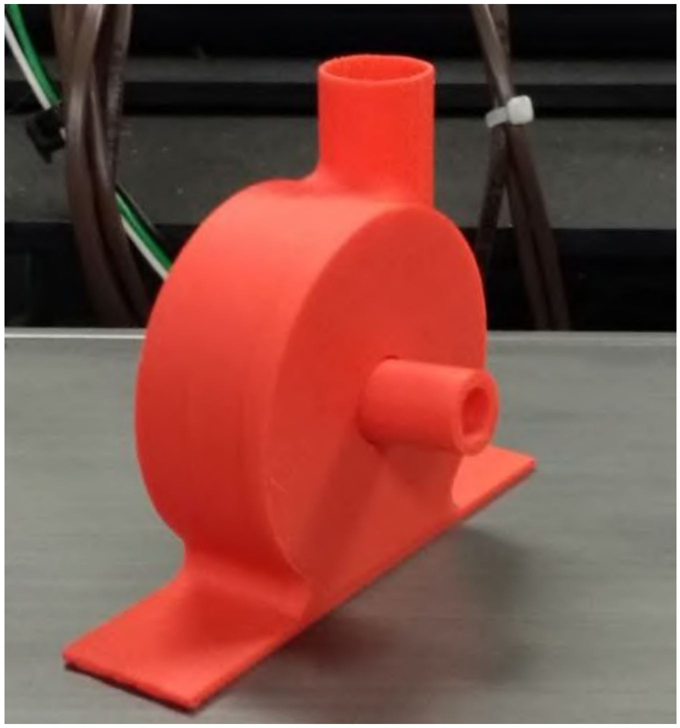


Figure 33. 3D printed pump with filleted edges.

7.5 Mass, Winch, and Pulley

There was not much manufacturing involved with the Mass-Pulley subsystem since it consisted of buying the winch, the pulley, the rope, and the weights. The only notable manufacturing was done on the winch to allow it to turn easier as the weight falls. The spring loaded lock and lock-nut were removed so that the winch could turn without getting locked as the weight falls. On top of that, two washers were added to the shaft of the large gear to keep the gear engaged throughout the the weights entire fall. These modifications resulted in some additional noise as the weight falls but was deemed negligible. The purchased weights are small fishing weights which were chosen for their small size but heavy weight. The fishing weights also have a loop at the top of them so that they can easily be attached to a carabiner. Figure 34 shows the set up of this subsystem.

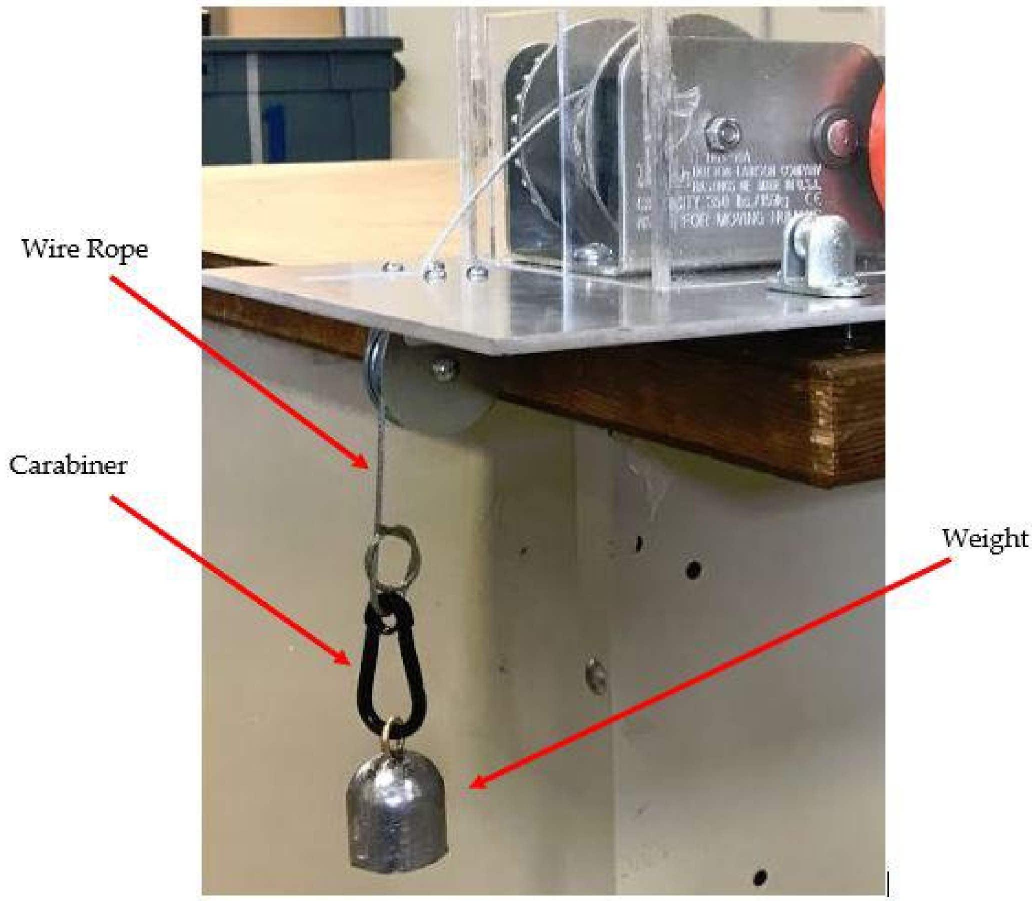


Figure 34. Mass-Pulley Subsystem to produce initial potential energy input

7.6 Final Assembly

The experiment was assembled in multiple steps in an attempt to limit the amount of problems that could have arose from a rushed assembly. The acrylic housing was done first, followed by the drivetrain and mass pulley subsystems, then the pump subsystem, and finally the cart subsystem. The fully assembled project can be seen in Figure 35.

Figure 35. Fully assembled experiment on top of one of the HVAC tables.

As mentioned above, the acrylic housing was assembled first. The finished acrylic pieces were inserted into their correct locations and fit was double checked. The team used a standard acrylic epoxy bought off Amazon to bond the acrylic together but found that the strength of the epoxy was not enough. The team then resorted to using Loctite silicone aquarium sealant which proved to be sufficient. At the same time, the ramp support was bonded with JB Weld to the baseplate so that the acrylic ramp could be epoxied to the back wall of the housing. The housing was then clamped and allowed to set for the required time.

Following the completion of the housing, the team proceeded to assemble the drivetrain and mass pulley subsystems. These two subsystems were done in conjunction since the winch was needed to correctly align the large gear and driveshaft. With the winch bolted down to act as a guide, the large gear bushing supports were located in the baseplate so that the large gear could fully engage with the gear on the winch. These supports were bonded to the baseplate with JB Weld. After allowing the JB Weld set, the team discovered that the supports had shifted slightly which caused the driveshaft to seize. To fix this, the team removed the shaft and cleared out some material from the bushings using a Dremel. Once the alignment problem was verified to be fixed, the pulley bushing support was aligned with the other supports and welded onto the baseplate. The team had difficulty placing the pump pulley onto the shaft due to its sheer size and its location on the shaft. As a result, an additional hole was drilled into the outer housing so that assembly could be completed.

The pump system was assembled by caulking the inner pump walls to the baseplate. Additional aquarium epoxy was added to the acrylic walls to ensure that the entire section was water tight. The small pump pulley was attached to the pump shaft by torquing the setscrew in place. The inside of the pump was sprayed with Flex Seal water sealant so that water would not be able to seep into the 3D printed layers. The casing of the pump was then bonded with the Loctite sealant to itself and to the baseplate. Similarly, the impeller was bonded with the pump shaft using the Loctite. Unfortunately, during the curing process, the pump and pump shaft shifted which caused the shaft to seize. This problem was unable to be fixed since the housing limited the space available to do any further manufacturing. Along with the pump shaft problems, the team had a lot of difficulty fusing the v-belt that

transfered energy from the large pump pulley on the driveshaft to the small pump pulley on the pump shaft. The team attempted to follow the recommended procedure of heating, or melting, the belt together but that method was unable to provide a strong bond. As a result, the team tried to use Gorilla brand super glue to bond the belt which proved to be more effective than heating. However, the team found that the super glue failed to hold when the pulleys were rotated. The v-belt was super glued to the large pump pulley itself which turned out to work well in comparison to the other methods but its strength was unable to be fully tested. Due to time constraints, the team deemed the pump subsystem to be unusable for testing.

The cart subsystem was the last subsystem to be assembled since it was the easiest of all. The first step of the assembly required the two small cart pulleys to be bolted down, one to the baseplate and one to the ramp. Then the cart track was super glued onto the ramp. Finally, the rope was strung through the pulley system and tied to the cart.

After fully assembling the experiment the team reflected on ways to make the assembly process easier for the future. It was concluded that placing the housing on first hurt the ability to adjust for problems that arose in the other subsystems. This problem could have been avoided if the slots were CNC'd, but they were not and the procedure was believed to work just as well. If the slots were to be waterjet again, the team would recommend to assemble the drivetrain and pump system (including the two inner pump walls) first so that more space is available to work on any issues. The acrylic could then be assembled afterward since they only affect the timing of assembling the ramp.

8. Testing and Validation

Due to the complications faced in the manufacturing stage and a lack of time, tests were not actually able to be performed on the experiment. However, a testing plan was made that details the steps required to test the experiment. The testing plan can be found in Attachment K. Most of the testing procedures that were planned to be performed would have to be iterated many times to get a consistent set of data that could have been replicated by the students. These tests would check each subsystem and the durability of their components.

The main component that the team wanted to test was the mass-pulley system that produces the input power to run each subsystem. This system was to be tested so that the calculated values of rpm correlate with the values that are read from the digital tachometer. The predicted values of rpm would be calculated using equation 10. The team did not expect these values to exactly match but they should at least be on the same order of magnitude. The other calculation that needed to be verified would be the time of the fall, which can easily be done with a stopwatch. A final mass range would have been decided through extensive and repetitive falling mass tests. The lowest mass of that range will be equal to the minimum mass required to power all three subsystems. At the opposite end of the spectrum, the value for the maximum mass is dependent on the maximum height of the cart and pump head. Additionally, various safety measures will have to be taken into account as well as it's overall compatibility with the system. These safety measures would include making sure the mass itself didn't topple over the whole experiment, or break off of the attachment rope. The other safety measure to best tested out would have been to make sure the fall weight does not fall on students toes as it falls, or possibly swing around and hit them in the legs.

As mentioned in the potential energy conversion subsection, testing will have to be done to determine the weight of the cart. In order to do so, the cart will start with no mass and the experiment will be run for dropped masses ranging from 1 to 10 lbs. If the mass of the cart is too low, it will then be increased by .5 lb increments until a usable range of heights for all dropped masses is found. It is important to note that the mass of the cart will also decrease or increase depending on the usable range for the pump. The heights produced for the ideal cart mass will then be tabulated and graphed for the ME 128 professors to reference.

Testing would have also been done on the pump subsystem to validate the head height calculations since the losses were assumed. This testing will be done in a similar manner as the previous tests mentioned. The head height will be determined by dropping the initial mass and recording how much head is produced. Since the pump is the most difficult component to change, it will have the most influence on the usable operation range for the experiment. Again, the head heights will be tabulated and graphed for the ideal input mass range for professors to reference.

Once subsystem testing is completed, the entire experimental procedure will be validated through simulated classroom trials. The team will run the experiment first to ensure that the students will have all the necessary equations and equipment to obtain consistent data. If the experiment performs satisfactorily, testing will move to student trials, using several sample groups to again run the full experiment. Any feedback will be recorded and taken into account

if modifications are required. Finally, the experiment will be tested by the faculty who will be teaching ME 128 regularly. Again, feedback will be recorded and modifications will be completed if necessary.

A set of preliminary tests should have been conducted with a possibly prototype to see if all the components would be able to be assembled as designed and if they would have given the results that were hoped for. The V belt should have been tested for strength before assembly, as it ended up breaking with student interface.

9. Cost Analysis

Part sourcing for this project was done with the idea that multiple experiments would be constructed in the years to come. The team also sourced the parts that would result in the cheapest overall costs, which include shipping. Item were ordered from a few large suppliers who have a history of lower shipping costs on bulkier orders.

It must be noted that our final cost is just under $800. This is due to several one-off purchases not required for reproduction, and also due to the fact that producing a prototype of a product is costlier than a production run.

It was thought that cheaper parts could be sourced to (such as those with educational deals), the total cost per unit may still fall above the specified $500 limit. However, no deals were found and with the cost remained above the $500 limit. Since these parts were no obtained from education resources due to the nature of the component no such educational deals or affiliation with the university could have helped in any sort of price reduction. It is because of this we are recommending all units be partially sponsored by MESFAC, the ME department student allocation committee. Their mission is to fund any purchase that enhances ME student learning here at Cal Poly, and this project provides learning for students from multiple aspects. Freshmen are handling the experimental part of the project, and upperclassmen shop techs are manufacturing the units, gaining experience in machining and fabricating processes. It is because of this that the team believes MESFAC will have no issue sponsoring a portion of these units, keeping the out-of-pocket costs under $500 per unit for the ME department. Preliminary discussions with the current 2016-2017 committee reflected this view. It was found to be quite easy to obtain MESFAC funds, since the experiment did not require an large amount of money compared to other projects the team was able to get a total of $360 in MESFAC funds. The committee was able to see the importance of a new experiment in the curriculum and the benefit it would have for anyone involved in the department.

9.1 Bill of Materials

The bill of materials for this project, including cost and weights, is included in Attachment F. The final assembly weighs a total of 14.75 lbs, which is light enough for a normal person to lift and store in the closet of the room. This weight does not include the volume of water that would have been added to the system, but this weight will be small since the height required and the tank dimensions only require a small amount of water to be used.

9.2 Ordering

All parts were ordered online once the design was approved. All parts arrived on campus between a day and a week from ordering, based on traditional turn around times from the sources picked. Some parts were ordered later than others to either try and find cheapest alternatives or the team was still contemplating the need for the material piece in the experiment. The most expensive shipping item was the lead fishing weights, however this particular vendor was chosen as they were the only vendor that did not sell these weights in bulk, but if bulk ordered of weights are bought they can be obtained from a vendor with a lower shipping cost.

9.3 Final Order Specs

The following table below shows what was eventually ordered and used in the final assembly. Most of the costs were covered by the alloted budget but other external, larger one off purchase were bought with MESFAC funds. Further details can be seen in Attachment G for more information on the budget.

Doing further analysis on these costs it was found that 76.9% of the project could be paid for using the alloted funds and 23.1% of the project was paid for using MESFAC funds. The majority of the cost come from the sheet orders, however if ordered in bulk the price per sheet can be reduced to possibly fit with the budget. Another way that

the total cost of production could be reduced would have been with CNCing the baseplate in the machine shops which could have been easily done by shop techs during the summer. This can prove for a simpler assembly the acrylic walls and aluminum parts with simpler methods can prove to be cost effective. Considering how fast all the material came and from accessible sources, it is entirely possible and simple for someone else to place an order. Hyperlinks to all materials and products used can also be found in the bill of materials

10. Design and Manufacturing Improvements and Recommendations

With the combination of over budget spending, difficulties in manufacturing, and non-operational status of the prototype, it can be quickly established that the concept for this project needs some improvements. The major constraint was the scope of the project with respect to the budget. For $500, it was very difficult to complete a device that covered all of the customer requirements. This was the main factor that led to the project's complications. If this project is to be attempted again, this issue can be resolved using the following recommendations.

One major flaw in the design was the pursuit of an all-in-one device that students could observe. Creating a single unit allowed for a large stack-up in design relationships, compatibilities, and tolerances. While a single unit would make an instructor's and student's time easier during lab time, the manufacturing and maintenance of a single unit that provides examples of thermodynamics, fluids, and heat transfer principles is overwhelmingly complex for the scope of the device. Even though we split the heat transfer demonstration up from the main unit, the complexity of the mechanism provided us with enough issues that we excluded the heat transfer apparatus from the deliverables.

Splitting the current design into two or three separate modules would ease the complexity of the experiment setup. For example, the thermodynamics experiment could be fragmented into a single module that students could power with via a crank. Another module would demonstrate fluid flow through a pipe, and another would demonstrate heat to mechanical energy transfer. By splitting up the concepts, small frames of 8020 or similar could be used to simplify construction and reduce cost from buying raw materials. Since a stock winch is no longer being used, plastic gearing can be used all around. Each sub-frame would only require 3-4 components to be attached to the rails, and would be wholly contained inside themselves, allowing for simple storage.

Figure 36. One concept that utilizes the modular experimental setup, demonstrating only fluid energy transfer through a pump using a drill-driven pump and a small custom made turbine. This is essentially what the pump side of the project design covered, but broken out to create an easier to make assembly. Small experimental stations like these would be made for the other forms of energy conversion.

Another option is to continue to use the concepts in the current design, but reduce the scope of both the data acquisition and relations to current industry energy problems and solutions. This concept, seen in Figure 36, is based off of a similar project done in ME 443, Turbomachinery. This design would, again, allow us to utilize more stock parts without the use of a restrictive stock input. Instead of printing a pump, this design would allow for use of a stock input and output pump/turbine combination. The open-aired design would allow for easy storage and maintenance of the fluid containment system. Additionally, the compact design would again allow for a self-contained design. Students would take data on digital tachometers and voltmeters, essentially simulating a hydroelectric dam. Power is inputted via a hand-powered drill, making recharging and replacing easy.

While being highly interactive and educationally engaging, the data collection (which was a major customer requirement) in the aforementioned experiments is fairly sparse. To remedy this, students could also use more passive experimental devices, such as our original Joule House concept. While definitely less stimulating than a more visually appealing project, the data collection would be much more extensive. Students would be able to collect multiple data points in varying conditions, and would be able to practice basic statistical analysis which they could comment on in their memorandums. Maintenance and manufacturing would be minimal, as there are no moving parts and setup is largely reliant on sensor calibration. However, as mentioned before, this experiment would be largely uninteresting to incoming freshmen and may detract from the overall lab experience in a similar fashion to the current spring lab.

These concepts are brief design iterations that may or may not be pursued in the future. In general, however, the following general notes should be taken into account:

- Reduce the scale of the experiment in terms of energy used and footprint (for self-sustainability and storage).
- Partition each concept covered into its own station within the lab environment.
- Ensure all devices in the lab have something physical students can observe. This can be as simple as a pinwheel fan and as complex as a rotating flywheel.

- Formulate calculations that can be done by incoming freshmen students and that include direct relationships between one another.
- Generate lab experiments that can be loosely tied back to a general mechanical component or assembly. The connection can be very loose, but it must allow students to make connections they can branch off of.
- Specify separate budgets for the prototyping and mass-production of the experiments, to allow the project team some leeway to test various types of subsystems.
- Unique manufacturing techniques must be accessible to the shop techs *and* must also be accessible by the project team members.

11. Conclusion

This project concept has great promise, and can be done. The design pursued in this iteration was overly complex in an attempt to capture the attention of the students and encapsulate all of the topics desired. As a result, the final product suffered from delayed manufacturing timelines, reliances, and quick-fixes resulting in a finished product that strayed too far from the original design.

We recommend that this project be pursued again, with the lessons learned from this experiment. The refined scope and better idea of budgeting gathered from this project would greatly benefit any future iterations, and would reduce the time used during the PDR and CDR phases where formation of just the general experimental concept and lab execution was developed.

While the final device was largely unsuccessful, the research and design development done in the first phases of the project offer valuable information for anybody pursuing a project similar to this, and we hope that it will be of use to all who read this paper,

References

[1] Michael J. Prince. "Best Paper PIC IV: The Use of Inquiry-based Activities to Repair Student Misconceptions Related to Heat, Energy, and Temperature". *2012 ASEE Annual Conference & Exposition, San Antonio, Texas, 2012, June*. ASEE Conferences, 2012. https://peer.asee.org/21014 Internet. 18 Oct, 2016

[2] Margot A Vigeant, Michael J. Prince, Katharyn E. K. Nottis, Milo Koretsky, and Thomas W Ekstedt. "Design For Impact: Inquiry-based Activities for Important Concepts in Heat Transfer that Faculty Will Actually Use". *2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, 2016, June*. ASEE Conferences, 2016. https://peer.asee.org/26678 Internet. 16 Oct, 2016

[3] Margot A. Vigeant, Michael J. Prince, and Katharyn E. K. Nottis. "Making their Brains Hurt: Quick and Effective Activities for Thermodynamics". *2012 ASEE Annual Conference & Exposition, San Antonio, Texas, 2012, June*. ASEE Conferences, 2012. https://peer.asee.org/21667 Internet. 18 Oct, 2016

[4] Adrienne Minerick. "A Desktop Experiment Module: Heat Transfer". *2009 Annual Conference & Exposition, Austin, Texas, 2009, June*. ASEE Conferences, 2009. https://peer.asee.org/5443 Internet. 27 Sep, 2016

[5] Timothy Scott. "Versatile, Low Cost External Convective Heat Transfer Apparatus". *2004 Annual Conference, Salt Lake City, Utah, 2004, June*. ASEE Conferences, 2004. https://peer.asee.org/13626 Internet. 20 Sep, 2016

[6] Afshin Goharzadeh, Peter Rodgers, and Christian Mandel. "Innovative Fluid Mechanics Experiments For Modern Mechanical Engineering Program". *2007 Annual Conference & Exposition, Honolulu, Hawaii, 2007, June*. ASEE Conferences, 2007. https://peer.asee.org/2034 Internet. 18 Oct, 2016

[7] *PASCO Engineering.* 2009 Catalog. Roseville, CA

[8] Cameron Curtis, Katie Gregory, Cherie Nixon, Sehyun Oh. "ASHRAE Senior Undergraduate Project Grant: Table Top Building Controls and Building Physics Trainer". *HVAC&R Concentration Senior Projects, Cal Poly, San Luis Obispo, CA, 2015,June*. Dr. Jesse Maddren, 10 June 2015. Print.

12. Attachments (12)

Attachment A - PASCO catalog excerpts
Attachment B - Quality of Function Development Chart
Attachment C - Pugh Matrices
Attachment D - Safety Checklist
Attachment E - Design Calculations
Attachment F - Bill of Materials
Attachment G - Final Budget and Costs
Attachment H - Gantt Chart
Attachment I - Design Verification Plan
Attachment J - Drawings and Specification Sheets
Attachment K - Proposed Testing Procedures
Attachment L - Supplemental Academic Materials

Attachment A - PASCO Catalog Excerpts

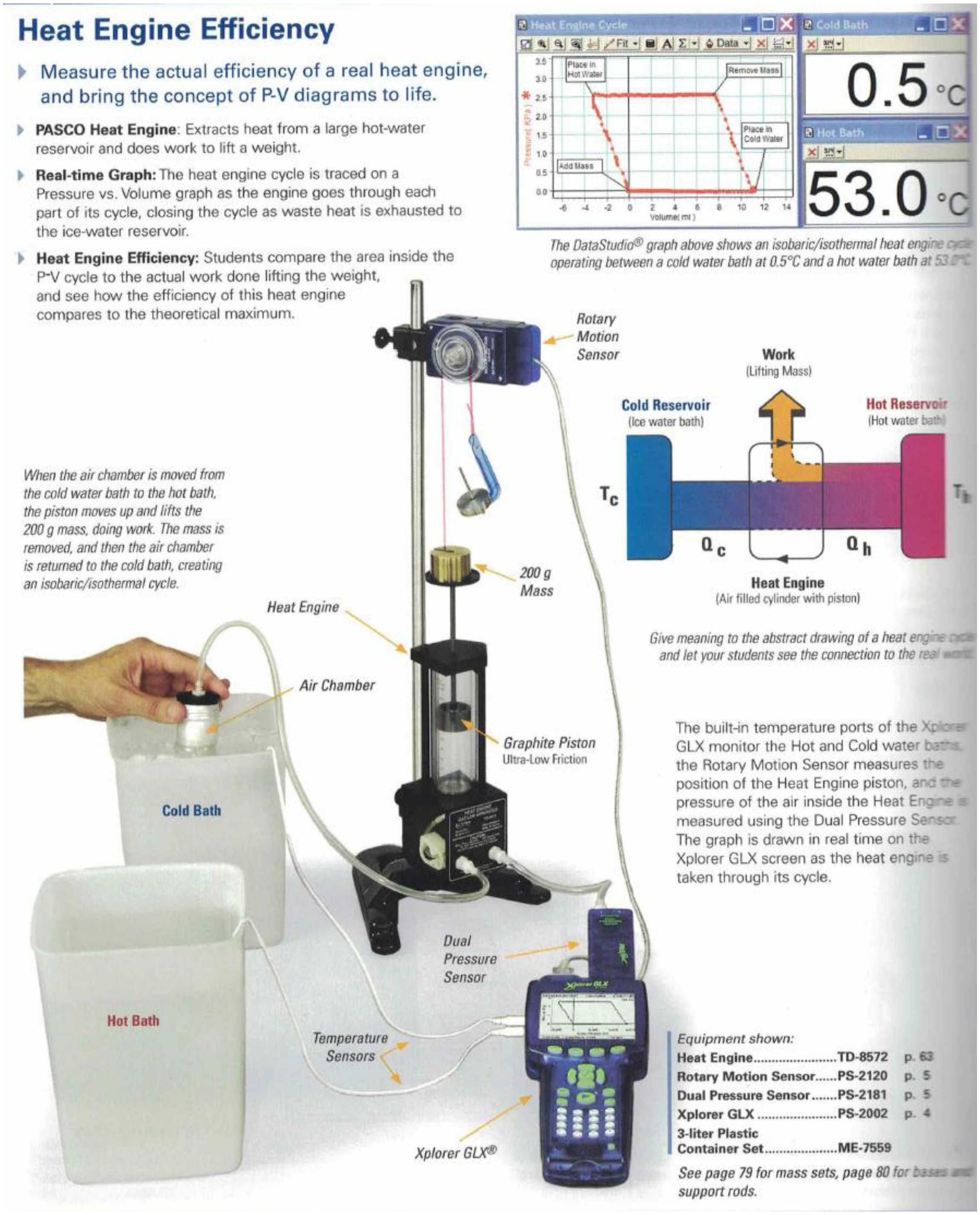
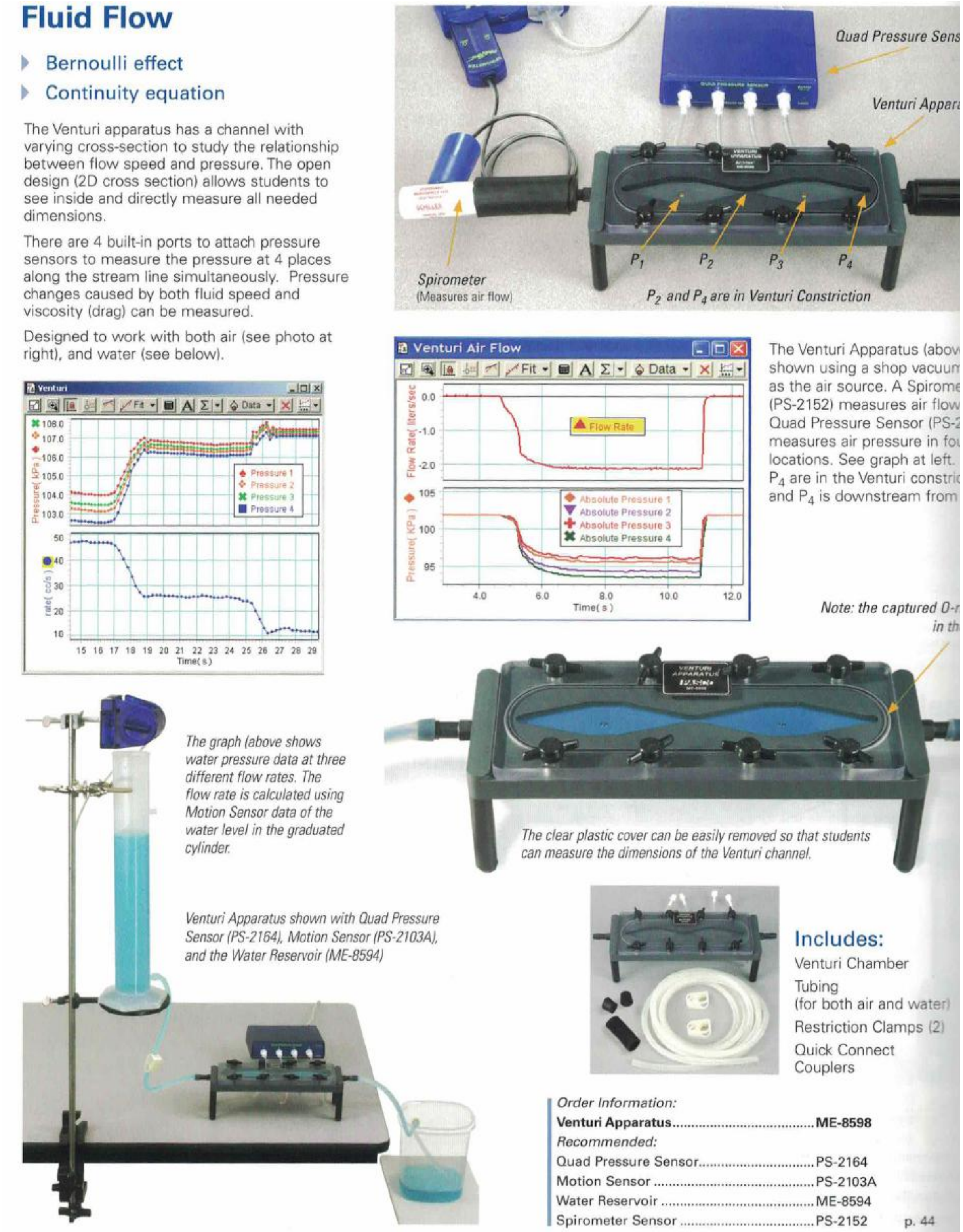


Figure A1. The Heat Engine Efficiency Lab by PASCO. This lab is rather complex mechanically, but covers all the relevant topics desired by the customer. It also contains a DAQ (data acquisition) device that specializes in thermodynamic process graphing. Sadly, the price is rather inflated, and some of the parts are rather delicate.

Figure A2. The PASCO Stirling Engine catalog entry. While engaging on a visual and mental level, this product is rather single-dimensional, targeting only simple conduction and an isothermal/isochoric process.



Fluid Flow

- Bernoulli effect
- Continuity equation

The Venturi apparatus has a channel with varying cross-section to study the relationship between flow speed and pressure. The open design (2D cross section) allows students to see inside and directly measure all needed dimensions.

There are 4 built-in ports to attach pressure sensors to measure the pressure at 4 places along the stream line simultaneously. Pressure changes caused by both fluid speed and viscosity (drag) can be measured.

Designed to work with both air (see photo at right), and water (see below).

The Venturi Apparatus (abov shown using a shop vacuum as the air source. A Spirome (PS-2152) measures air flow Quad Pressure Sensor (PS-2 measures air pressure in fo locations. See graph at left. P_4 are in the Venturi constric and P_4 is downstream from

Note: the captured 0-r in th

The graph (above shows water pressure data at three different flow rates. The flow rate is calculated using Motion Sensor data of the water level in the graduated cylinder.

The clear plastic cover can be easily removed so that students can measure the dimensions of the Venturi channel.

Venturi Apparatus shown with Quad Pressure Sensor (PS-2164), Motion Sensor (PS-2103A), and the Water Reservoir (ME-8594)

Includes:
Venturi Chamber
Tubing
(for both air and water)
Restriction Clamps (2)
Quick Connect
Couplers

Order Information:
Venturi Apparatus....................ME-8598
Recommended:
Quad Pressure Sensor....................PS-2164
Motion Sensor....................PS-2103A
Water Reservoir....................ME-8594
Spirometer Sensor....................PS-2152

p. 44

Figure A3. The PASCO fluid flow lab, which highlights various fluid properties by changing cross sectional areas, pressures, and surfaces. This lab is rather large in size, and requires fluids in open containers that must be prepared before lab. However, it does have numerous DAQ sources, making data collection of the fluid properties easy for users.

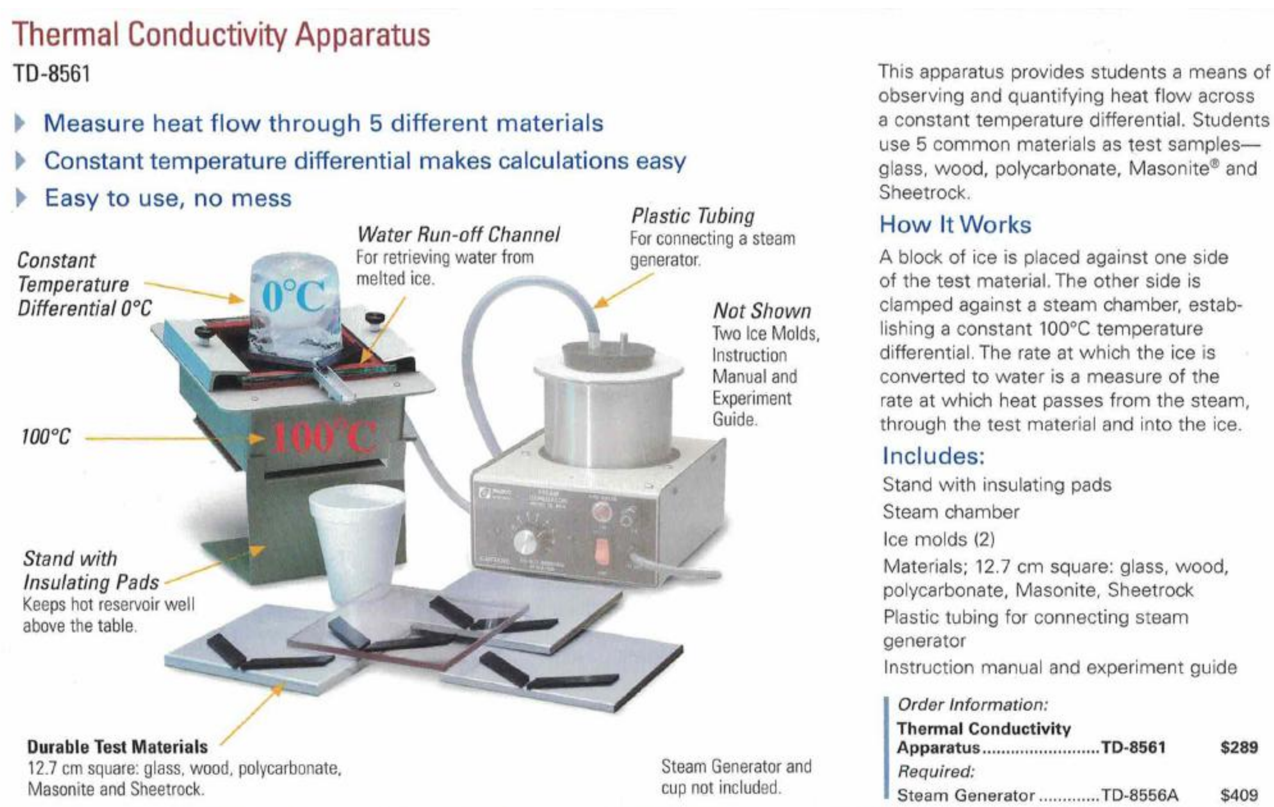
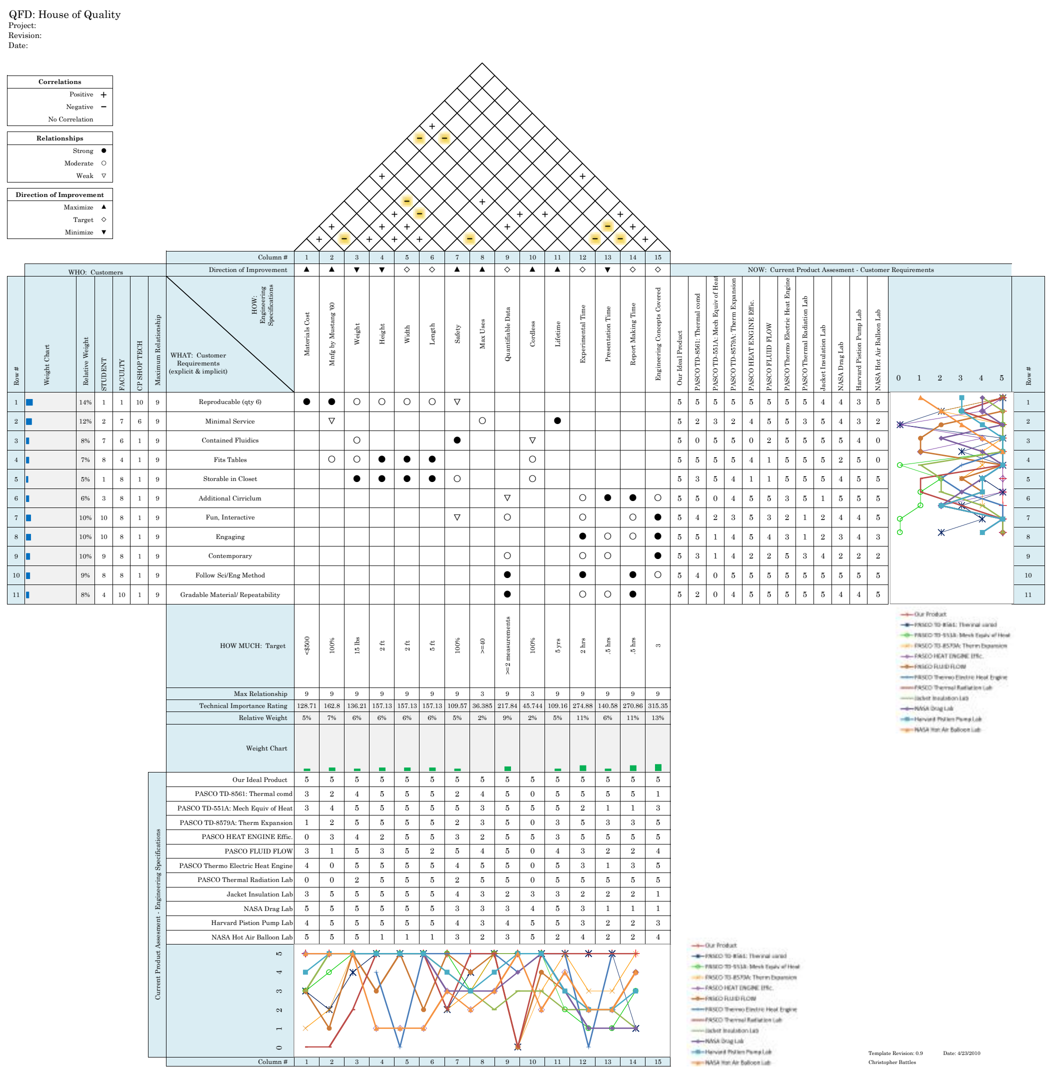


Figure A4. The catalog excerpt for the PASCO Thermal Conductivity Apparatus. This product offers a hands-on way to observe the conductive properties of various materials, but is very slow as it relies on ice melting to demonstrate heat transfer. It also requires ice to be frozen and water to be boiled, hindering setup times.

Attachment B - Quality of Function Development Chart



Column #						1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direction of Improvement						▲	▲	▼	▼	◇	◇	▲	▲	◇	▲	▲	◇	▼	◇	◇
Row #	Relative Weight	STUDENT	FACULTY	CP SHOP TECH	Maximum Relationship	Materials Cost	Mnfg by Mustang '60	Weight	Height	Width	Length	Safety	Max Uses	Quantifiable Data	Cordless	Lifetime	Experimental Time	Presentation Time	Report Making Time	Engineering Concepts Covered
1	14%	1	1	10	9	●	●	○	○	○	○	▽								
2	12%	2	7	6	9		▽						○			●				
3	8%	7	6	1	9			○				●			▽					
4	7%	8	4	1	9		○	○	●	●	●				○					
5	5%	1	8	1	9			●	●	●	●	○			○					
6	6%	3	8	1	9									▽			○	●	●	○
7	10%	10	8	1	9							▽		○			○		○	●
8	10%	10	8	1	9												●	○	○	●
9	10%	9	8	1	9									○			○	○		●
10	9%	8	8	1	9									●			●		●	○
11	8%	4	10	1	9									●			○	○	●	

Row #	WHAT: Customer Requirements (explicit & implicit)	Our Ideal Product	PASCO TD-8561: Thermal comd	PASCO TD-551A: Mech Equiv of Heat	PASCO TD-8579A: Therm Expansion	PASCO HEAT ENGINE Effic.	PASCO FLUID FLOW	PASCO Thermo Electric Heat Engine	PASCO Thermal Radiation Lab	Jacket Insulation Lab	NASA Drag Lab	Harvard Pistion Pump Lab	NASA Hot Air Balloon Lab
1	Reproducable (qty 6)	5	5	5	5	5	5	5	5	4	4	3	5
2	Minimal Service	5	2	3	2	4	5	5	3	5	4	3	2
3	Contained Fluidics	5	0	5	5	0	2	5	5	5	5	4	0
4	Fits Tables	5	5	5	5	4	1	5	5	5	2	5	0
5	Storable in Closet	5	3	5	4	1	1	5	5	5	4	5	5
6	Additional Cirriclum	5	5	0	4	5	5	3	5	1	5	5	5
7	Fun, Interactive	5	4	2	3	5	3	2	1	2	4	4	5
8	Engaging	5	5	1	4	5	4	3	1	2	3	4	3
9	Contemporary	5	3	1	4	2	2	5	3	4	2	2	2
10	Follow Sci/Eng Method	5	4	0	5	5	5	5	5	5	5	5	5
11	Gradable Material/ Repeatability	5	2	0	4	5	5	5	5	5	4	4	5

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
HOW MUCH: Target	<$500	100%	15 lbs	2 ft	2 ft	5 ft	100%	>=40	>=2 measurements	100%	5 yrs	2 hrs	.5 hrs	.5 hrs	3
Max Relationship	9	9	9	9	9	9	9	3	9	3	9	9	9	9	9
Technical Importance Rating	128.71	162.8	136.21	157.13	157.13	157.13	109.57	36.385	217.84	45.744	109.16	274.88	140.58	270.86	315.35
Relative Weight	5%	7%	6%	6%	6%	6%	5%	2%	9%	2%	5%	11%	6%	11%	13%
Our Ideal Product	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
PASCO TD-8561: Thermal comd	3	2	4	5	5	5	2	4	5	0	5	5	5	5	1
PASCO TD-551A: Mech Equiv of Heat	3	4	5	5	5	5	5	3	5	5	5	2	1	1	3
PASCO TD-8579A: Therm Expansion	1	2	5	5	5	5	2	3	5	0	3	5	3	3	5
PASCO HEAT ENGINE Effic.	0	3	4	2	5	5	3	2	5	5	3	5	5	5	5
PASCO FLUID FLOW	3	1	5	3	5	2	5	4	5	0	4	3	2	2	4
PASCO Thermo Electric Heat Engine	4	0	5	5	5	5	4	5	5	0	5	3	1	3	5
PASCO Thermal Radiation Lab	0	0	2	5	5	5	2	5	5	0	5	5	5	5	5
Jacket Insulation Lab	3	5	5	5	5	5	4	3	2	3	3	2	2	2	1
NASA Drag Lab	5	5	5	5	5	5	3	3	3	4	5	3	1	1	1
Harvard Pistion Pump Lab	4	5	5	5	5	5	4	3	4	5	5	3	2	2	3
NASA Hot Air Balloon Lab	5	5	5	1	1	1	3	2	3	5	2	4	2	2	4

Figure B1. Quality of Function Development Chart for this proposal phase, correlating customer requirements to create engineering specifications.

Attachment C - Pugh Matrices

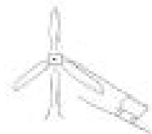
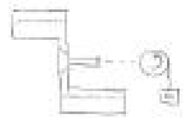
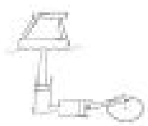
Concept / Criteria					
Cost	+	S	D	-	-
Safety	-	-		S	-
Turn Around Time	+	+	A	S	+
NO. of Data Points	-	-		+	+
Lifetime	+	-	T	-	-
Power Req	+	+		S	-
Lab Time (2hr)	+	+	U	S	-
Reportable Material	-	+		S	-
Educational Content	-	+	M	S	+
Real World Problem	-	-		+	+
Σ +	5	5	0	2	4
Σ -	5	4	0	2	6
Σ S	0	1	0	6	0

Figure C1. Experiment ideas compared in a Pugh matrix. The insulated house was used as a datum since it is a relatively common demonstration or example used in universities, including Cal Poly.

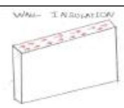
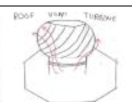
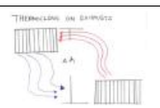
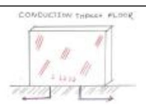
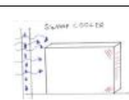
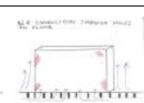
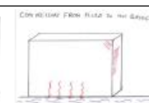
Concept / Criteria								
Modular	D	+	+	S	+	-	-	+
Real World		+	+	S	+	+	+	+
Points of Interest	A	-	+	+	+	+	+	+
Tangible		S	-	+	-	+	+	+
Relatable	T	-	S	-	-	-	-	-
Clean		S	S	-	+	-	+	-
Easy Set Up	U	S	-	+	S	S	-	-
Σ +		2	3	4	4	3	4	4
Σ -	M	2	2	1	2	3	3	3
Σ S		3	2	2	1	1	0	0

Figure C2. A concept component refinement Pugh matrix looking at the various heat transfer and HVAC component possibilities and their use to the project.

Criteria \ Concept	Wall Insulation	Fans	Ducts	Wall Radiation	Moving Car	Incline	Pump Impeller	Piping
Modular		-	-	-	-	-	S	-
Real World	D	S	-	-	S	-	-	S
Points of Interest	A	-	-	-	-	-	-	-
Tangible	T	+	-	-	+	+	-	-
Relatable	U	+	-	-	S	+	-	-
Clean	M	-	-	-	+	+	-	-
Easy Set Up		S	-	-	S	+	-	-
Σ +	0	2	0	0	2	4	0	0
Σ -	0	3	7	7	2	3	6	6
Σ S	0	2	0	0	3	0	1	1

Figure C3. Another concept component refinement matrix, this time looking at potential energy conversion components compared to heat transfer and HVAC components from the house idea.

Attachment D - Safety Checklist

ME 428/429/430 Senior Design Project 2016-2017

DESIGN HAZARD CHECKLIST

Team: ME 123 / Energy Advisor: HARDING

Y	N	
☑	☐	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☑	☐	2. Can any part of the design undergo high accelerations/decelerations?
☐	☑	3. Will the system have any large moving masses or large forces?
☐	☑	4. Will the system produce a projectile?
☐	☑	5. Would it be possible for the system to fall under gravity creating injury?
☐	☑	6. Will a user be exposed to overhanging weights as part of the design?
☐	☑	7. Will the system have any sharp edges?
☑	☐	8. Will any part of the electrical systems not be grounded?
☐	☑	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☑	☐	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☑	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☑	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☑	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☑	14. Can the system generate high levels of noise?
☐	☑	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☑	☐	16. Is it possible for the system to be used in an unsafe manner?
☐	☑	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Figure 4: Design Hazard Checklist, Page 1

Student Success Guide 17

Figure D1. Safety checklist for the recommended double tank energy conversions and losses experiment. This checklist is subject to change if the experiment concept is modified.

Attachment E - Design Calculations

Design analysis for the pump and pulley subsystems, to solve for design variables.

Mass (g)	Mass (kg)	Mass (lbm)	Mass (slugs)	Force (lbf)	Energy (lbf*ft)	Torque (gear/drum)(in-lbf)	Torque pinion
453.7	0.454	1.00	0.0311	1.00	3.00	0.50	0.16
680.6	0.681	1.50	0.0466	1.50	4.50	0.75	0.23
907.4	0.907	2.00	0.0622	2.00	6.00	1.00	0.31
1134.3	1.134	2.50	0.0777	2.50	7.50	1.25	0.39
1361.2	1.361	3.00	0.0932	3.00	9.00	1.50	0.47
1588.0	1.588	3.50	0.1088	3.50	10.50	1.75	0.55
1814.9	1.815	4.00	0.1243	4.00	12.00	2.00	0.63
2041.7	2.042	4.50	0.1399	4.50	13.50	2.25	0.70
2268.6	2.269	5.00	0.1554	5.00	15.00	2.50	0.78
2495.5	2.495	5.50	0.1709	5.50	16.50	2.75	0.86
2722.3	2.722	6.00	0.1865	6.00	18.00	3.00	0.94
2949.2	2.949	6.50	0.2020	6.50	19.50	3.25	1.02
3176.0	3.176	7.00	0.2176	7.00	21.00	3.50	1.09
3402.9	3.403	7.50	0.2331	7.50	22.50	3.75	1.17
3629.8	3.630	8.00	0.2486	8.00	24.00	4.00	1.25
3856.6	3.857	8.50	0.2642	8.50	25.50	4.25	1.33
4083.5	4.083	9.00	0.2797	9.00	27.00	4.50	1.41
4310.3	4.310	9.50	0.2953	9.50	28.50	4.75	1.48
4537.2	4.537	10.00	0.3108	10.00	30.00	5.00	1.56

Figure D1. Calculations for torque output of the winch.

alpha rad/s^2	atpulley (in/s^2)	atdrum	t (s)	rad/s	rpm
20	6	10	0.7746	92.952	9.7339
30	9	15	0.6325	113.842	11.9215
40	12	20	0.5477	131.453	13.7658
50	15	25	0.4899	146.969	15.3906
60	18	30	0.4472	160.997	16.8596
70	21	35	0.4140	173.897	18.2104
80	24	40	0.3873	185.903	19.4677
90	27	45	0.3651	197.180	20.6487
100	30	50	0.3464	207.846	21.7656
110	33	55	0.3303	217.991	22.8279
120	36	60	0.3162	227.684	23.8430
130	39	65	0.3038	236.981	24.8166
140	42	70	0.2928	245.927	25.7534
150	45	75	0.2828	254.558	26.6573
160	48	80	0.2739	262.907	27.5315
170	51	85	0.2657	270.998	28.3789
180	54	90	0.2582	278.855	29.2016
190	57	95	0.2513	286.496	30.0018
200	60	100	0.2449	293.939	30.7812

Figure D2. Calculations for the RPM output of the winch.

ft/s^2	eq.force (lbmft/s^2)	rpm_{os}	$rpmp_{shaft}$	Pin (W)	P_{out}	Energy	Pump Head (m)	Pump Head (in)
0.50	31.67	31.15	36.34	0.1283	0.0513	0.0398	0.0192	0.755
0.75	47.14	38.15	44.51	0.2357	0.0943	0.0596	0.0288	1.132
1.00	62.35	44.05	51.39	0.3629	0.1452	0.0795	0.0383	1.509
1.25	77.31	49.25	57.46	0.5072	0.2029	0.0994	0.0479	1.887
1.50	92.02	53.95	62.94	0.6667	0.2667	0.1193	0.0575	2.264
1.75	106.48	58.27	67.99	0.8401	0.3361	0.1391	0.0671	2.641
2.00	120.70	62.30	72.68	1.0265	0.4106	0.1590	0.0767	3.019
2.25	134.66	66.08	77.09	1.2248	0.4899	0.1789	0.0863	3.396
2.50	148.37	69.65	81.26	1.4345	0.5738	0.1988	0.0958	3.773
2.75	161.83	73.05	85.22	1.6550	0.6620	0.2187	0.1054	4.151
3.00	175.04	76.30	89.01	1.8857	0.7543	0.2385	0.1150	4.528
3.25	188.01	79.41	92.65	2.1263	0.8505	0.2584	0.1246	4.906
3.50	200.72	82.41	96.15	2.3763	0.9505	0.2783	0.1342	5.283
3.75	213.18	85.30	99.52	2.6354	1.0542	0.2982	0.1438	5.660
4.00	225.39	88.10	102.78	2.9033	1.1613	0.3180	0.1534	6.038
4.25	237.35	90.81	105.95	3.1797	1.2719	0.3379	0.1629	6.415
4.50	249.07	93.45	109.02	3.4643	1.3857	0.3578	0.1725	6.792
4.75	260.53	96.01	112.01	3.7570	1.5028	0.3777	0.1821	7.170
5.00	271.74	98.50	114.92	4.0574	1.6230	0.3975	0.1917	7.547

Figure D3. Calculations for torque output of the winch.

<u>Attachment F - Bill of Materials</u>

Including sources, weights, and costs.

Ordered	Recieved	Assym #	P/N	Component	TYPE	Op Sheet?	Stock Desc	Weight	Qty	Cost per	Total Cost	Vendor	Serial/SKU/ASIN No.
		100		Student Station Assembly									
		200		BASE									
3-2	3-6		201	Base plate	DWG	Y	6061 T6 sheet .125 thick 2x2	2.09	1	0	$0.00		
3-2	3-6		202	Front cleat side	DWG	N	6061 T6 sheet .125 thick 2x2	0.18	1	0	$0.00		
3-2	3-6		203	Front cleat bottom	DWG	N	6061 T6 sheet .125 thick 2x2	0.06	1	0	$0.00		
3-2	3-6		204	Side cleat side	DWG	N	6061 T6 sheet .125 thick 2x2	0.29	1	0	$0.00		
3-2	3-6		205	Side cleat bottom	DWG	N	6061 T6 sheet .125 thick 2x2	0.09	1	0	$0.00		
3-2	3-6		206	Gusset	DWG	Y	6061 T6 sheet .125 thick 2x2	0.04	1	0	$0.00		
		300		WALLS									
2-25	2-28		301	XY wall	DXF	N	.118 thick acryllic	0.21	2	0	$0.00		
2-25	2-28		302	YZ wall	DXF	N	.118 thick acryllic	0.54	2	0	$0.00		
2-25	2-28		303	Lid	DXF	N	.118 thick acryllic	0.48	1	0	$0.00		
2-25	2-28		304	Fluid Divider Wall	DXF	N	.118 thick acryllic	0.21	1	0	$0.00		
2-25	2-28		305	Rear wall	DXF	N	.118 thick acryllic	0.56	1	0	$0.00		
2-25	2-28		306	Shifter holder	DXF	N	6061 T6 sheet .125 thick 2x2	0.01	1	0	$0.00		
		400		PULLEY									
1-21	1-25		401	Rope Winch	SPEC	N	Hand Winch for Lifting with Wire Rope & Hook, 350 lb. Maximum Capacity	5	1	70	$70.00	McMaster-Carr	3196T55
2-25	2-28		402	Mass Pulley	SPEC	N	Mounted Pulley, for 3/16" Rope Diameter	0.56	1	7.02	$7.02	McMaster-Carr	3099T34
		600		GEARBOX									
1-21	1-28		601	Shaft	DWG	Y	Keyed Rotary Shaft 1045 Carbon Steel, 3/4" Diameter, 9" Long	0.82	1	19.7	$19.70	McMaster-Carr	1497K116
1-21	1-28		614	Key	DWG	Y	Oversized key stock	0.05	1	0.93	$0.93	McMaster-Carr	98830A150
1-21	1-28		602	Bushing Mount	DWG	Y	6061 T6 sheet .125 thick 2x2	0.05	2	0	$0.00		
1-21	1-28		603	Gearbox Bushing	DWG	Y	PTFE-Filled Delrin ® Acetal Resin Rod, 1" dia	0.05	3	0	$0.00		
1-21	1-28		604	Dogtooth	DWG	Y	Low-Carbon Steel Rod, 1" dia	0.08	1	10.82	$10.82	McMaster-Carr	8920K231
1-21	1-28		605	Gear	SPEC	N	Metal Gear - 14-1/2 Degree Pressure Angle	1.15	1	97.81	$97.81	McMaster-Carr	6867K79
1-21	1-28		606	Bushing Mount	SPEC	Y	6061 T6 sheet .125 thick 2x2	0.03	1		$0.00		
1-21	1-28		607	V belt	SPEC	N	Type 3L V-Belt with 3/8" Wide Top	0.04	1	1.85	$1.85	McMaster-Carr	59735K31
1-21	1-28		608	Large Pulley	N/A	Y	128 Pulley 3.5"	0.62	1	0	$0.00	Provided by Department	
1-21	1-28		609	Pump Pulley	N/A	N	128 pulley 1"	0.15	1	0	$0.00	Provided by Department	
1-21	1-28		610	Cart pulley	N/A	Y	128 pulley 2"	0.23	1	0	$0.00	Provided by Department	
			611	Shifter Fork	DWG	Y	6061 T6 sheet .125 thick 2x2	0.08	1	0	$0.00		
1-21	1-28		612	Shifter	SPEC	N	10-32 Thread, 3" Handle Length, 3/4" Ball Diameter	0.1	1	5.21	$5.21	McMaster-Carr	6303K3
1-21	1-28		613	Bushing	DWG	Y	Delrin	0.01	1	0	$0.00		
		700		FLUID PUMP									
3-7			701	Pump main housing	SLT	N	3D printed	0.04	1	0	$0.00	Provided by Department	
3-7			702	Pump housing end	SLT	N	3D printed	0	1	0	$0.00	Provided by Department	
3-7			703	Pump blades	SLT	N	3D printed	0	1	0	$0.00	Provided by Department	
1-21	1-28		704	Pump shaft	DWG	Y	Delrin	0.04	1	0	$0.00		
		800		CART									
2-2	2-6		801	Ramp	DXF	N	.118 thick acryllic	0.24	1	0	$0.00		
2-2	2-6		802	Ramp Support	DXF	N	6061 T6 sheet .125 thick 2x2	0.03	1	0	$0.00		
5-30			803	Track	SPEC	N	Bachmann Trains Snap-Fit E-Z Track 9 inch Straight Track	0.02	1	11.52	$11.52	Amazon	B0000CGB3F
1-21	1-28		804	Horizontal Pulley	SPEC	N	Mounted Pulley for Fibrous Rope, Steel, for 1/4" Rope Diameter, 11/16" OD	0.1	1	8.22	$8.22	McMaster-Carr	3071T7
5-30			805	Car	N/A	N	Bachmann Chugginton Industries Flat Car	0.35	1	19.22	$19.22	Amazon	B00FK4Z0UQ
1-21	1-21		806	String	SPEC	N	Braided rope, 1/8	0.1	1	5.28	$5.28	Miner's	
5-30			807	Rubber Feet	SPEC	N	Guitar Amplifier Cabinet	0.05	8	0.61	$4.88	Amazon	B00JJ191Z6
		1FF		Fastners									
			1F1	Lift pulley fastners	SPEC	N	10-24 hex scew and bolts	XXXX	4	0.75	$3.00	Home Depot	
			1F2	Horiz pulley fastners (2)	SPEC	N	3/16 hex screws and bolts	XXXX	8	0.53	$4.24	Home Depot	
			1F3	RTX caulking	SPEC	N	1 tube	XXXX	1	10	$10.00	Home Depot	
			1F4	Epoxy Adhesive	SPEC	N	1 tube	XXXX	1	5	$5.00	Home Depot	
			1F5	Winch Fasteners	SPEC	N	3/8 Hex Screws and Bolts	XXXX	3	0.75	$2.25	Home Depot	

		SHEET		SHEET ORDERS								
3-2	3-6		Y	Acryllic		2x2' sheet .25 thick, ultra scratch resistance	XXXX	1	98.55	$98.55	McMaster-Carr	03-50002
3-2	3-6		Y	6061		.190 2x2	XXXX	1	72.12	$72.12	Aircraft Spruce	03-29860
1-21	1-28		Y	Delrin Round		PTFE-Filled Delrin ® Acetal Resin Rod, 1" dia	XXXX	1	17.1	$17.10	McMaster-Carr	
		11000		WEIGHTS								
4-25	5-8			0.5 lb weights (2 pack)	N	Lead weight		1	10.03	$10.03	Amazon	B003CU51JK
4-25	4-28			1 lb weight	N	Lead weight		3	3.26	$9.78	The Greatful Lead	
4-25	4-28			2 lb weight	N	Lead weight		3	6.52	$19.56	The Greatful Lead	
4-25	4-29			5 lb weight	N	Cast iron weight plate		2	8.18	$16.36	Walmart	RPG-005#2
4-25	4-29			10 lb weight	N	Cast iron weight plate		1	13.02	$13.02	Walmart	RPG-005#2
						Total Weight	**14.75**		**Shipping+Tax**	**21.05**		
						CURRENT TOTAL			**TOTAL**	**564.52**		
						*Some costs include shipping and tax			**MESFAC Awarded**	**$360.00**		
									Total-MESFAC	**$204.52**		
									Budget	**$500.00**		
									Total MESFAC used	**$130.44**		

Attachment G - Final Budget and Costs

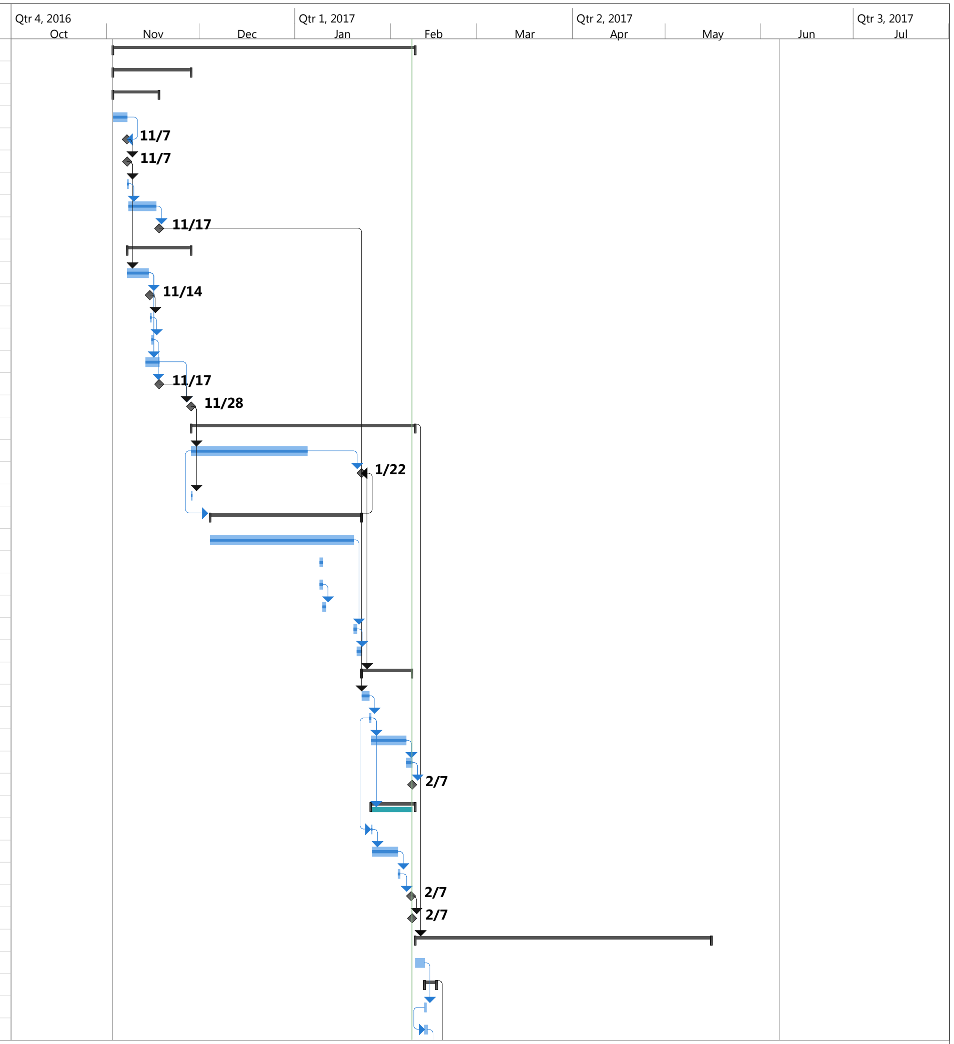
Assym #	**P/N**	**Component**	**Qty**	**Cost per**	**Total Cost**	**Vendor**
100	**Student Station Assembly**					
400	**PULLEY**					
	401	Rope Winch	1	70	$70.00	McMaster-Carr
	402	Mass Pulley	1	7.02	$7.02	McMaster-Carr
600	GEARBOX					
	601	Shaft	1	19.7	$19.70	McMaster-Carr
	614	Key	1	0.93	$0.93	McMaster-Carr
	604	Dogtooth	1	10.82	$10.82	McMaster-Carr
	605	Gear	1	97.81	$97.81	McMaster-Carr
	607	V belt	1	1.85	$1.85	McMaster-Carr
	608	Large Pulley	1	0	$0.00	Provided by Department
	609	Pump Pulley	1	0	$0.00	Provided by Department
	610	Cart pulley	1	0	$0.00	Provided by Department
	612	Shifter	1	5.21	$5.21	McMaster-Carr
700	FLUID PUMP					
	701	Pump main housing	1	0	$0.00	Provided by Department
	702	Pump housing end	1	0	$0.00	Provided by Department
	703	Pump blades	1	0	$0.00	Provided by Department
800	CART					
	803	Track	1	11.52	$11.52	Amazon
	804	Horizontal Pulley	1	8.22	$8.22	McMaster-Carr
	805	Car	1	19.22	$19.22	Amazon
	806	String	1	5.28	$5.28	Miner's
	807	Rubber Feet	8	0.61	$4.88	Amazon
1FF	FASTENERS					
	1F1	Lift pulley fasteners	4	0.75	$3.00	Home Depot
	1F2	Horizontal pulley fasteners (2)	8	0.53	$4.24	Home Depot
	1F3	RTX caulking	1	10	$10.00	Home Depot
	1F4	Epoxy Adhesive	1	5	$5.00	Home Depot
	1F5	Winch Fasteners	3	0.75	$2.25	Home Depot
SHEET	SHEET ORDERS					
	Y	Acrylic	1	98.55	$98.55	McMaster-Carr
	Y	6061	1	72.12	$72.12	Aircraft Spruce
	Y	Delrin Round	1	17.1	$17.10	McMaster-Carr
11000	WEIGHTS					

	0.5 lb weights (2 pack)	1	10.03	$10.03	Amazon
	1 lb weight	3	3.26	$9.78	The Grateful Lead
	2 lb weight	3	6.52	$19.56	The Grateful Lead
	5 lb weight	2	8.18	$16.36	Walmart
	10 lb weight	1	13.02	$13.02	Walmart
			Shipping+Tax	**21.05**	
			TOTAL	**564.52**	
			MESFAC Awarded	**$360.00**	
			Total-MESFAC	**$204.52**	
			Budget	**$500.00**	
			Total MESFAC used	**$130.44**	

Attachment H - Gantt Chart

The Gantt chart outlining the manufacturing process and the testing phase of the project.

ID	Task Mode	Task Name	Duration	Start
1		**Design**	**116.94 days?**	**Thu 11/3/16**
2		**PDR**	**25.06 days**	**Thu 11/3/16**
3		**Report**	**24.06 days**	**Thu 11/3/16**
4		Continue Background Research	7 days	Thu 11/3/16
5		Lay Out Learning Goals	1 hr	Mon 11/7/16
6		Select Final Overall Concept	1 hr	Mon 11/7/16
7		Outline Report	1 day	Mon 11/7/16
8		Write Report	14 days	Mon 11/7/16
9		Turn in Report	1 day	Thu 11/17/16
10		**Presentation**	**17.94 days**	**Mon 11/7/16**
11		Prepare Presentation	10 days	Mon 11/7/16
12		Complete Slides	1 day	Mon 11/14/16
13		Rehersal	1 day	Mon 11/14/16
14		Rehersal 2	1 day	Tue 11/15/16
15		Schedule PDR	8.56 days	Sun 11/13/16
16		In-class Presentation	1 day	Thu 11/17/16
17		PDR	1 day	Thu 11/17/16
18		**CDR**	**91.88 days?**	**Mon 11/28/16**
19		Start Initial CAD	30 days	Mon 11/28/16
20		Finish CAD	1 day	Sat 1/21/17
21		Order Long-Lead Parts	1 day	Mon 11/28/16
22		**Testing/Analysis**	**50.44 days?**	**Sun 12/4/16**
23		Pulley-Mass Analysis	46.31 days?	Sun 12/4/16
24		Cart design and trials	2.06 days?	Mon 1/9/17
25		Gear conceptualization	2.06 days?	Mon 1/9/17
26		Heat Generation calcs	2.06 days?	Tue 1/10/17
27		Pump Sizing calc	2.06 days?	Thu 1/19/17
28		Pump modelling	2.06 days?	Fri 1/20/17
29		**Report**	**30 days**	**Sun 1/22/17**
30		Revise PDR Report	5 days	Sun 1/22/17
31		Outline New Sections	1 day	Tue 1/24/17
32		Write Report	20 days	Wed 1/25/17
33		Edit and Review	4 days	Mon 2/6/17
34		Turn in Report	1 day	Tue 2/7/17
35		**Presentation**	**25.31 days**	**Wed 1/25/17**
36		Outline Slides	1 day	Wed 1/25/17
37		Prepare Slides	15 days	Wed 1/25/17
38		Schedule CDR	1 day	Fri 2/3/17
39		Present to Class	1 day	Tue 2/7/17
40		Present to Sponsor	0.5 days	Tue 2/7/17
41		**Build**	**170.88 days?**	**Wed 2/8/17**
42		Order All Online Parts	5 days	Wed 2/8/17
43		**Shop Manufacturing**	**8.06 days?**	**Sat 2/11/17**
44		Rough out base plate	1.13 days	Sat 2/11/17
45		CAM base slots	2.06 days?	Sat 2/11/17



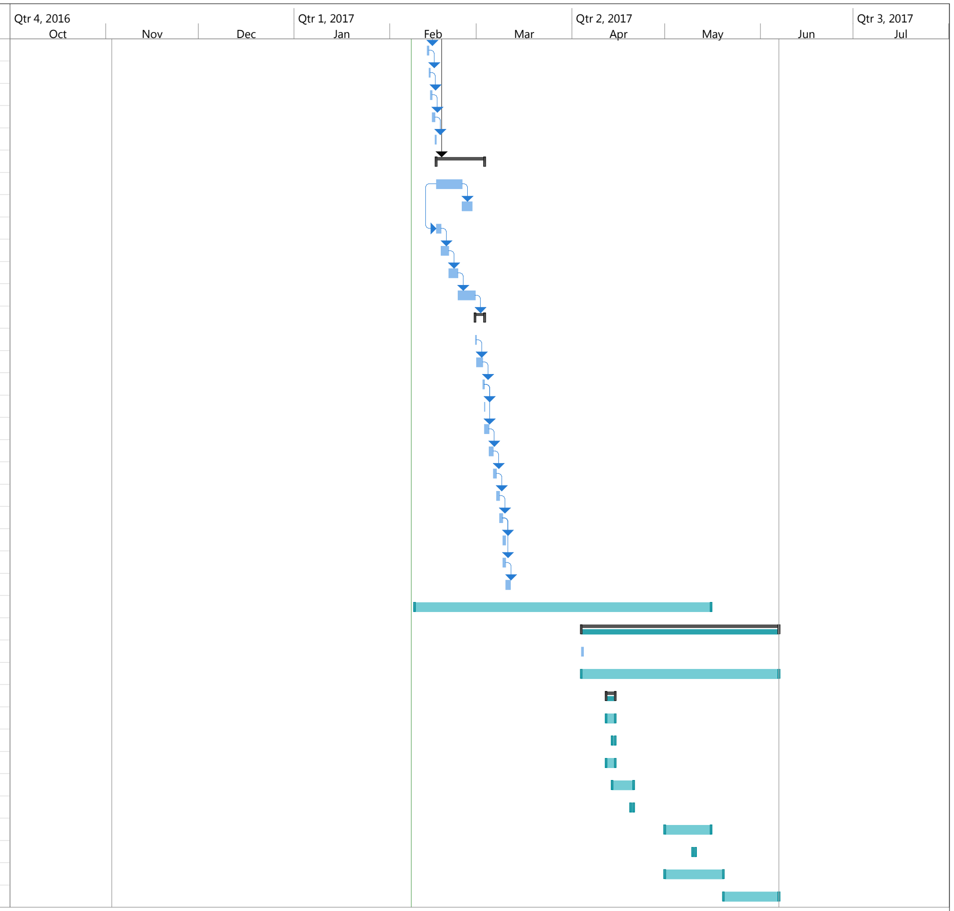
Project: Master Gantt
Date: Wed 2/8/17

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

Page 1

Figure H1. Page one of the Gantt chart leading up to the current date. We have completed the design phase...

ID	Task Mode	Task Name	Duration	Start
46		CNC Base	1 day?	Sun 2/12/17
47		Cut cleat sheet	1 day	Mon 2/13/17
48		Prep welds	1 day	Mon 2/13/17
49		Weld Cleats	2 days	Tue 2/14/17
50		Inspect	1 day	Wed 2/15/17
51		**Manual Manufacturing**	**28.5 days**	**Wed 2/15/17**
52		Laser Cut Acryllic	3 wks	Wed 2/15/17
53		Begin Test Fits	5 days	Fri 2/24/17
54		Machine shaft	3 days	Wed 2/15/17
55		Machine Keys	3 days	Fri 2/17/17
56		Waterjet Shift Fork	6 days	Sun 2/19/17
57		Mill out Dogteeth	2 wks	Wed 2/22/17
58		**3D Print Pump**	**6.5 days**	**Tue 2/28/17**
59		Schedule 3D printer	1 day	Tue 2/28/17
60		Review SLT file	4 days	Tue 2/28/17
61		Print Part	1 day	Thu 3/2/17
62		Finish and clean part	0.5 days	Fri 3/3/17
63		Mount shaft hardware	2.06 days?	Fri 3/3/17
64		Fasten Pump	2.06 days?	Sat 3/4/17
65		Secure Shaft	2.06 days?	Mon 3/6/17
66		Fasten Track to Ramp	2.06 days?	Tue 3/7/17
67		Fasten Ramp system	2.06 days?	Wed 3/8/17
68		Add V-belt	2.06 days?	Thu 3/9/17
69		Caulk acryllic	2.06 days?	Thu 3/9/17
70		Add Fastners	2.06 days?	Fri 3/10/17
71		Generate Instructions and Media	170.88 days	Wed 2/8/17
72		**Test**	**113.63 days**	**Tue 4/4/17**
73		Weigh Assembly	1 day	Tue 4/4/17
74		Endurance Tests	113.63 days	Tue 4/4/17
75		**Gauge tests**	**5.25 days**	**Wed 4/12/17**
76		RPM tests	5.25 days	Wed 4/12/17
77		Amperage Tests	1.13 days	Fri 4/14/17
78		Pump tests	5.25 days	Wed 4/12/17
79		Define pump curve	11.56 days	Fri 4/14/17
80		Run through equations	1.13 days	Thu 4/20/17
81		Time experiment	26.13 days	Mon 5/1/17
82		Time presentaions	1.13 days	Wed 5/10/17
83		Write mock report	35.19 days	Mon 5/1/17
84		Generate grading critera	31.63 days	Sat 5/20/17



Project: Master Gantt
Date: Wed 2/8/17

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			

Figure H2. ...and are moving onto the build and testing phase (page two).

Attachment I - Design Verification Plan

For Critical Design Review...

ME430 DVP&R Format

CDR	2/8/2017		Sponsor	Steffen Peuker							
TEST PLAN								**TEST REPORT**			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	SAMPLES TESTED	TIMING		TEST RESULTS			NOTES
					Quantity	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Must be under 15 lb	Weigh the final assembly	~15lb	NL	1	4/4/2017	4/4/2017				
2	Parts must be easy to access	Attempt full teardown and re-assembly	All parts within housing accessible	All	1	5/20/2017	6/6/2017				Only do once
3	Must last at least 1 quarter of use	Continuously run all sub-systems	Failures within accepted limit	All	~60	4/4/2017	6/6/2017				
4	Data must be consistent	Record and compare RPM outputs using experimental masses	RPM: 40% Difference	NB	20	4/12/2017	4/14/2017				Input, pump, and engine
5	Data must be consistent	Record and compare amperage using experimental output	A: 20% difference	NB	10	4/14/2017	4/14/2017				
6	Data must be consistent	Record and compare head of pump for multiple input masses	Inches: 40% difference	DM	20	4/12/2017	4/14/2017				
7	Data must be recordable	Verify gauges using above tests	Measureable data	All	60	4/4/2017	6/6/2017				
8	Data must be recordable	Pump has a defined operating scale	Pump curve generated	DM	20	4/14/2017	4/20/2017				Must be referenceable by students
9	Experiment must be completed in a lab period	Time the operation period for a complete system run-through	<2.5 hours	All	5	5/1/2017	5/15/2017				Use multiple groups of people
10	Presentations do not consume extra time	Run through presentations and time	<.5 hours	All	5 - 10	5/1/2017	5/20/2017				Use multiple people (professors?)
11	Report is not too lengthy	Write multiple mock reports based on instructions and requirements	2-3 pages	All	3	4/20/2017	5/20/2017				

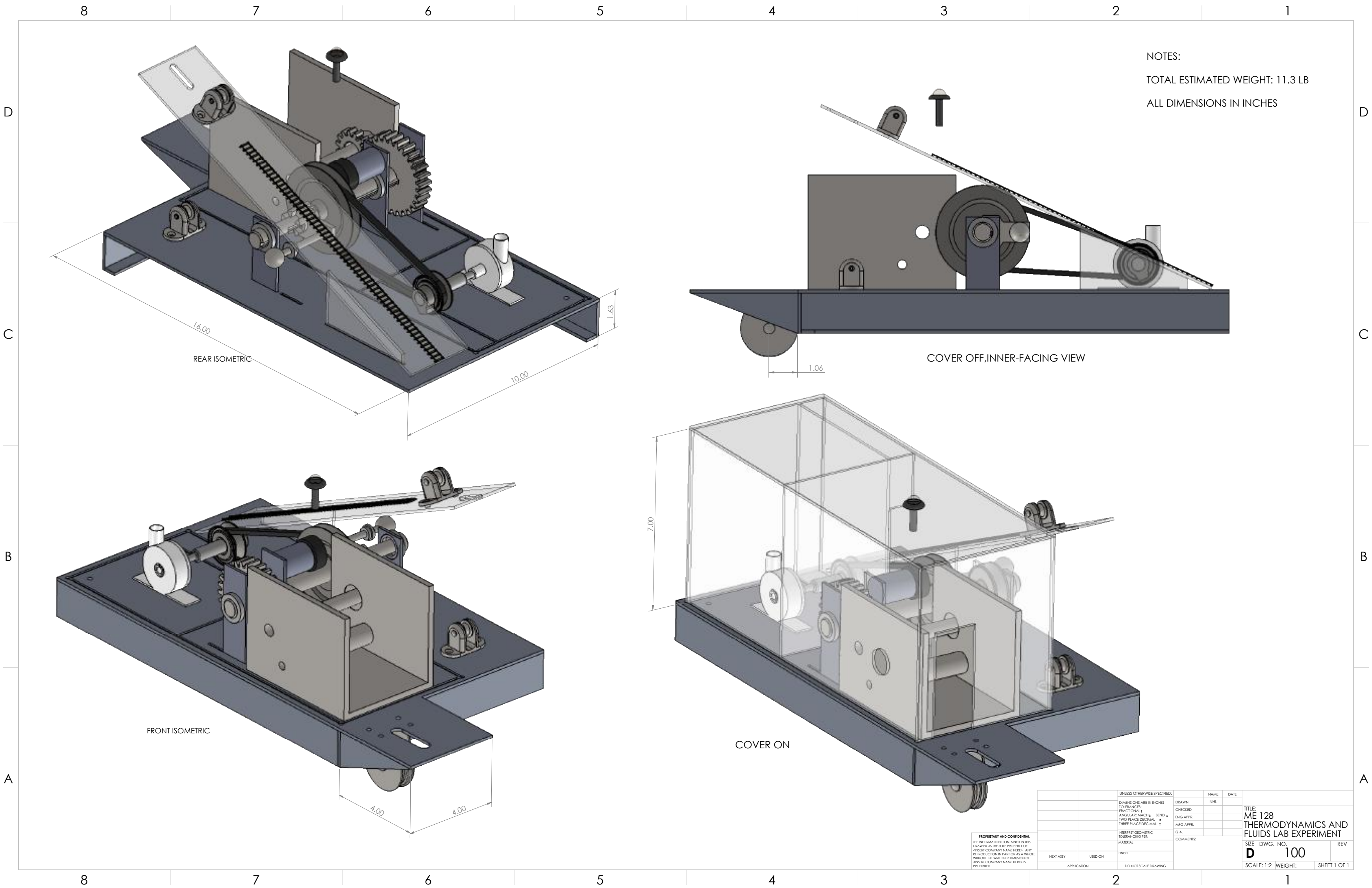
Attachment I - Assembly, Subassembly, and Part Drawings and Specification Sheets

Drawings:

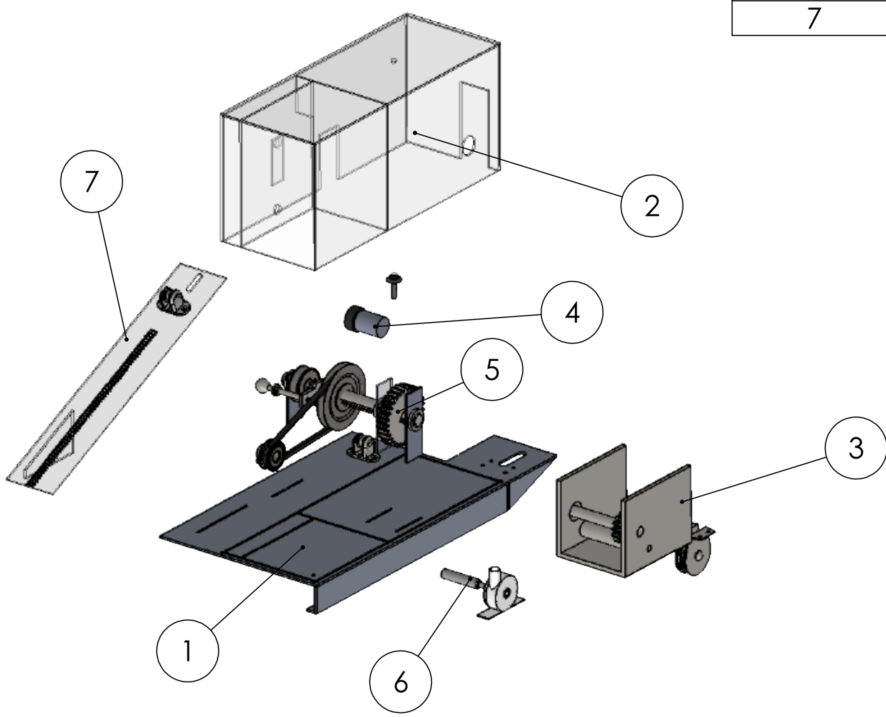
100 - Assembly View
100x - Exploded Assembly View
200 - Base Plate Subassembly
201 - Base Plate CNC Guide
202 - Front Cleat Side
203 - Front Cleat Bottom
204 - Side Cleat Side
205 - Side Cleat Bottom
206 - Gusset
2WW - Base Welds
300 - Housing Subassembly
400 - Pulley Subassembly
500 - Electric Subassembly
600 - Power Transfer Subassembly
601 - Shaft
602 - Bushing Mount
603 - Gearbox Bushing
604 - Dogtooth
611 - Shifter Fork
613 - Shifter Bushing
700 - Pump Subassembly
704 - Pump Shaft
800 - Cart Subassembly

Specifications:

401 - Rope Winch
402 - Mass Pulley
501 - Motor/Generator
502 - Housed LED, Amber
601 - Main shaft
604 - Dogtooh
605 - Gear
607 - V-belt
612 - Shifter
614 - Key
901 - Hall Effect RPM Sensor
902 - Analog Tachometer
1001 - Heat Engine


NOTES:
TOTAL ESTIMATED WEIGHT: 11.3 LB
ALL DIMENSIONS IN INCHES
REAR ISOMETRIC
16.00
10.00
1.63
COVER OFF,INNER-FACING VIEW
1.06
FRONT ISOMETRIC
4.00
4.00
COVER ON
7.00
TITLE:
ME 128
THERMODYNAMICS AND
FLUIDS LAB EXPERIMENT
SIZE
D
DWG. NO.
100
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

ITEM NO.	PART NUMBER	DESCRIPTION	QTY
1	200	BASE	1
2	300	COVER	1
3	400	PULLEY SYSTEM	1
4	500	ELECTRICAL	1
5	600	GEARBOX	1
6	700	PUMP	1
7	800	CART	1



UNLESS OTHERWISE SPECIFIED:

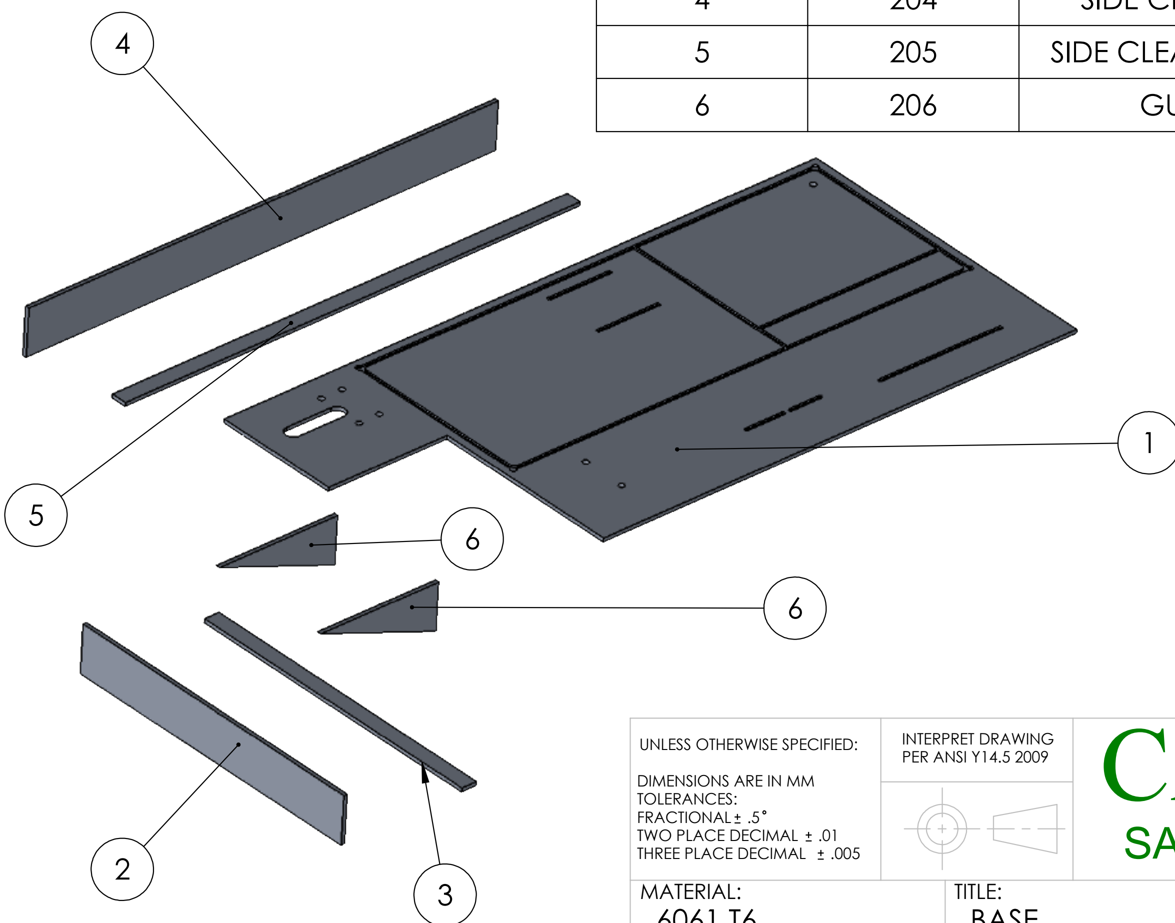
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ANSI Y14.5 2009

CAL POLY
SAN LUIS OBISPO

MATERIAL: MULTIPLE	TITLE: ME128 ASSM. (EXPLODED)	DRAWING NUMBER 100-X		
DRAWN BY: NHL	SHEET 1 OF 2	SCALE: 1:8	REV	SIZE A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY
1	201	BASE PLATE	1
2	202	FRONT CLEAT SIDE	1
3	203	FRONT CLEAT BOTTOM	1
4	204	SIDE CLEAT SIDE	1
5	205	SIDE CLEAT BOTTOM	1
6	206	GUSSET	2



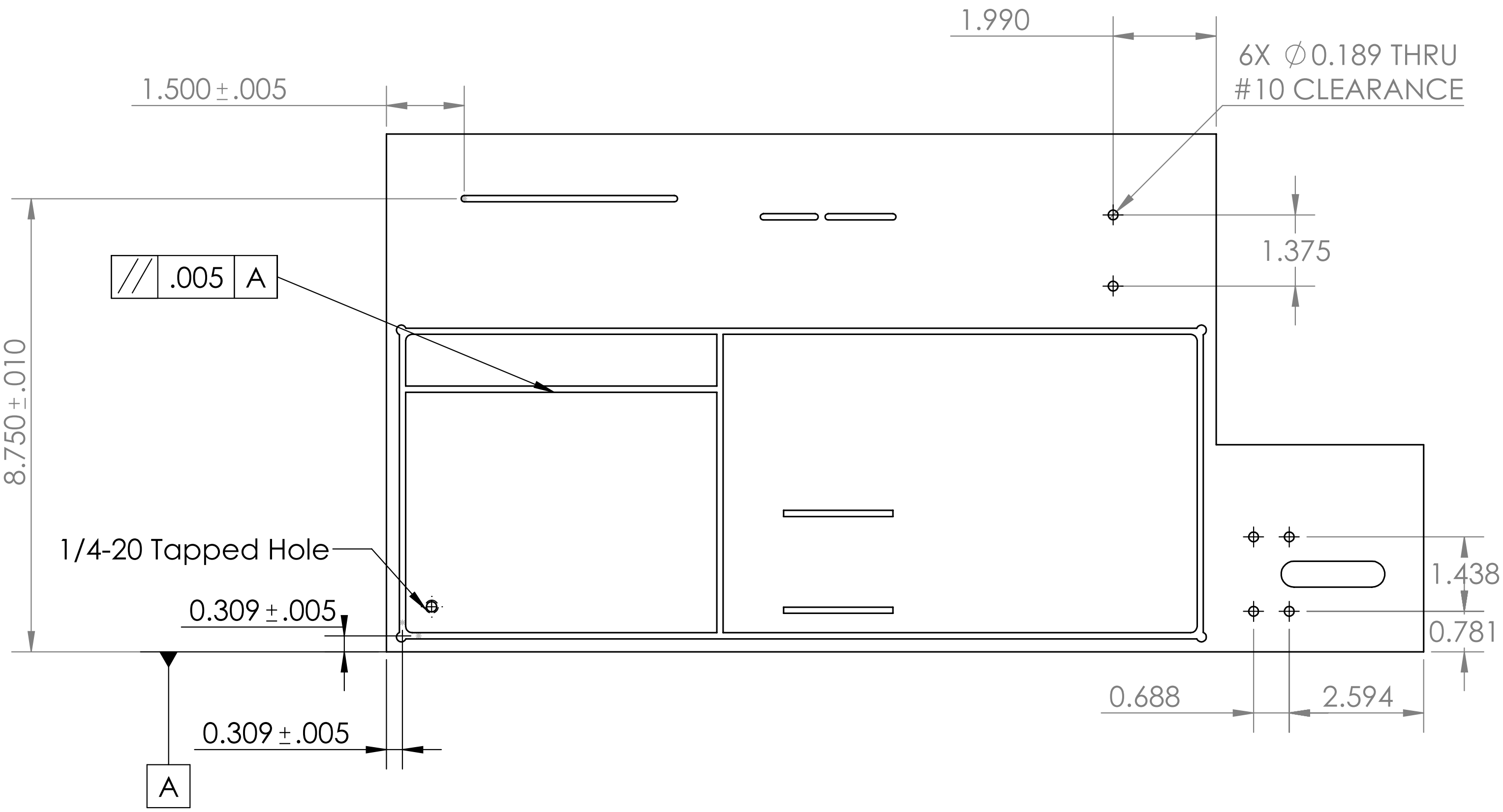
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ANSI Y14.5 2009

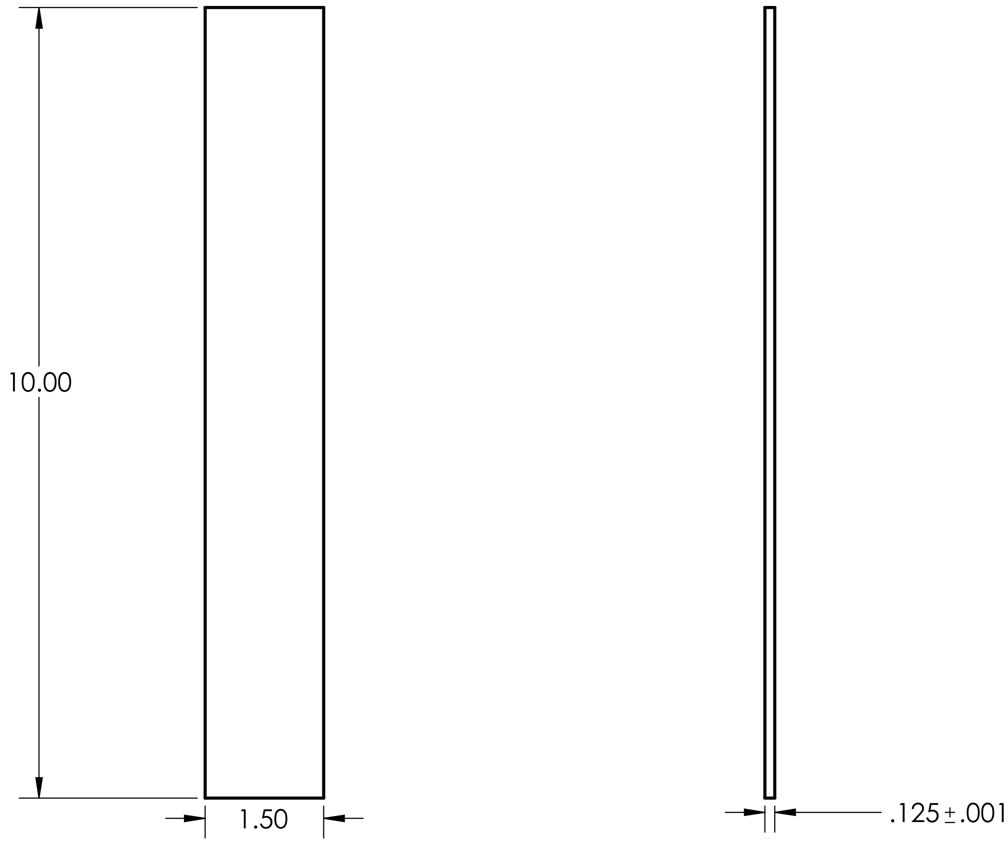
CAL POLY
SAN LUIS OBISPO

MATERIAL: 6061 T6	TITLE: BASE	PART NUMBER: 200
DRAWN BY: DANIEL MIRANDA	SHEET 1 OF 1	SCALE: 1:4
	REV	SIZE A



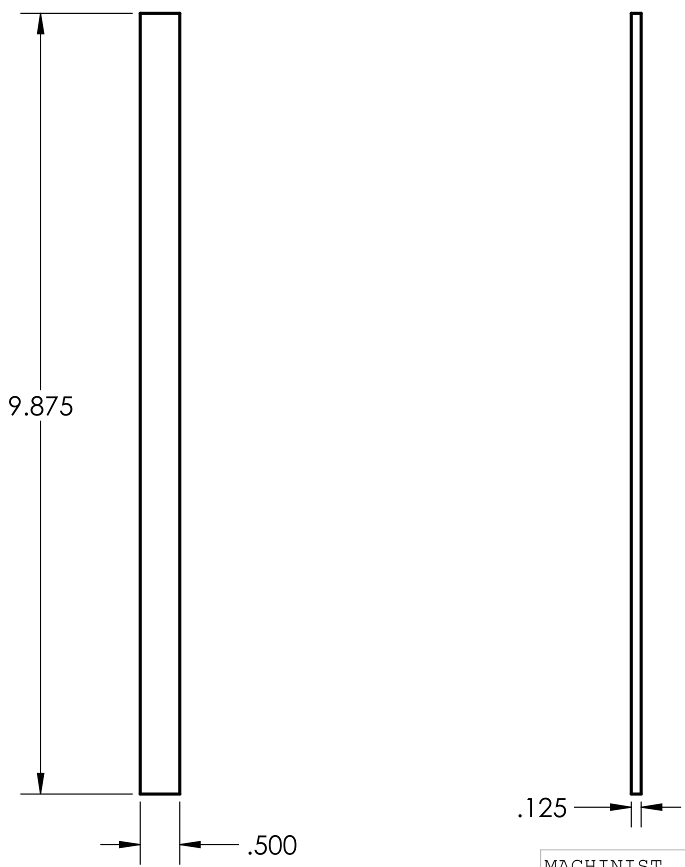
NOTES:
-ALL SLOTS ARE 0.060" DEPTH OF CUT
-HOLE LOCATIONS ARE CRITICAL RELATIVE TO EACH OTHER
-SLOTS CIRITICALLY PARALLEL/PERPENDICULAR TO EACH OTHER

MACHINIST NAME&#:			
MATERIAL	6061-T6	PART NAME: BASE PLATE	
DATE STARTED			
DATE COMPLETED			
STOCK SIZE & LOCATION: 6061-T6 .125" THICK PLATE		SIZE A	DWG# 201	REV A
		SCALE: 1:8	QTY: 1	SHEET 1 OF 1



NOTES:
TOLERANCES UNLESS OTHERWISE STATED
X.XX = ±.01

MACHINIST NAME&#:		PART NAME: FRONT CLEAT SIDE
MATERIAL	6061 T6	
DATE STARTED		
DATE COMPLETED		
STOCK SIZE & LOCATION: 6061 T6 SHEET .125" THICK		SIZE A · DWG# 202 · REV A
		SCALE: 1:2 · QTY: 1 · SHEET 1 OF 1



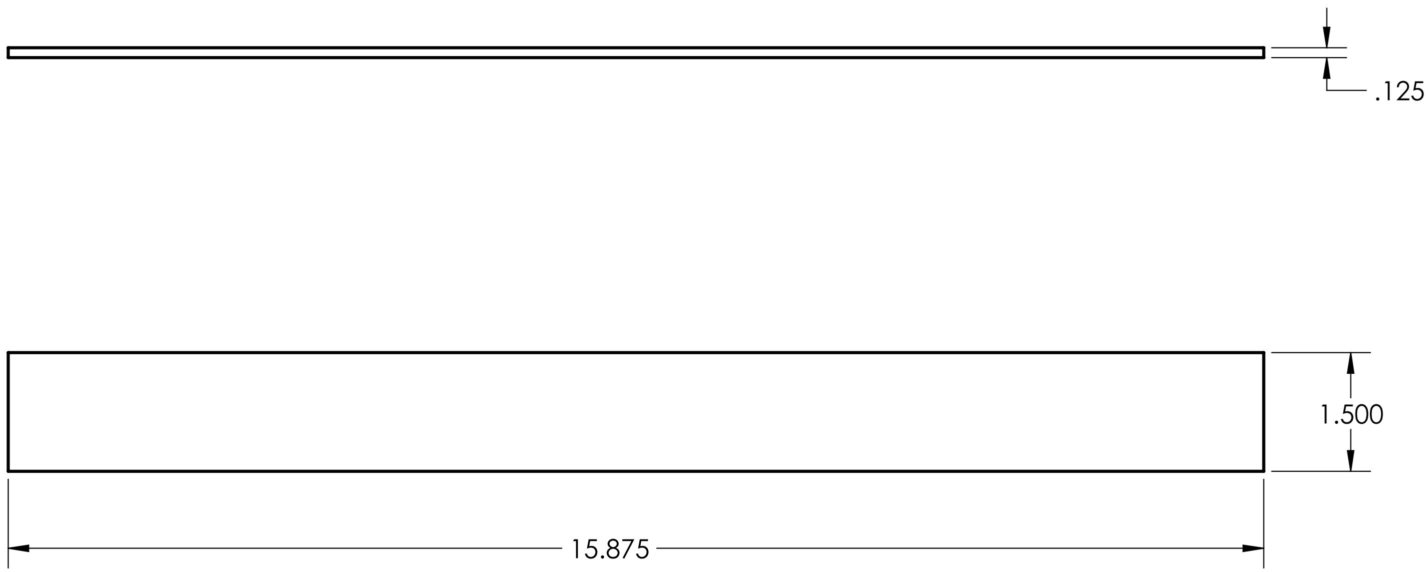
NOTES:
TOLERANCES UNLESS OTHERWISE STATED
X.XXX = ±.005

MACHINIST NAME&#:	
MATERIAL	6061 T6
DATE STARTED	
DATE COMPLETED	
STOCK SIZE & LOCATION: 6061 T6 SHEET .125" THICK	

PART NAME:
FRONT CLEAT BOTTOM

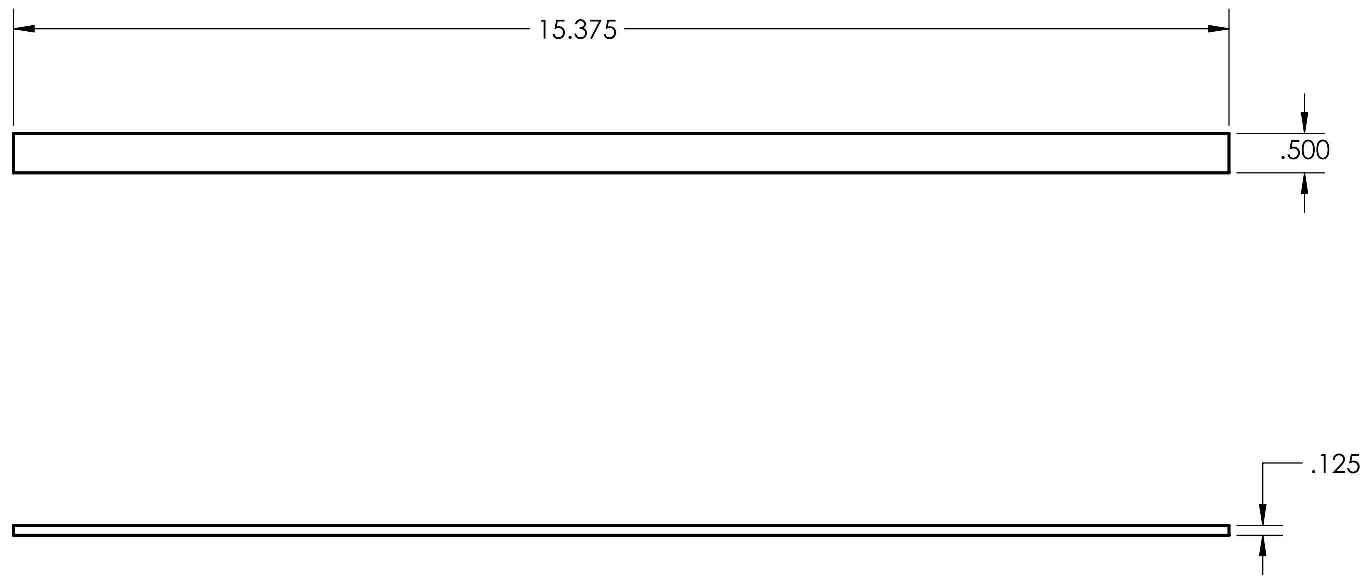
SIZE	DWG#	REV
A	203	A

SCALE: 1:2	QTY: 1	SHEET 1 OF 1



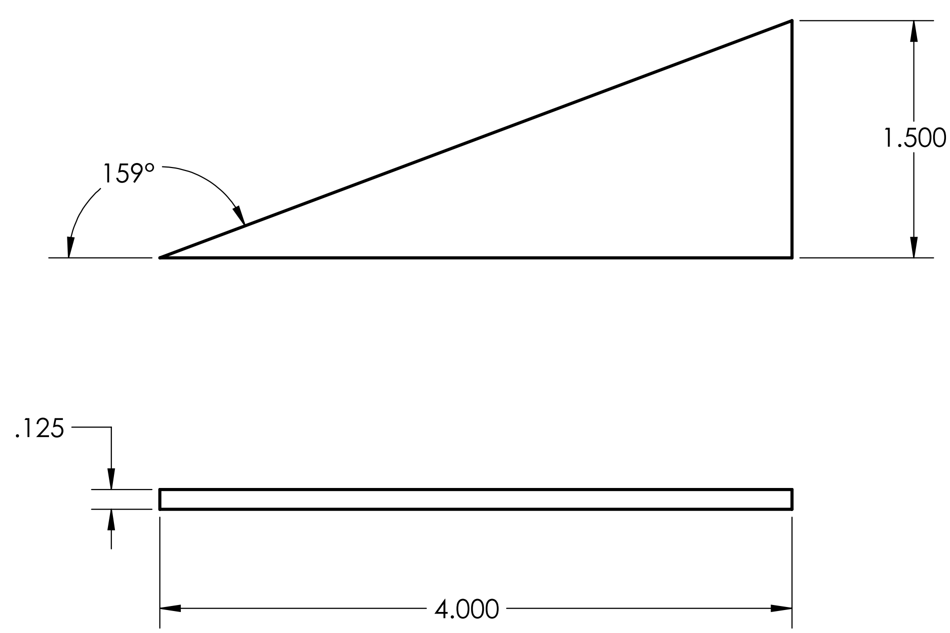
NOTES:
TOLERANCES UNLESS OTHERWISE STATED
X.XXX = ±.005

MACHINIST NAME&#:		
MATERIAL	6061 T6	PART NAME: SIDE CLEAT SIDE
DATE STARTED		
DATE COMPLETED		
STOCK SIZE & LOCATION: 6061 T6 SHEET .125" THICK		SIZE A · DWG# 204 · REV A
		SCALE: 1:2 · QTY: 1 · SHEET 1 OF 1



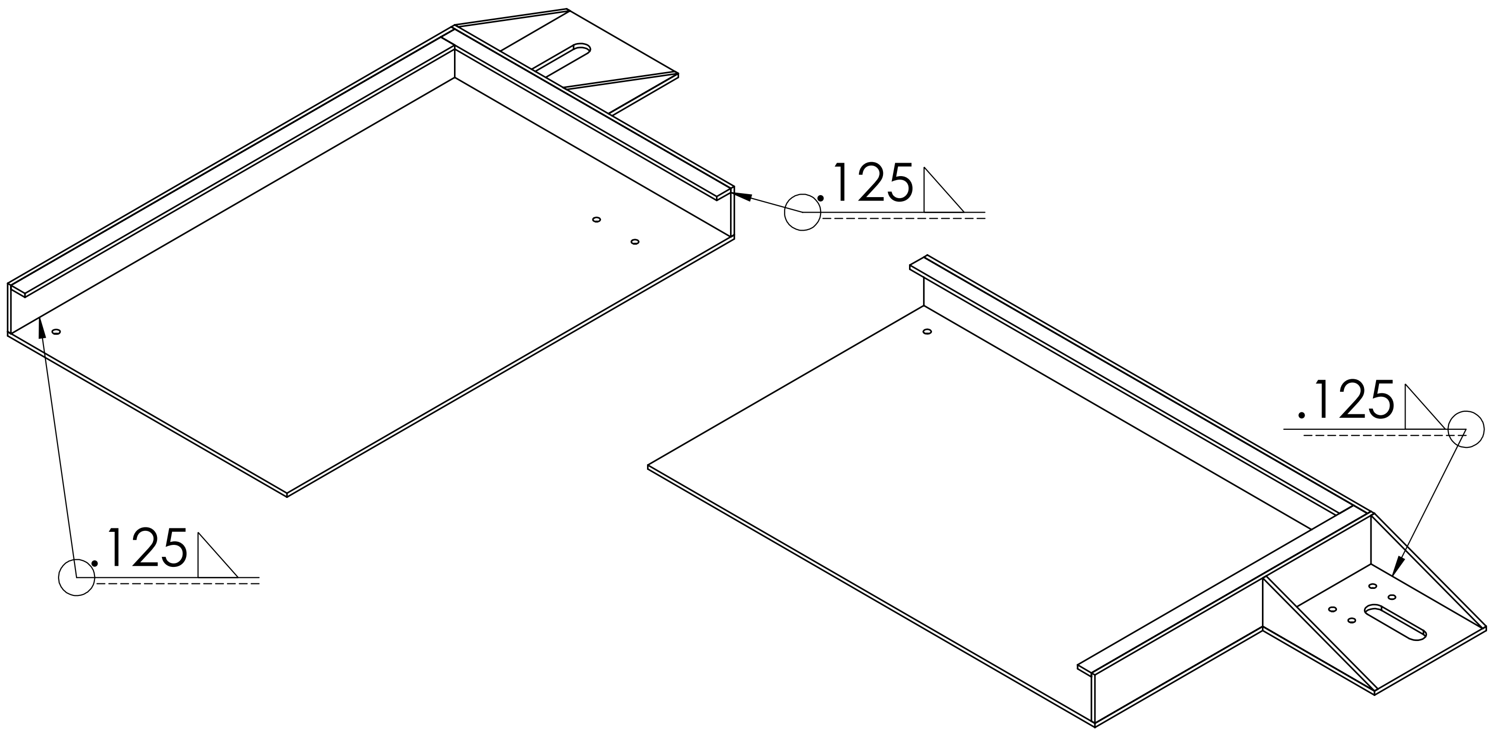
NOTES:
TOLERANCES UNLESS OTHERWISE STATED
X.XXX = ±.005

MACHINIST NAME&#:		
MATERIAL	6061 T6	PART NAME: SIDE CLEAT BOTTOM
DATE STARTED		
DATE COMPLETED		
STOCK SIZE & LOCATION: 6061 T6 SHEET .125" THICK		SIZE A · DWG# 205 · REV A
		SCALE: 1:2 · QTY: 1 · SHEET 1 OF 1



NOTES:
TOLERANCES UNLESS OTHERWISE STATED
X.XXX = ±.005
ANGLES = ±2

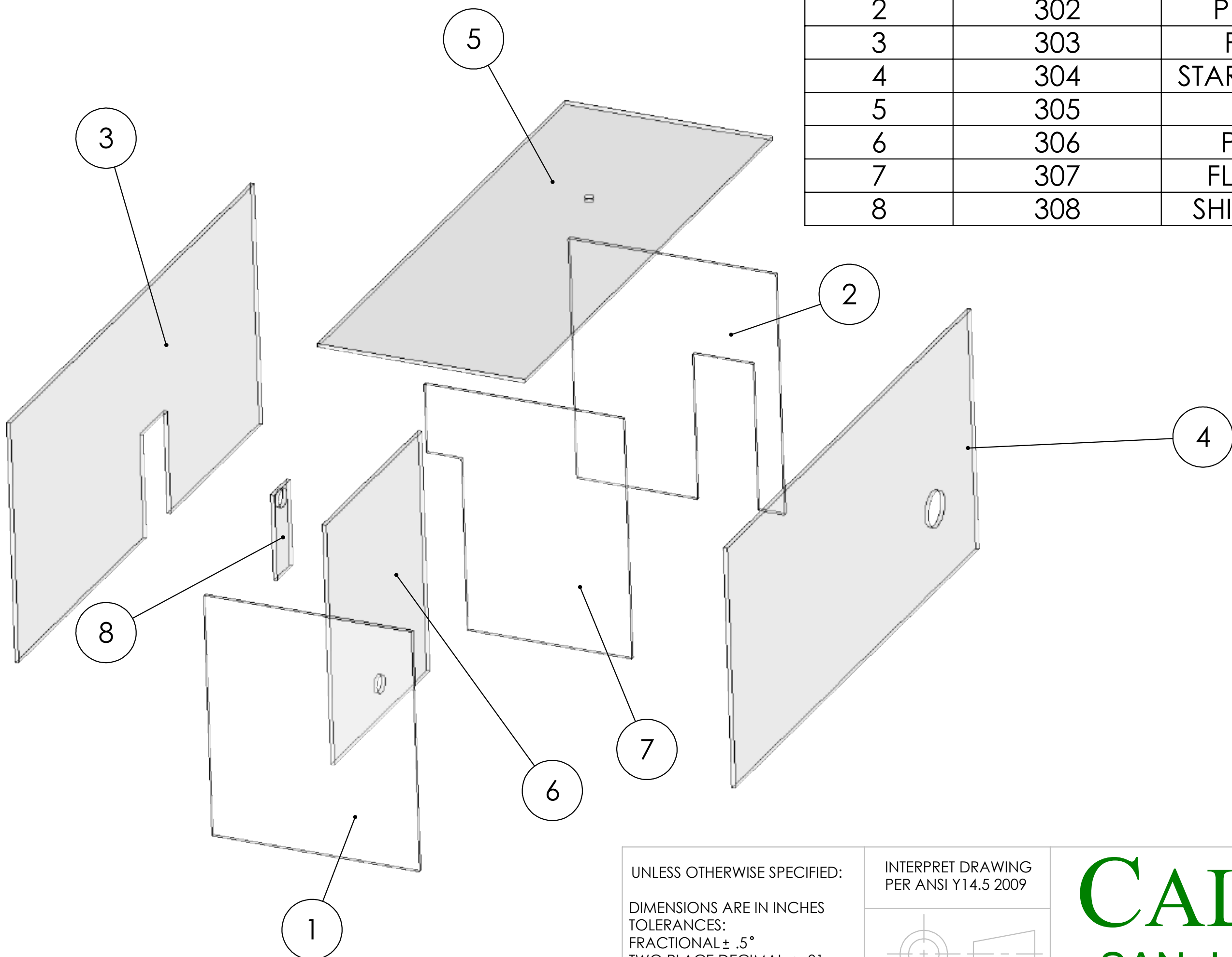
MACHINIST NAME&#:					
MATERIAL	6061 T6	PART NAME: GUSSET			
DATE STARTED					
DATE COMPLETED					
STOCK SIZE & LOCATION: 6061 T6 SHEET .125" THICK		SIZE A	DWG# 206		REV A
		SCALE: 1:2	QTY: 2	SHEET 1 OF 1	



MACHINIST NAME&#:		
MATERIAL	6061-T6	PART NAME: BASE WELDS
DATE STARTED		
DATE COMPLETED		
STOCK SIZE & LOCATION:		

SIZE A	DWG# 2WW	REV A
SCALE: 1:8	QTY: 1	SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY
1	301	SIDE WALL	1
2	302	PULLEY WALL	1
3	303	PORT WALL	1
4	304	STARBOARD WALL	1
5	305	LID	1
6	306	PUMP WALL	1
7	307	FLUID DIVIDER	1
8	308	SHIFTER HOLDER	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ANSI Y14.5 2009

CAL POLY
SAN LUIS OBISPO

MATERIAL: ACYLLIC SHEET

TITLE: HOUSING SUBASSEMBLY

PART NUMBER: 300

DRAWN BY: NHL

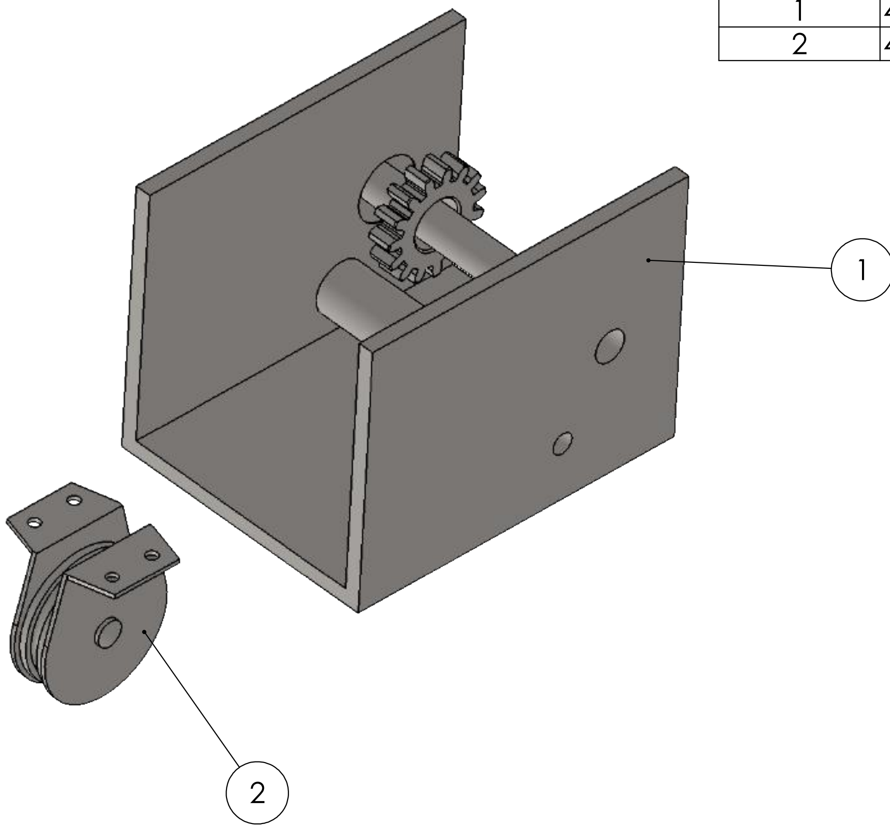
SHEET 1 OF 1

SCALE: 1:4

REV

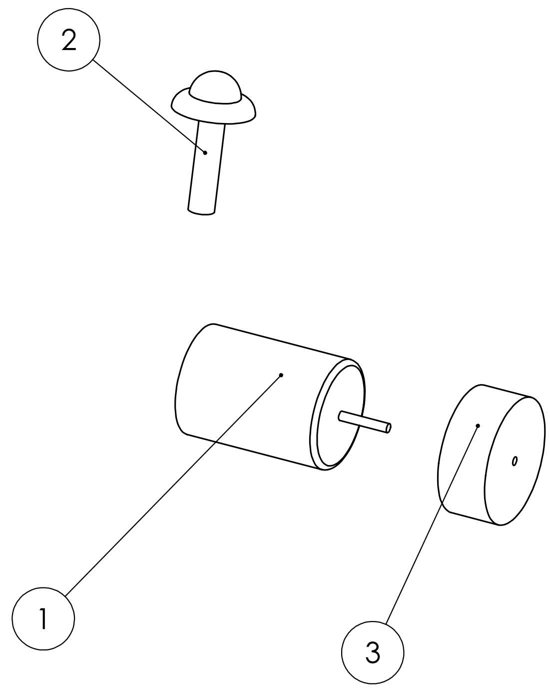
SIZE A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	401	WINCH	1
2	402	MASS PULLEY	1



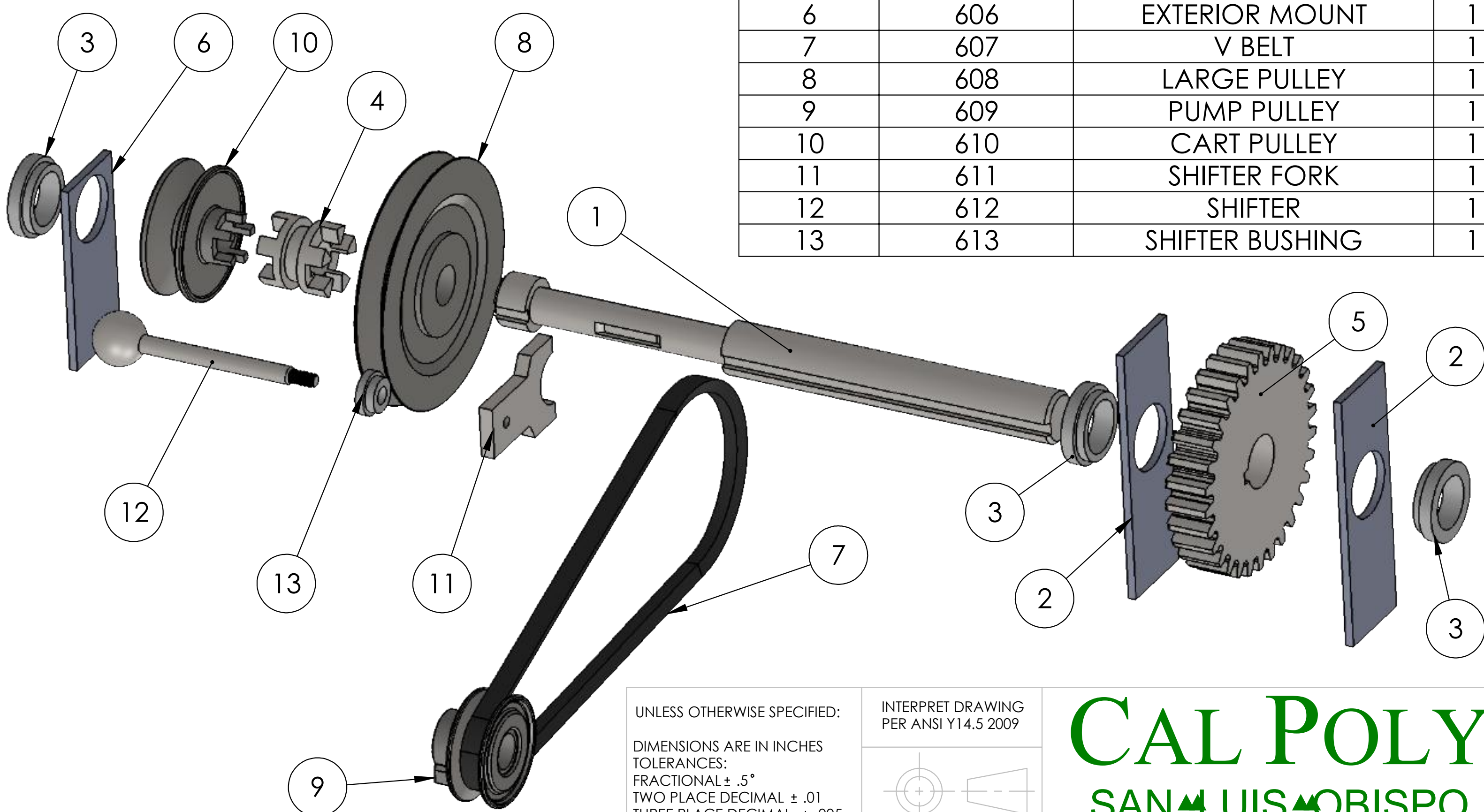
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO			
MATERIAL: MULTIPLE	TITLE: PULLEY-MASS SYSTEM (EXPLODED)		DRAWING NUMBER: 400		
DRAWN BY: DANIEL MIRANDA		SHEET 1 OF 1	SCALE: 1:4	REV	SIZE A

ITEM NO	PART NUMBER	DESCRIPTION	QTY
1	501	MOTOR	1
2	502	LED	1
3	503	RUBBER PLUG	1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: MULTIPLE	TITLE: ELECTRICAL SUBASSEMBLY	PART NUMBER: 500
DRAWN BY: NHL	SHEET 1 OF 1	SCALE: 2:3 · REV · SIZE A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY
1	601	SHAFT	1
2	602	BUSHING MOUNT	2
3	603	BUSHING	3
4	604	DOGTOOTH	1
5	605	GEAR	1
6	606	EXTERIOR MOUNT	1
7	607	V BELT	1
8	608	LARGE PULLEY	1
9	609	PUMP PULLEY	1
10	610	CART PULLEY	1
11	611	SHIFTER FORK	1
12	612	SHIFTER	1
13	613	SHIFTER BUSHING	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ANSI Y14.5 2009

CAL POLY
SAN LUIS OBISPO

MATERIAL: MULTIPLE

TITLE: POWER TRANSFER

PART NUMBER: 400

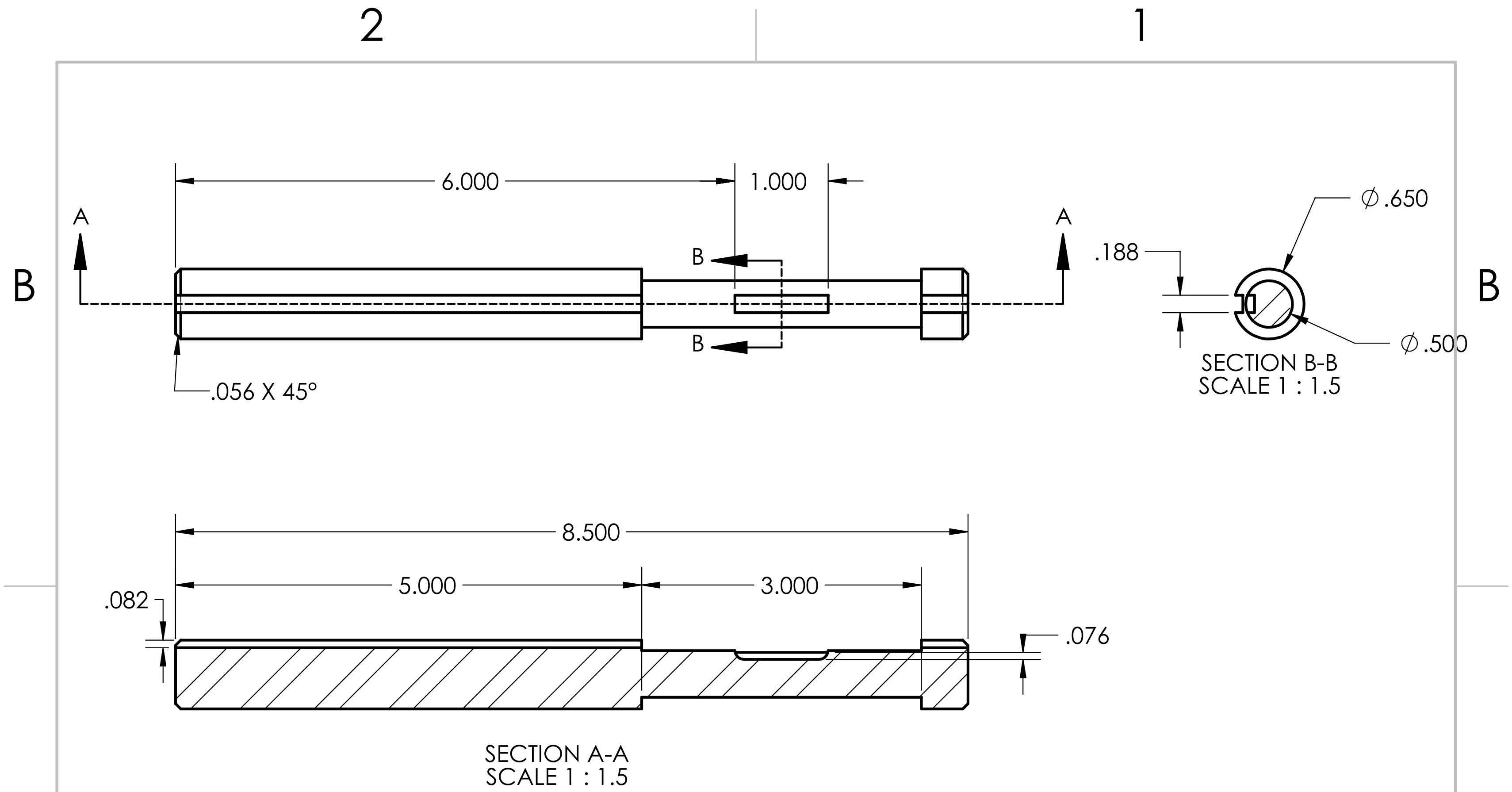
DRAWN BY: NHL

SHEET 1 OF 1

SCALE: 1:2

REV

SIZE A



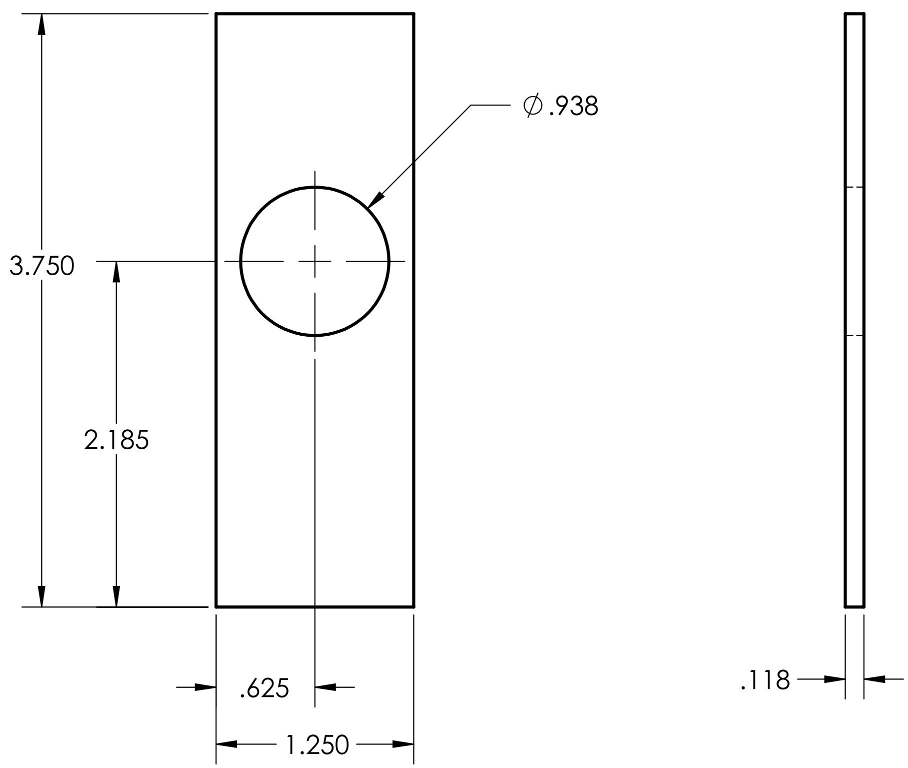
NOTE:
TOLERANCES UNLESS OTHERWISE SPECIFIED
X.XXX = ±.005
ANGLES = ±2

MACHINIST NAME&#:	
MATERIAL	1045
DATE STARTED	
DATE COMPLETED	
STOCK SIZE & LOCATION: 1045 Carbon Steel, 3/4" Diameter, 9" Long	

PART NAME: SHAFT

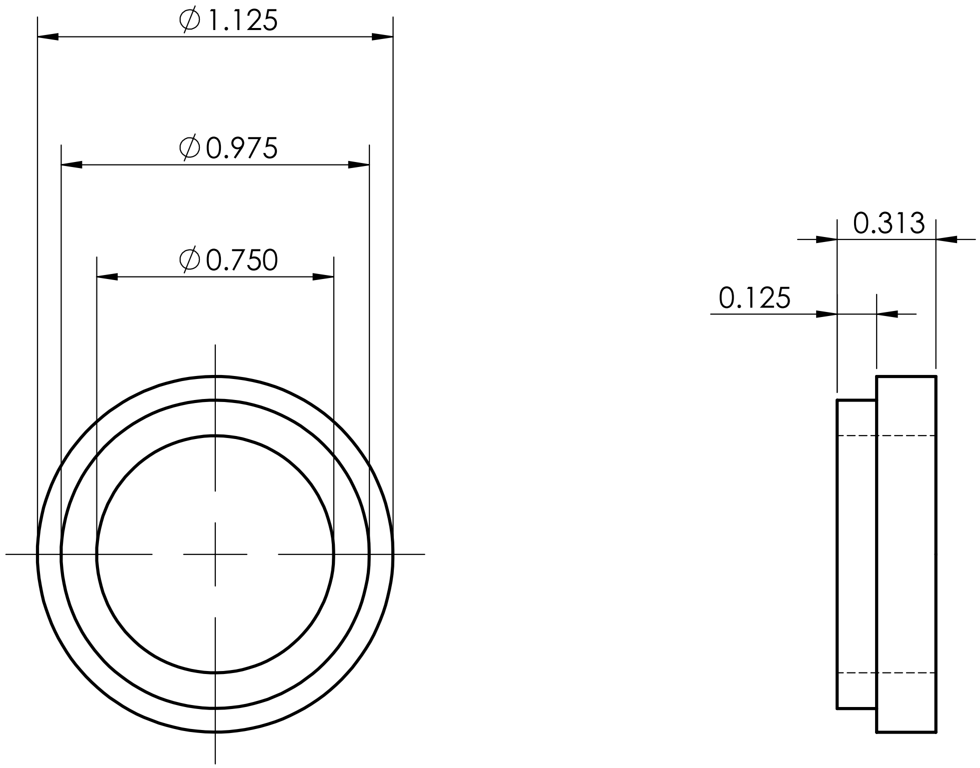
SIZE	DWG#	REV
A	601	A

SCALE: 1:2	QTY: 1	SHEET 1 OF 1



NOTE:
TOLERANCES UNLESS OTHERWISE SPECIFIED
X.XXX = ±.005

MACHINIST NAME&#:		SYSTEM LEAD:	
MATERIAL	ACRYLLIC	PART NAME: BUSHING MOUNT	
DATE STARTED			
DATE COMPLETED			
STOCK SIZE & LOCATION: .118" THICK ACRYLLIC		SIZE A	DWG# 602	REV A
		SCALE: 1:1	QTY: 2	SHEET 1 OF 1

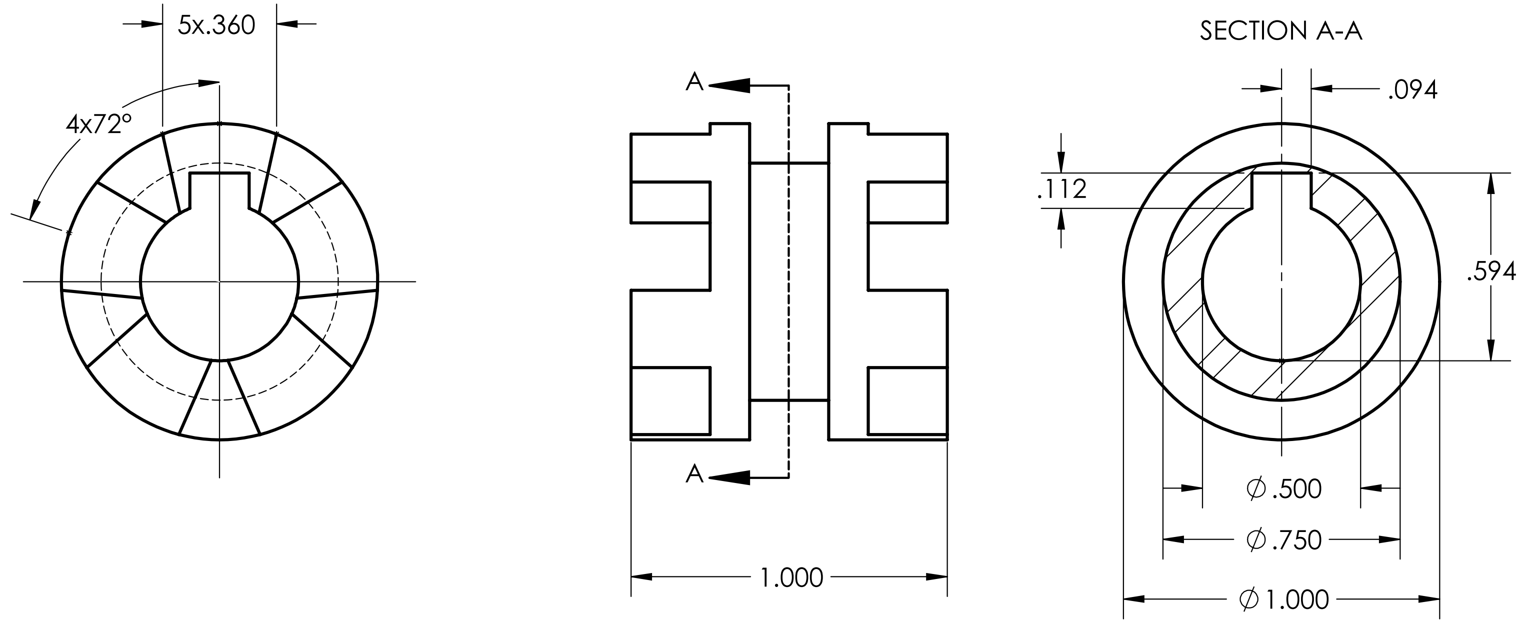


NOTE:
TOLERANCES UNLESS OTHERWISE SPECIFIED
X.XXX = ±.005

MACHINIST NAME&#:	
MATERIAL	DELRIN
DATE STARTED	
DATE COMPLETED	
STOCK SIZE & LOCATION:	1" DELRIN ROD

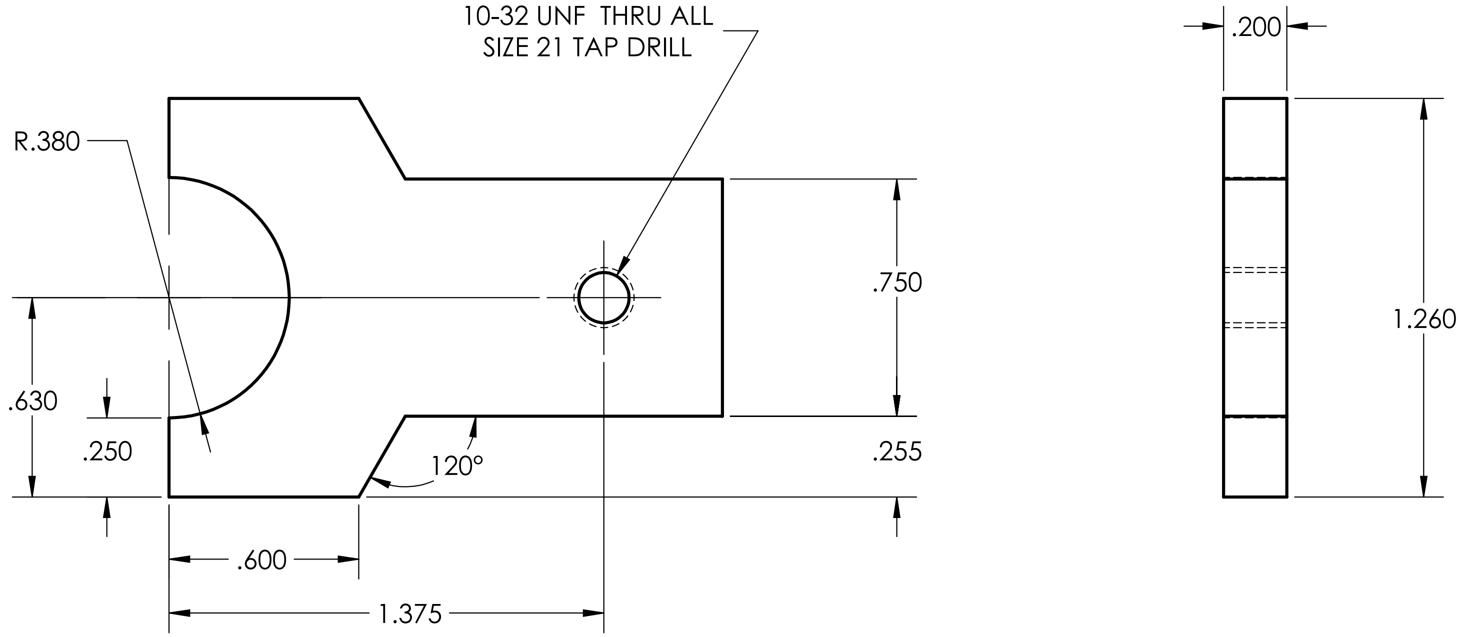
PART NAME: GEARBOX BUSHING

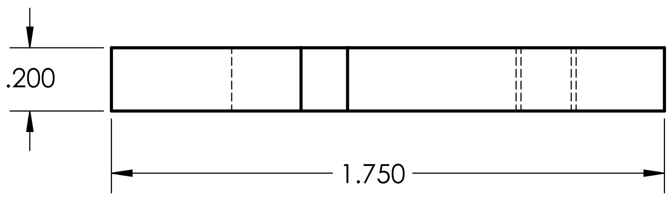
SIZE	DWG#	REV
A	603	A
SCALE: 2:1	QTY: 3	SHEET 1 OF 1



NOTE:
TOLERANCES UNLESS OTHERWISE SPECIFIED
X.XXX = ±.005
ANGLES = ±2

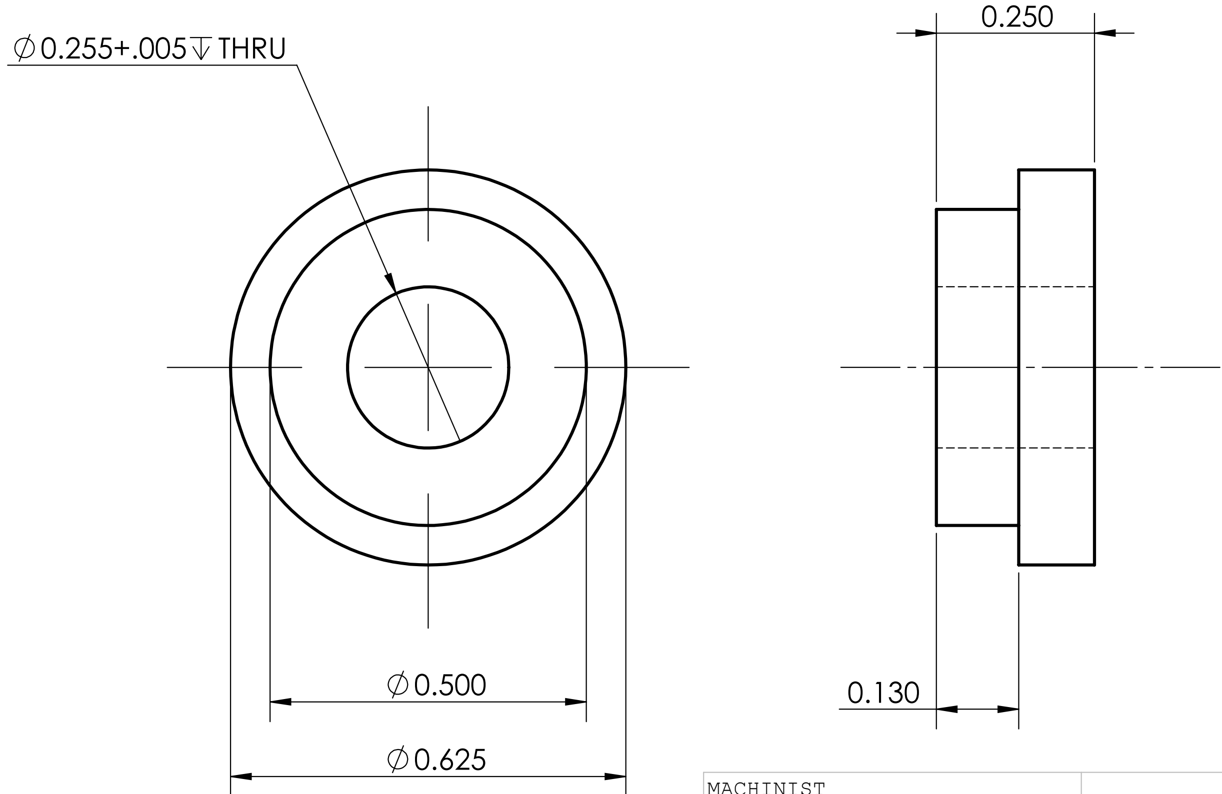
MACHINIST NAME&#:				
MATERIAL	1018	PART NAME: DOGTOOTH		
DATE STARTED				
DATE COMPLETED				
STOCK SIZE & LOCATION: 1" 1018 LOW CARBON STEEL ROD		SIZE A	DWG# 604	REV A
		SCALE: 2:1	QTY: 1	SHEET 1 OF 1





NOTES:
TOLERANCES UNLESS OTHERWISE SPECIFIED
X.XXX = ±.005
ANGLES = ±2°

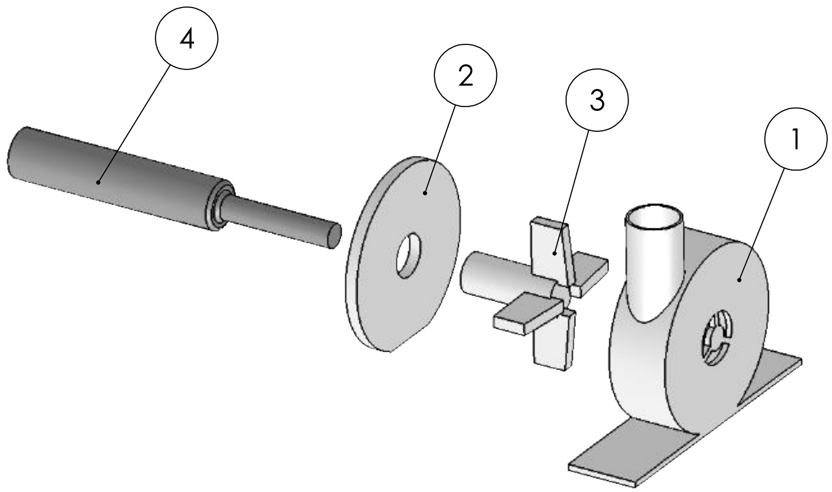
MACHINIST NAME&#:				
MATERIAL	1018	PART NAME: SHIFTER FORK		
DATE STARTED				
DATE COMPLETED				
STOCK SIZE & LOCATION: 1018 .25" THICK 2X2		SIZE A	DWG# 611	REV A
		SCALE: 1:1	QTY: 1	SHEET 1 OF 1



NOTE:
UNLESS OTHERWISE SPECIFIED:
TOLERANCES: X.XXX = ±.005

MACHINIST NAME&#:		
MATERIAL	DELRIN	PART NAME: SHIFTER BUSHING
DATE STARTED		
DATE COMPLETED		
STOCK SIZE & LOCATION: 1" DELRIN ROD		SIZE A / DWG# 613 / REV A
		SCALE: 4:1 / QTY: 1 / SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY
1	701	PUMP MAIN HOUSING	1
2	702	PUMP REAR HOUSING	1
3	703	PUMP BLADES	1
4	704	PUMP SHAFT	1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCH
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ANSI Y14.5 2009

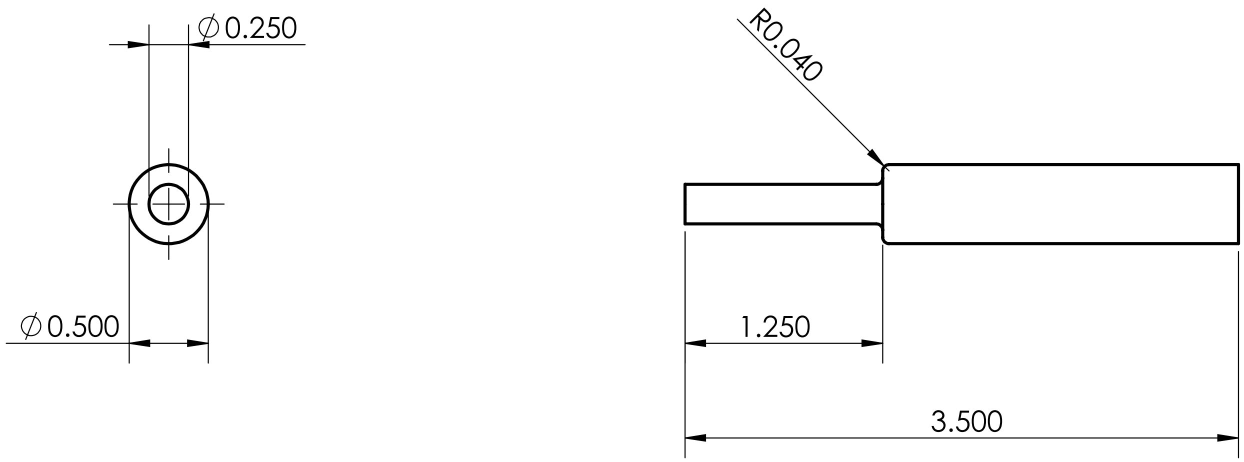
CAL POLY
SAN LUIS OBISPO

MATERIAL:	TITLE:	PART NUMBER:
DELRIN, ABS	PUMP SUBASSEMBLY	700

DRAWN BY:	SHEET 1 OF 1	SCALE: 2:3	REV	SIZE
NHL				A

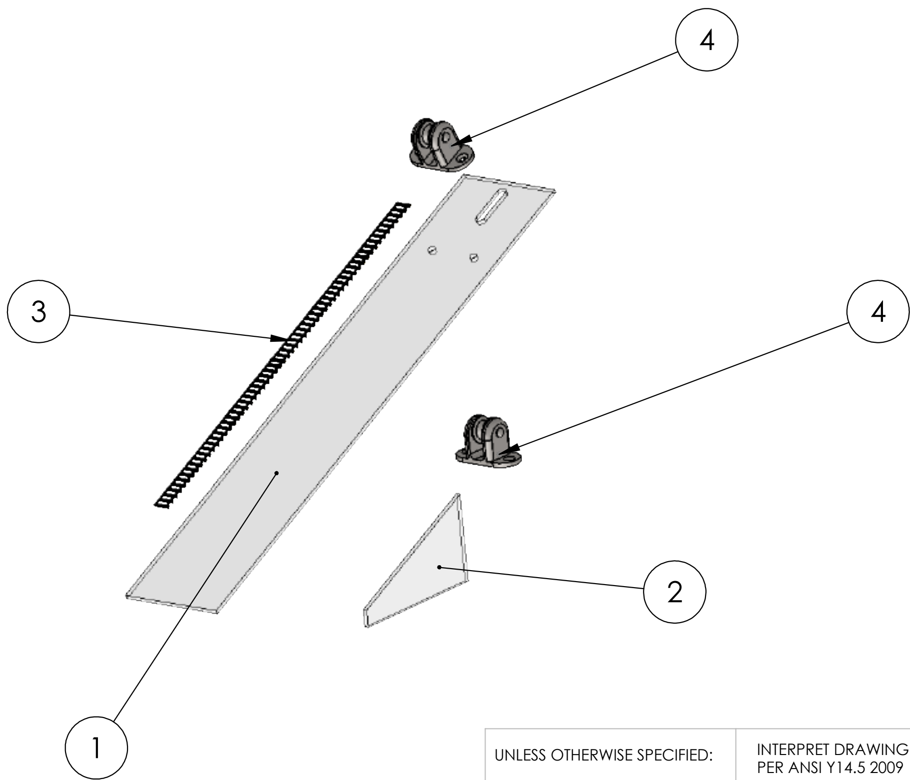
NOTES:

-ALL DIMENSIONS ± 0.005



MACHINIST NAME&#:			
MATERIAL	DELRIN	PART NAME: PUMP SHAFT	
DATE STARTED			
DATE COMPLETED			
STOCK SIZE & LOCATION: 1" DELRIN ROD		SIZE A	DWG# 704	REV A
		SCALE: 1:1	QTY: 1	SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	801	RAMP	1
2	802	RAMP SUPPORT	1
3	803	TRACK	1
4	804	HORIZONTAL PULLEY	2



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ANSI Y14.5 2009

CAL POLY
SAN LUIS OBISPO

MATERIAL: MULTIPLE

TITLE: CART SUBSYSTEM

PART NUMBER: 800

DRAWN BY: DANIEL MIRANDA

SHEET 1 OF 1

SCALE: 1:4

REV

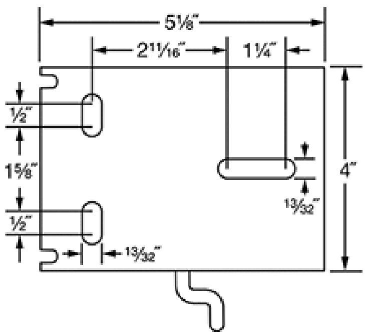
SIZE A

PART 401

Hand Winch for Lifting

with Wire Rope & Hook, 350 lb. Maximum Capacity

Rope Length, ft.		
10		Each
20		ADD TO ORDER
30		3196T11



Maximum Capacity	350 lbs.
Fully Wound Capacity	100 lbs.
Number of Speeds	1
For Maximum Rope Length	84 ft.
For Rope Diameter	1/8"
Base Width	4"
Base Length	5 1/8"
Winch Height	4 1/4"
Mounting Hole Width	13/32"
Number of Mounting Holes	3
Handle Length	7"
Handle Attachment Type	Permanent
Power Source	Manual
Brake Type	Automatic
Material	Steel
Application	For Lifting
Body Type	Open
Pulling Direction	Horizontal, Incline, Vertical
For Use With	Wire Rope
Rope Diameter	1/8"
Rope with Hook Included	Yes

PART 402

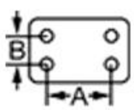
Steel Pulley for Wire Rope

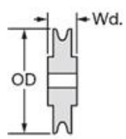
Mounted Pulley, for 3/16" Rope Diameter

Each

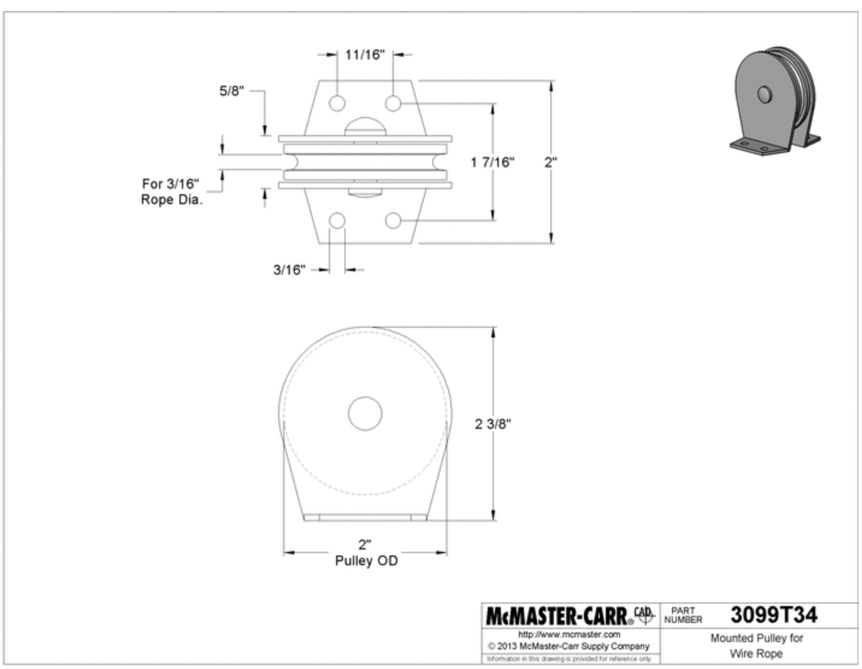
ADD TO ORDER

In stock
$7.02 Each
3099T34





Style	1
Application	For Lifting
For Use With	Wire Rope
Pulley Type	Mounted
For Rope Diameter	3/16"
Capacity	600 lbs.
Number of Grooves	1
Insertion Style	Feed Through
OD	2"
Width	5/8"
Overall Length	2"
Overall Height	2 3/8"
Material	Steel
Housing Material	Steel
Mounting Hole	
Number of	4
Diameter	3/16"
Center-to-Center (A)	1 7/16"
Center-to-Center (B)	11/16"
Specifications Met	ASME B30.26



PART 501

12V DC 6000RPM Torque Magnetic Mini Electric Motor for DIY Toys Cars

by uxcell

45 customer reviews | 48 answered questions

Price: $5.13 & **FREE Shipping** on orders over $49. Details

In Stock.

Want it Friday, Feb. 10? Add it to a qualifying order within **17 hrs 59 mins** and choose **One-Day Shipping** at checkout. Details

Sold by uxcell and Fulfilled by Amazon. Gift-wrap available.

Size: **12 Volt**

7.4V | 10.8V | **12 Volt** | 12V | 15.6V | 16.8V

Color: **6000RPM**

Technical Details

Part Number	a12032000ux0179
Item Weight	0.3 ounces
Product Dimensions	5.3 x 3.7 x 1.1 inches
Item model number	a12032000ux0179
Size	12 Volt
Color	6000RPM
Material	Metal
Item Package Quantity	1
Number of Handles	1
Batteries Included?	No
Batteries Required?	No

Additional Information

ASIN	B008595SC8
Customer Reviews	45 customer reviews 4.1 out of 5 stars
Best Sellers Rank	#11,574 in Home Improvements (See top 100) #2 in Home Improvement > Electrical > Electric Motors > Permanent Magnet Motors
Shipping Weight	0.3 ounces (View shipping rates and policies)
Domestic Shipping	Currently, item can be shipped only within the U.S. and to APO/FPO addresses. For APO/FPO shipments, please check with the manufacturer regarding warranty and support issues.
International Shipping	This item can be shipped to select countries outside of the U.S. Learn More
Date First Available	May 22, 2012

PART 502

Blue Sea Systems LED Indicator Lights

by Blue Sea Systems

143 customer reviews | 22 answered questions

Available from these sellers.

Style Name: **12/24V DC**

12/24V DC | 120V AC | 250V AC

Color: **Amber**

- Easily installed in any Blue Sea Systems circuit breaker panel
- Simple push-in installation mounts in any thickness material
- Useful as general indicator and alarm lights
- 26 AWG and 11/64 inch mounting hole size

New (33) from $4.99 & FREE shipping.

Product Details

Shipping Weight: 0.5 ounces (View shipping rates and policies)

Domestic Shipping: Item can be shipped within U.S.

International Shipping: This item is not eligible for international shipping. Learn More

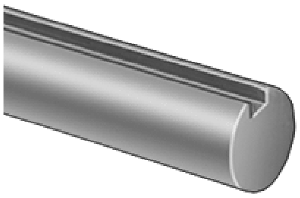
ASIN: B00HL9N1PY

Item model number: 8169-Parent

PART 601

Keyed Rotary Shaft

1045 Carbon Steel, 3/4" Diameter, 9" Long



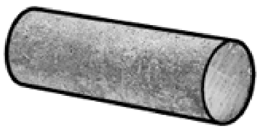
Each

ADD TO ORDER

In stock
$19.70 Each
1497K116

Material	1045 Carbon Steel
Diameter	3/4"
Length	9"
Keyway	
Width	3/16"
Depth	3/32"
Length	9"
ANSI Keys Included	No
Diameter Tolerance	-0.0025" to -0.001"
Straightness Tolerance	0.012" per ft.
Length Tolerance	-0.0313" to 0.0313"
End Shape	Chamfered
Hardness Rating	Medium
Hardness	Rockwell B95
Yield Strength	75,000 psi
For Motion Type	Rotary
Shaft Type	Keyed
End Type	Straight
RoHS	Compliant

PART 604



Low-Carbon Steel Rod

1" Diameter

Length	Each
1 ft.	
3 ft.	ADD TO ORDER 8920K231
6 ft.	

Grade	1018
Shape	Rod
Finish	Unpolished
Diameter	1"
Diameter Tolerance	-0.002"
Yield Strength	54,000 psi
Hardness	Medium (Rockwell B70)
Specification Met	ASTM A108
Construction	Cold Drawn
Material Composition	
Carbon	0.13-0.20%
Manganese	0.30-0.90%
Silicon	0.15-0.30%
Phosphorus	0.04% Max.
Sulfur	0.50% Max.
Iron	98.06-99.42%
Nominal Density	0.283 lbs./cu. in.
Electrical Resistivity	15.9 microhm-cm @ 32° F
Thermal Conductivity	29.4 Btu/sq. ft./ft./hr./°F @ 212° F
Coefficient of Thermal Expansion (Text)	$6.7\text{-}7.5 \times 10^{-6}$
Elongation Range	10-36%

PART 605

Metal Gear - 14-1/2 Degree Pressure Angle

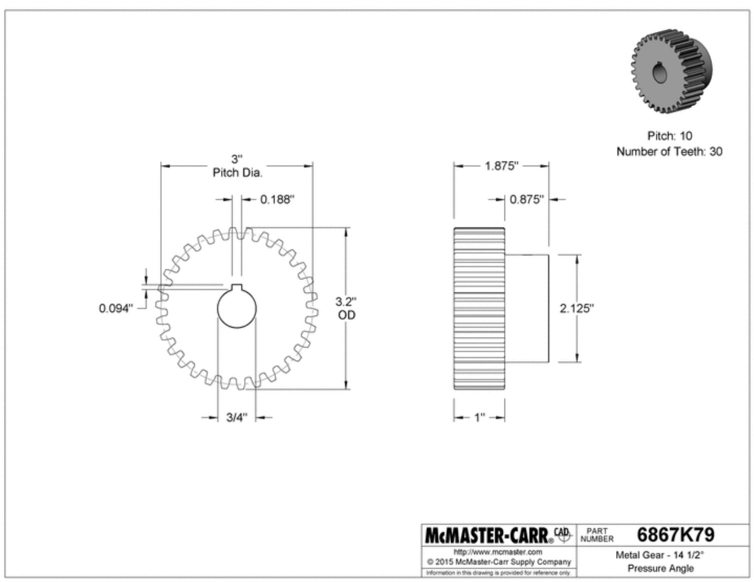
Press-Fit Mount, Set Screw & Keyway, 10 Pitch, 30 Teeth

Each

ADD TO ORDER

In stock
$97.81 Each
6867K79

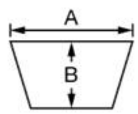
Pressure Angle	14 1/2°
Pitch	10
Number of Teeth	30
Pitch Diameter	3"
OD	3.2"
Face Width	1"
Overall Width	1.875"
Material	Steel
Bore Type	Finished
Mount Type	Keyway, Press Fit
Includes	Set Screw
For Shaft Diameter	3/4"
Keyway	
Width	0.188"
Depth	0.094"
Hub	
Diameter	2.125"
Width	0.875"
RoHS	Compliant



PART 607

3L-Section V-Belt

Trade Size 3L170, 17" Outer Circle



Each

ADD TO ORDER

In stock
$6.09 Each
6190K17

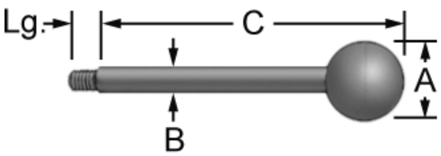
Section	3L
Trade Size	3L170
Outer Circle	17"
Top Width (A)	3/8"
Height (B)	7/32"
Color	Black
Material	Rubber

Commonly used on light duty drives with fractional-horsepower motors, these belts are rubber with polyester reinforcing cords. Color is black.

PART 612

Lever Handle

1/4"-20 Thread, 6" Handle Length, 1" Knob Diameter



Each

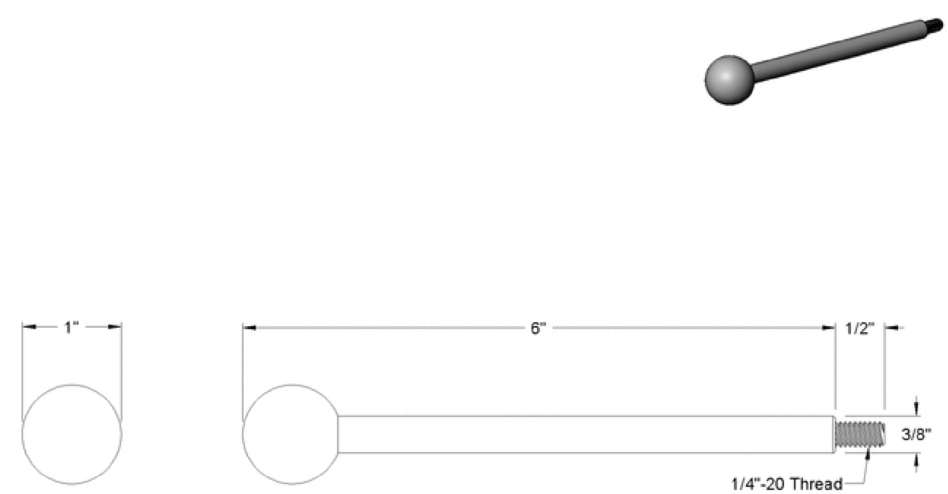
ADD TO ORDER

In stock
1-9 Each $6.32
10 or more $5.71
6303K3

Thread Size	1/4"-20
Thread Length	1/2"
(A)	1"
(B)	3/8"
(C)	6"
Additional Specifications	With Fixed Ball Knob—Inch
RoHS	Not Compliant

Handles with fixed ball knob are an ideal replacement for gear levers. Knob is black phenolic with a temperature range of -70° to +200° F. Shaft is black-oxide steel.

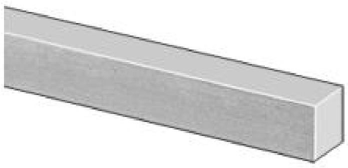
Handles with revolving ball knob provide a friction-free grip—perfect for hand wheels and cranks. Knob is black phenolic with a temperature range of -4° to +300° F. Shaft is zinc-plated steel.



PART 614

Steel Oversized Key Stock

3/16" x 3/16", 12" Length



Each

ADD TO ORDER

In stock
$0.93 Each
98830A150

Material	Steel
Size	3/16" × 3/16"
Length	12"
Tolerance	
Size	0" to 0.003"
Length	-0.125" to 0.125"
Tolerance Rating	Oversized
Minimum Hardness	Not Rated
Key Type	Straight
System of Measurement	Inch
RoHS	Compliant

PART 901

Click to open expanded view

DIGITEN 4 Digital LED Tachometer RPM Speed Meter+Hall Proximity Switch Sensor NPN Red

by DIGITEN

16 customer reviews | 14 answered questions

Price: $18.99 Prime | **Fast, FREE Shipping** with Amazon Prime

In Stock.

Want it Friday, Feb. 10? Order within **18 hrs 16 mins** and choose **One-Day Shipping** at checkout. Details

Sold by DIGITEN and Fulfilled by Amazon. Gift-wrap available.

- Measure range: 5-9999RPM.
- Power requirement:DC 8-15V
- Come with hall sensor and magnet
- Display:red 0.56" LED
- Measure varied motor RPM

› See more product details

New (1) from $18.99 & FREE shipping on orders over $49.00. Details

Technical Details

Part Number	RPM1204RHA
Item Weight	2.4 ounces
Product Dimensions	2.8 x 1.4 x 0.8 inches
Power Source	dc
Voltage	12 volts
Batteries Included?	No
Batteries Required?	No

PART 902

Analog Dial Tachometer, 50 to 4000 rpm

Item# **3BY11** Mfr. Model# **3BY11** Catalog Page# 582 UNSPSC# **41112802**

Price
$73.05 / each

Auto-Reorder Every 1 Month
Deliver one time only

1 **ADD TO CART**

+ Add to List

Jump to: Replacement Parts (1)

Be the first to write a review

PART 1001

Alcohol Engine

SKU# XB.CC.647 net weight: 24.16 oz shipping weight: 25oz 1- BOX A 2 - MEDIUM BOX

Detailed Testing Procedures: Intro to ME 128 Team

Item 1: Weighing the final assembly

1. Place the experiment on a flat scale, such as the large blue digital scale in the engines lab.
2. Ensure that the bottom pulley is taken off it is a floor scale. This weight should be 20 pounds or less.
3. Ensure that there are no external masses attached

Item 2: Must last at least 1 quarter of use

To withstand a quarter of use we may not have time to do the testing for the whole quarter , however we will do as many runs of the experiment as we can. For this all subsystems must be continuously run for a period of time

Test Procedure

1. Set up experiment
    a. Lay down the experiment on the table with pulley hanging off ledge
    b. Attach it to table with clamps
    c. Have the all the string spooled around
2. Make sure water levels in pump enclosure are constant to ensure all other factors remain
3. Make sure cart is at bottom of track
4. Attach ruler to backside of pump with markings facing towards front
5. Make sure water levels in pump part are constant to ensure all other factors remain
6. Attach desired weight to the end of the rope, record this weight
7. Release mass once secured to end of rope, gear may need to be slightly pushed dot induce the fall
8. Record and compare head of pump, by visually inspecting pump height with ruler
9. Release mass once secured, gear may need to be slightly pushed dot induce the fall
10. Using shifter fork pull to change the settings to the ramp subsystem
11. Repeat steps 7 and 8
12. Once cart has come to stand still record vertical position on track
13. Repeat steps 4-12 at each different weight 10 times per weight
14. Listen for any unwanted vibrations in the housing while mass is falling
15. Check for any loose components after a few trials of the heavier weights

<u>Item 3: Data must be consistent for falling masses and resulting RPMS's</u>

Test Procedure

1. Set up experiment
    a. Lay down the experiment on the table with pulley hanging off ledge
    b. Attach it to table with clamps
    c. Have the all the string spooled around
2. Attach analog tachometer to shaft
3. Make sure water levels in pump part are constant to ensure all other factors remain
4. Attach desired weight to the end of the rope, record this weight
5. Release mass once secured, gear may need to be slightly pushed dot induce the fall
6. Record RPM of shaft with analog tachometer
7. The acceptable limit is 20% difference between each RPM at the same weight
8. Perform this test 20 times per weight
9. Compare recorded data by plotting a graph of RPM vs weight for each run of this test procedure then using a visual comparison and the slope of the graphs will show any inconsistencies between data sets

<u>Item 4 : Data Must be Consistent and recordable for Pump Subsystem</u>

Test Procedure

1. Set up experiment
    a. Lay down the experiment on the table with pulley hanging off ledge
    b. Attach it to table with clamps
    c. Have the all the string spooled around
2. Attach analog tachometer to shaft
3. Attach ruler to backside of pump with markings facing towards front
4. Make sure water levels in pump part are constant to ensure all other factors remain
5. Attach desired weight to the end of the rope, record this weight
6. Release mass once secured, gear may need to be slightly pushed dot induce the fall
7. Record and compare head of pump, by visually inspecting pump height with ruler and noting down value
8. Record RPM of shaft with analog tachometer
9. Perform steps 4-8 20 times per weight
10. A difference of 40% in the pump height readings is acceptable
11. Take average of these readings per weight

12. Plot a curve with head height vs RPM to generate pump curve
13. Plot head height vs Input mass
14. Once curves are generated these values can be referenced by seeing if a new data point with generated curves

Item 5: Experiment must be completed in a lab period

This would require running the experiment fully through multiples times. The time is takes for the team to do a full run through of the experiment will be recorded every time

A full run through of the experiment should be performed at least 5 times and each system run-through should last for a maximum of 2.5 hrs.

Refer to the Test Procedure in Item 2 for a full run through of the experiment

Item 6: Presentation does not consume extra time

The pre-lab presentation will be run through around 5-10 times and each presentations should fall within the maximum time limit of 30 minutes.

A timed run-through of the presentations will be done by the teams once the pre-lab presentation is finalized.

ME 128
ME 229

Energy Conversion and Heat Transfer

California Polytechnic State University, San Luis Obispo
Mechanical Engineering

Updated 2017

Introduction

The transfer of energy through multiple domains is a critical part of mechanical engineering. We use various ways of manipulating energy to power systems, change the state of a design, or move from one point to another.

As you already know, energy is always transferred from one component to another, and never created. This can be through a belt, lever, piston, fluid, gas, and many other objects. In mechanical engineering the study of energy transfer is largely divided into three areas: mechanical energy, fluid energy, and heat transfer. These three areas cross over each other in many ways, however they also act as standalone areas of expertise for many mechanical engineers.

This transfer is never an ideal, and engineers must account for this in their designs. Whether it is a car drive train, a wind or wave turbine, or a piezoelectric mechanism, energy is constantly dissipated by other elements of a system or the environment surrounding it. As a mechanical engineer, you must understand how these losses form and how to calculate and quantify them. This is important in understanding how energy behaves in a system, and must be communicated to a customer as precisely as possible to allow for proper and ethical engineering.

In the development of clean energy, the losses seen by electrical systems are becoming more and more important. Clever methods of energy storage and generation are constantly being developed, however transfer of this energy to the national grid can result in unfavorable returns if the system is inefficient or designed poorly.

One example of this is the water-powered car, where hydrogen gathered from water molecules is used to power a hydrogen-combustion engine to power a vehicle. This concept is flawed in that it requires more energy to break apart the molecules of water than it produces as horsepower to the tires. Ideally this system may produce enough raw energy to balance the energy used to break the hydrogen out, but the dissipation from the motor, gearbox, drive shaft, and tires is enough to make this concept unusable with current technology.

Wind powered turbines are one of the most efficient methods to generate power, but are power-limited in that the wind can only spin the turbine blades so fast before the generator begins to resist any faster rotation. To overcome this issue, engineers installed gearboxes and elevated the turbines. This allowed the system to generate higher torque within the generator, and at a higher speed, creating more electricity than before. In this case, engineers used an intermediate system to overcome an energy limit.

This experiment has some basic systems that do not necessarily represent a single device, but rather generalize many systems seen in industries across the field of engineering. The following are relationships you may wish to draw while running this experiment:

Mass-Pulley Subsystems

This subsystem, which consists of a large mass being dropped from a height, represents every any form of potential to kinetic energy storage and generation. Potential energy storage is commonly used on a large scale in hydroelectric systems, where fluids can be stored in reservoirs to supplement energy demands. Elevators utilize weights to balance the energy usage during travel, where a counterweight changes the effective weight of the elevator car. In our case, the main subsystem the weight turns a pulley which can power other systems. This is the source of the system. There is also a massive cart on a track that can be pulled or dropped on its incline as dictated by the tension of the rope and pulley it is attached to. This acts a a coupled system to the dropped mass.

Geartrain

Geartrains are used in many different applications to reduce speed or increase torque. One you may instantly recall is the gearbox in a car. This geartrain converts the torque-limited high engine speed into a lower speed but higher torque wheel output. All servo motors have a built-in gearbox that produces a much higher shaft torque than the voltage would normally allow, making most robotic and electric motion possible. As mentioned before, wind turbines use a gearbox to reduce the torque requirement seen by the fan blades to turn the generator. In our system, the geartrain drives a shaft that provides power to other rotary elements: a v-belt, a generator, and another winch pulley. The geartrain is important in that it transfers energy from the mass-pulley to the other systems in 3D space, however due to its inertia, friction between systems, and tolerances between parts there is a significant amount of energy lost in the transfer process. This is what we will investigate today.

Pump

Fluid has been used to generate energy since the dawn of time. Waterwheels have powered rotational systems to grind, saw, and machine various substances. Pumps have allowed us to move fluids to locations and heights once impossible in short amounts of time. One easy way to characterize a pump's performance, besides horsepower measurements, is to measure the height the pump can move fluid straight up. This height is typically called a pump head. In essence, this measurement is equivalent to a maximum pressure the pump can output, but in a form that allows the user to understand their maximum elevation for a fluid system. Like other rotary systems, pumps fall ill to friction losses in the shaft, the pump blades, and the pipe flow along the walls. We will attempt to calibrate the pump in our experiment to create a specification sheet for interested parties.

Procedure

This lab involves the collection of data as a group in order to write a formal engineering report. Each student must participate in measuring and calculating the energy transfered from each subsystem.

I. Potential to Rotational Energy

Mass released from a height will transform its potential energy into kinetic energy. In the case of the experimental apparatus, this energy is also converted into energy stored by rotational inertia by the rope.

1. Using the lever on the ramp side of, push the shifting mechanism inwards to engage the large pulley (you can visibly check to see if the teeth are engaging). This will run the system in the pump mode, which is safer to run than the ramp since it does not have a hard stop.
2. Choose a mass or combination of masses that you think will provide enough energy to overcome stiction (stationary friction within the system) and start the gearing system. Record this mass.
3. Attach the masses via the carabiner(s) at the end of the winch rope and place them on the surface of the table. *Do not drop the masses until the system is set up.*
4. Ensure the Hall sensor is on and drop the masses. Record the fall time and the max RPM readout on the Hall sensor. **<u>WARNING:</u> Do not stand directly underneath the pulley, and mind your toes as the mass drops.**
5. If the masses do not fall, increase the amount of mass until stiction is overcome.
6. Once you mind a minimum mass required, repeat steps 3-4 with at least **two** more masses.

Energy can be calculated for both sides of the system using the appropriate equations found in the Reference Information section. You will compare these values in your report.

II. Rotational Energy to Pump Head

1. In a fashion similar to Part I, set up the machine to transfer power to the pump. If you are moving on directly from Part I this should already be done.
2. Begin dropping the same masses you used from Part I and measure the maximum pump head (the height the water reaches). Record these in your table.

III. Rotational Energy to Potential Energy

1. Using the shifting knob, switch the gears around so power is transfered to the cart ramp. Pull the lever out and rotate the shaft partially until the teeth engage for the pulley-cart system.
2. Drop your lowest usable mass and record the height gain of the cart. Note you will have to account for the slope of the ramp when you do your energy calculations.

IV. Comparison to a Thermal System

1. Your instructor will demonstrate an alcohol engine and measure the flywheel RPM. Be sure to record this for comparison in your memo.

Report Requirements

Your team will turn in your results and calculations in a formal engineering report. The formatting and presentation of data in this report is important. It communicates to the person reading the report what your findings were, and how they can replicate the experiments if they so desire.

The report format and guidelines will be provided by your instructor. Use your data and the relationships presented in the introduction to generate the requested results.

Reference Information

Table 1. Elemental Relationships for Ideal Elements in Multiple Domains.

Element	Energy
Stationary Mass	$\mathscr{E} = mgh$
Translational Mass	$\mathscr{E} = \frac{1}{2}mv^2$
Rotating Inertia	$\mathscr{E} = \frac{1}{2}J\Omega^2$
Fluid Capacitance	$\mathscr{E} = \frac{1}{2}C_f P^2$
Fluid Inertance	$\mathscr{E} = \frac{1}{2}I_f Q^2$

Table 2. Elemental Relationships for Ideal Dissipators in Multiple Domains.

Element	Power Dissipated ($\mathscr{P} = \frac{\mathscr{E}}{t}$)
Translational Damper	$\mathscr{P} = \frac{1}{B}F^2 = Bv^2$
Rotating Damper	$\mathscr{P} = \frac{1}{b}T^2 = B\Omega^2$
Fluid Resistance	$\mathscr{P} = Q^2R = \frac{1}{R}p^2$