PROJECT SELECTION AND PROCESS PLAN DESIGN

FOR ALTERNATIVE IME 143/144 FINAL PROJECT

A Senior Project

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Executive Summary

Hundreds of students each year enroll in IME 143 or IME 144, freshmen-level machining classes, and complete an air motor to demonstrate the skills they have acquired on a variety of manufacturing processes. The air motor, however, is useful only as a teaching tool in the classroom; once the students bring them home, the air motor becomes little more than a trophy at best.

With the capabilities of the machining lab, a final project can be developed that can have a benefit to people in need while maintaining educational value. This project details a process plan for a manual water pump. The pump can be donated for use in developing countries where access to clean water is still in desperate need.

The process for manufacturing the water pump had to be deconstructed into specific machining processes and balanced appropriately between the machines available to the classes. The machining lab has a number of different machines that enable students to use 14 different processes. Unlike a production environment, all processes have to be used and balanced to make use of lab time. This often meant using sub-optimal processes and/or procedures.

The critical benchmark for implementing the water pump into the curriculum is cost. Students in IME 143/144 pay lab fees, which cover the cost of materials for the quarter. The fees are $10 for IME 143 and $50 for IME 144. Based on rough estimates from these lab fees, the actual cost of the air motor is between $10 and $20. As designed currently, the water pump has a material cost of about $30. However, this project is larger and more complex. It is recommended that one pump be made for every two students bringing the per student cost to about $15, within the cost range of the air motor.

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Contents

Tables

Figures

Equations

Introduction

The Industrial and Manufacturing Engineering (IME) department at California Polytechnic State University (Cal Poly) offers two similar freshman-level machining classes designated IME 143 and IME 144. Students from many of the engineering disciplines are required to take one of these courses to help them understand how parts are actually made. Both classes culminate in a final project where students manufacture the parts for an air motor using a Just-In-Time (JIT) manufacturing strategy. The air motor is a simple piston and flywheel that is powered by a stream of compressed air.

Every year, hundreds of students enroll in IME 143 or 144 and each gets his or her own air motor. The air motor is an excellent tool for students to gain experience with and demonstrate their skills on a variety of machines. One problem with the air motor is that after the class has ended, the air motor is virtually useless both because most students do not have compressed air available and also that it is not designed to serve any function. For many students, the air motor is relegated to a paperweight, for others it is even thrown away. This project is intended to find an alternative project that leaves the classroom as a functioning, useful product. The alternative had to meet a basic set of criteria in order to be considered:

- Simplistic in design and operation
- Relatively small in size (less than ~6″ per side)
- Manufacturable using the processes available in the machining lab
- Useful outside the classroom

After some initial research and deliberation, a hand-cranked, rotary water pump was tentatively selected as the product of focus.

The motivation for this project originally stemmed from a series of classes available at Cal Poly called Appropriate Technologies for Developing Countries. In this class, simple technologies were designed and developed using available resources that are culturally and economically appropriate for specific impoverished areas of the world. The dire need for simple, easy-to-produce technology all over the world is tragic. Cal Poly as a university has an abundance of resources that can be shared with people who need them, and the IME 143/144 project is a way that the Industrial and Manufacturing Engineering Department can make good use of its resources.

After selecting a project that meets the outlined criteria, a process plan will be developed. This will take into account any changes that must be made to make the project feasible in the IME 143/144 lab. Using an existing product as a template, engineering drawings will be produced from the art files modeled in Pro/ENGINEER. A Pro/E module called Pro/Manufacturing will be used to generate CNC code to assist in the creation of a prototype.

In this project, there are several deliverables:

1. Engineering drawings of all parts
2. A process plan that breaks the production into specific manufacturing steps
3. CNC code for automated machining steps
4. A prototype produced by following the process plan
5. Cost analysis comparing the Air Motor to our alternative
6. A proposal to the IME Department requesting modification of the IME 143/144 courses
7. A presentation to the faculty and Industrial Advisory Board

Most of these deliverables are presented in this report. This report will first present relevant background and a review of literature, then will progress from the design through methodology and finally, present the results and conclusions.

This project does not address the actual implementation of the project into the class curriculum. We hope that other students will be able to continue the project and develop a course manual, plan the distribution and scheduling of work on the parts, and development and analysis of inspection and gaging. There is also some work to be done on designing dedicated fixtures for use in the classroom as well as mold design for the raw castings.

Background

This project incorporates a multitude of different aspects of manufacturing engineering, from design for manufacturability to process planning to economic analysis. The review will cover some of the basic topics and information used in the course of the project, but previous knowledge and experience will also be drawn from in order to complete the project.

Selection of a Product

Selecting an item to be manufactured by students in IME 143 and 144 presents a unique challenge. As a premise of this project, the product must have a useful function. Additionally, there are certain characteristics that are necessary to make the project worthwhile for the classes:

- Comprised of 5–15 components
- Requires machining to manufacture
- Can be fabricated out of machinable metals and plastics
- Does not require any welding
- Can be die cast to near net shape
- Is not too large

After consulting several resources—including local non-profits, Cal Poly professors, Kennedy Library, and the internet—a list of possible products was compiled. On the list were items such as a windmill, solar panels, a specialized clamp for water pump repair, and a manual water pump. After evaluating the feasibility of each, we decided to adapt the water pump for this project. The pump is suitable for the class because all of the non-purchase parts can be

machined, it is a relatively simple mechanism, and it serves a function that is needed all over the world (Proby 2009).

Water Pump

In spring quarter of 2009, a group of Cal Poly students designed, analyzed, and tested a bicycle-powered rotary water pump. According to their calculations and estimates, the bicycle powered pump was cheaper to produce, more portable, could be used in deeper wells, and had an equal flow rate to that of the more common treadle pumps. This project will use a similar pump as the basis of the IME 143/144 project.

The pump we selected is a standard rotary barrel pump that can move water with a flow rate of 7 gallons per 100 revolutions, this equates to different velocities depending on the rate of rotation of the crank arm. Table 1 displays the parameters recorded by the bicycle pump project group using a similar pump design as we have selected. Using these figures, we have estimated an average flow rate of about 5 gallons per minute. It should also be noted that the pumping head for the rotary pump is about 8 meters (~26 feet), which is greater than the common treadle pump and is sufficiently deep for a shallow, freshwater well (Hosbach, Brew and Sorenson n.d.).

Table 1: Treadle vs. Bicycle-Powered Water Pump

Pump Type:	Treadle Pump	Bike Pump
Cost:	$100	$50 (projected)
Head:	6 meters	8 meters (projected)
Flow rate:	.5 Liters/S	.5 Liters/S
Imported Parts	60% per pump	40% per pump
Energy Usage	Demanding	Demanding
Portability	Low	High (Projected)

The selected pump is a rotary barrel pump that works using positive displacement. Unlike other types of pumps, rotary pumps can output a constant volume of water per revolution regardless of the pressure they encounter, only limited by the available power to turn the pump and the strength of the pump itself. In rotary pumps, there is no radial thrust transferred to the shaft, so there is little need for concern regarding the strength of the internal shaft unlike other pump designs (McNally 2007).

The final design of the pump used for this project is based on two similar pumps manufactured by ATD Tools, one plastic and one cast iron. The best qualities of each will be incorporated into the final design of the pump to be used for the final project of the IME 143 and IME 144 classes. For a basic assembly drawing and parts list of the original pump please see Figure 8 on page 113.

Design for X

In response to the expensive and time consuming sequential product development process, a concurrent design system was established. A key aspect of concurrent engineering is design for X, where X can be one of a wide variety of "-ilities" such as manufacturability, reliability, sustainability, etc. In each case, the specific -ility is considered early in the design phase and drives important design decisions. The following are those that are most applicable to this project.

Design for Manufacturability

Design for Manufacturability (DFM) is a process in the design phase of a new product development that aims to avoid problems when the design is passed along to manufacturing, and to ensure that the product can be manufactured at a reasonable cost and with minimal

difficulty. There are a set of basic principles and best practices for almost every manufacturing process and material imaginable. One of the most well regarded books on the subject is James Bralla's *DESIGN FOR MANUFACTURABILITY HANDBOOK*.

Design for Assemblability

Similar to DFM, Design for Assemblability (DFA) is another member of the DFX family. DFA focuses not on a part level like DFM, but on the assembly and sub-assembly-level. DFA also has a set of best practices to use in the initial product design that ease the assembly of the final product. Some of the more popular DFA techniques are to design the product so that all the parts are added from the same direction, to avoid part designs that can tangle together in a parts bin, to use a symmetrical design on parts so that they cannot be assembled "backwards."

Part Naming Conventions

An aspect of DFM/A that is often overlooked is the naming of parts. "In designing instructions, we do not want actually following and using the instructions to become a barrier to performing the task," Patricia Baggett discusses her research into DFA through experiment into how people interact with certain technology (Baggett 1992). Especially pertinent to this project is the naming of unfamiliar objects in a way that a majority of people can understand. Based on Baggett's experiments, an algorithm for part naming was created:

1. Names should contain some segments that are unique for the object. This guarantees that names are distinct.
2. The more often segments occur in the name, the better.
3. The smaller the frequency of a segment in names for other objects, the better.
4. Shorter names are preferred.

Using two criteria, matching and recall, names created using this algorithm were found to be the most successful in recognizing parts compared with the manufacturers' naming schemes (Baggett, 189–203).

Process Planning

When creating a process plan, the resources available at Cal Poly regarding tools, machines, budget, and time will need to be taken into account. The IME 143/144 laboratory is basically a job shop, designed with a process layout. Seeing as this cannot be changed, a process will have to be planned that takes into account a process layout. Other considerations for this process will be the fact that the volume of parts and rate of production for this product will be low. The lab is also used for other projects and classes, and so the variety of parts produced in this lab is high, but the variety of parts actually produced throughout the duration of the final project is low.

Process planning is mostly associated with choosing which processes to use and in what order they will be performed. Years of manufacturing and engineering have established certain patterns and sequences. For example, a hole that must be reamed first must be drilled. Much of manufacturing relies on these previously established sequences, and many of these sequences are learned purely by experience. However, certain tables and charts are available to aid in the breakdown of highly complicated processes. Some such tables can be found in *PROCESS PLANNING* by Mark A. Curtis, which include types of processes and information about each such as advantages and disadvantages, approximate cost, common usages, production rates, etc. Using this information, even the most hard-to-manufacture item's process could be broken down into the most basic manufacturing processes (Curtis 1988). For this project, a

manufacturing process will need to be selected for each component of the pump, each of which will be relatively simple.

Certain paperwork is commonly used to direct and record the manufacturing process, such as route sheets and operation sheets. A route sheet is a form that displays a process plan, displaying the sequence of operations for a specific part. Route sheets display a brief description of the operation to be done, a listing of the equipment to be used, special tooling, and possibly setup and cycle times for each part. A more detailed description of each operation, called an operation sheet, is also sometimes used. Operation sheets contain more detailed information, such as cutting speeds and feeds, tools, other instructions, and setup sketches or photos (Warnecke and Steinhilper 1985).

Yet another important factor in the design process will be to consider lean manufacturing, not only because this concept is stressed in the curriculum of the classes, but also because it will be the basis for an efficient process plan. Because this project takes place in a learning environment and not a competitive market-driven company, there is a temptation to not take into account the importance of waste elimination. However, the principles of lean can be applied to any and all aspects of production. Lean is a challenging concept to define, and is more often than not defined by what it is not: waste. In his book *Lean Enterprise Systems*, Steve Bell lists the seven types of waste identified during the development of the Toyota Production System: inventory, delay, motion, transportation, overproduction, over-processing, and defects. Creating a lean system is, simply put, looking at each step of a process and eliminating those without purpose (Bell 2006, 17).

Especially important lean principles to take into account when designing this particular process flow are reduction of inventory, overproduction, and elimination of bottlenecks. Implementation of a kanban system would help to eliminate bottlenecks as well as teach students the principles and importance of a pull system of manufacturing. The basic principle of lean is that parts move through the factory as if attached to a rope—all at the same rate. A kanban system is a way of achieving this through signaling that more items are needed. There are several ways of achieving an efficient pull system, with many different types of kanban signals. These may be in the form of cards, containers, baskets, golf balls, buzzers, bells, lights, etc. (Bell, 140). Implementing a kanban system in this production would not only increase efficiency, but also give students the chance to understand a lean system by taking part in it themselves. This will empower the students to take an active role in the manufacturing process as well as help them to understand even better the just-in-time (JIT) manufacturing concept.

Some other important factors in lean manufacturing that apply specifically to this project include small batch sizes, setup time reductions, reliable equipment, a stable schedule, zero defects, and the pull system of production control (Groover 2004, 965). The project is inherently equipped for small batch sizes, and our part in the production design will attempt to reduce setup time through effective fixtures and operation sheets. The reliability of the equipment generally is not a problem, but is out of the control of the project design itself. A stable schedule and zero reductions are both factors that will depend on the students' ability to operate equipment without mistakes or problems. Because this is an introductory course, the students cannot be relied upon to do their parts like efficient machines, but mistakes and problems will be a part of the learning process for them. Continuous flow manufacturing is most

effective in large-scale high volume production, but it is also useful on a smaller scale such as the process in these classes.

A lean principle that should be used for this project is the PDCA cycle: plan, do, check, act (Bell, 24). Planning is always largely focused on when beginning a new process, but just as important is testing the process and making any needed changes before putting the plan into action. Applying this principle with the final project for IME 143/144 will not only facilitate the creation a better system, it will assist in proving to the people involved that the change will be a positive one.

Materials

The decision regarding which materials to use for a product does not only depend on the performance of the product with regards to mechanical stresses, but must also satisfy other functions and be manufacturable. Choosing a material that is easy to mold or machine can make a large difference in ease with which the manufacturing process can be completed.

Taking into consideration the forces on the pump and other factors, a material will need to be chosen out of which to make the pump. These types of pumps are typically made of plastic, cast iron, aluminum, or a combination of these. Each material has its advantages and disadvantages as far as manufacturability, durability, and price. Some benefits of plastic are the relative ease of manufacturing and low cost. The most common shaping process for plastics is generally injection molding, with which complex shapes and varying sizes are possible (Groover 2004, 275). Other advantages of plastics are their ability to be designed for increased manufacturability, since the number of necessary parts "can often be combined by using moulded plastic." Another advantage of using plastic is the ease of machining such a soft

material, allowing parts to be provided with chamfers, notches, and guides that are helpful with mounting other parts (Helander and Furtado 1992, 175)

Taking into account the fact that these pumps will be getting a lot of use under harsh conditions and will be exposed to the elements, a thermoset polymer, with its highly cross-linked structure and high strength, would be the best choice if a plastic were used. However, thermoset plastics are non-recyclable and more complicated to produce. Another viable option would be fiber-reinforced thermoplastics, but these have the same problems: non-recyclability and difficulty of production (Groover, 148)

In considering possible metals to be used for this pump, the two most fitting options to consider are cast iron and aluminum, not excluding the possibility of using both. As suggested in its name, cast iron is highly suitable as a casting metal. There are several types of cast irons, each of which has its advantages and disadvantages. Grey cast iron is the most commonly used. Its two most attractive properties are good vibration damping and internal lubricating properties that enhance machinability. Its strength can range depending upon composition from 20,000 to 50,000 psi. Problems with grey cast iron are its low tensile strength and the fact that it is relatively brittle. Aluminum is a lighter, abundant metal. It has an excellent resistance to corrosion, a property that is important in water-use applications. Aluminum is easily machinable and formable due to its ductility, but is relatively low in strength. For this reason, aluminum is often heat-treated after it is shaped, a process that Cal Poly does not have the facilities for (Groover, 124).

The water pump has several components, and the size, features, and manufacturing process for each piece will need to be taken into consideration when choosing the material to be

used in the fabrication of each. A description of some of the less common materials and the rationale for choosing them is in the following sections.

Delrin (Acetal)

Delrin is a very versatile plastic that has many properties that make it a very suitable material. When machining Delrin, the cutting speed can be significantly higher than any metals and does not require lubrication as the material is self-lubricating. One characteristic of Delrin that particularly appealed to us for the water pump is that it can be certified by the U.S. Food and Drug Administration (FDA) as being safe for food contact. Since our intention with this project is to provide water pumps for developing countries, the FDA certification was a reassurance that the pump could be used for drinking water.

Silicone

In our pump design, we have chosen to include O-rings to ensure a good seal between the center body and the end plates. There are many O-ring materials available, but we selected silicone as the best option. One of the primary reasons is that unlike many other vulcanized rubbers, silicone is not susceptible to ozone cracking. This is commonly seen on automobile tires as small cracks and is caused by exposure to ozone (O_3) gas, even in very small concentrations.

Manufacturing Processes

In designing a manufacturing process, there are two main categories to consider: primary shaping processes and secondary processing. The purpose of primary shaping processes is to form the basic shape of the product or component. Some examples of primary processes are

casting, forging, extrusion, sheet metal working, and machining. Because of the limitations posed by available machinery and tooling as well as budget and time, many types of manufacturing processes can be eliminated immediately. Thus, because the most feasible and cost-effective forms of primary shaping processes are casting and machining, they will be used for this manufacturing process. Because this is a machining class, any parts that must be cast will not be a part of the final project that the students perform, but it will need to be taken into consideration for this report.

Secondary processing creates final surfaces and dimensions for meeting tolerance, material property, and visual appearance requirements. For this project these requirements will be met primarily using machining, but processes such as grinding will be considered as well. The most desirable manufacturing process takes into account primary and secondary processes, either combining them or purposefully selecting them to complement each other (Creese 1999, 119).

Casting

Casting is the process of pouring molten metal or plastic into a mold to create a certain shape. Casting is a primary shaping process, and will probably be a necessary step in the manufacturing of the water pumps for IME 143/144. The casting process is typically thought of as having four major steps:

1. **Patternmaking.** This includes applying allowances for shrinkage, draft, and machining, as well as designing sprues, runners, gates, sinks, and risers. Any cores that will create inside features also need to be designed.

2. Manufacturing of the Mold and Cores. This includes creation of the mold (generally with a CNC mill), and the cores. Cores may be reusable, in which case they are most likely machined, or disposable, in which case a separate mold must be made for core formation.
3. Melting of the Casting Material. This step is often performed simultaneously with mold preparation. Once the material is at the desired temperature, it is poured or injected into the mold cavity.
4. Solidification and Cooling. Once the material has solidified, it can be removed from the mold and either left to cool or cooled by artificial means.

Before the created part(s) are sent to the next step, they are rough finished, which includes removal of runners and sprues and any flash that may have occurred (Creese, 157)

There are several different types of molds, each with its own benefits and costs. Some are more cost-efficient, but produce a lower quality part, while others are more expensive and have a high lead time, but produce a higher quality part. Parts that are cast are generally not as strong as those that are created by other means. The most common ways of casting are: sand casting, permanent mold casting, investment casting, die casting, and plaster mold casting. Casting has several advantages over other primary processes, and thus will probably be utilized in this project. Some advantages include its ability to produce relatively complicated shapes, its ability to produce large products, its ability to be used with specific materials and alloys, and its relatively low cost (Creese, 161–165).

Machining

Machining is the shaping of a part through material removal. Machining is the most commonly used manufacturing process, mainly because it can be used as both a primary and secondary shaping process. The four basic types of machining operations are turning, drilling, milling, and shaping. Some benefits of machining are the ability to produce good surface finishes and part tolerances, as well as low-cost tooling and short lead times. However, production rates are slower and machine operator costs tend to be higher (Creese, 129).

In designing and choosing tools and fixtures, some important requirements are that it perform certain functions, meet precision requirements, have an acceptable working life, and be operated safely. Other important factors are keeping costs to a minimum, being available when needed, and possibly have some element of adaptability. Of course, the first element to be considered should always be safety, but it is especially important in the context of this project, seeing as students will little machining experience will be using the fixtures and tools (Society of Manufacturing Engineers 2003, 3).

When choosing tools for each machining step of this process, several factors will need to be taken into account. The type of machine used, the size of feature to be cut, and the surface roughness requirements of the feature to be created will determine tool size and type. Once a tool is chosen, feed speed, depth of cut, and rotations per minute will also need to be decided. The following equations will be of use in deciding these values, but testing and adjustment of these calculated values will also be an important part of the decision (Groover, 485, 496).

Equation 1: Material Removal Rate

$$MRR = vFd$$

MRR=material removal rate (in^3/min)

v=cutting speed (ft/min)

Equation 2: Unit Horsepower

$$HP_u = \frac{HP_c}{MRR}$$

HP_u=unit horsepower (hp)

Equation 3: Cutting Horsepower

$$HP_c = \frac{Fv}{33{,}000}$$

HP_c=cutting horsepower (hp)

F=cutting force (lb-f)

Generally, machining is associated with being a metal fabrication process. However, in some applications and for some purposes, plastic is also machined. For the water pump, plastic will be one of the materials used, and it will most likely be machined. While plastic is a much softer material than metal, and thus requires much less cutting forces and can withstand higher cutting speeds, certain problems are associated with machining plastics. One is that each type of plastic has its own unique machining characteristics, rendering typical modes of calculation of cutting speeds almost useless. Guidelines for machining plastics can be found in *TROUBLESHOOTING MANUFACTURING PROCESSES*, a technical manual provided by the Society of Manufacturing Engineers (Gillespie 1988, 2-93). Another major problem with machining plastics is excessive tool wear. A few guidelines to avoid tool wear are: reducing friction by using tools with polished surfaces, selecting tools with geometry that is conducive to generating continuous chips, and using twist drills with wide, polished flutes, low helix angles, and large

tool-point angles (El Walik 1989, 268–269). Plastics are generally relatively resilient when compared to metals, so stock material must be properly supported by proper tooling to minimize distortion due to cutting forces (Gillespie, 2-94).

Engineering Economics

A subdivision of design for manufacturing is design for cost, a factor that can make or break a project. Keeping costs low without sacrificing quality and durability will be an important part of this project. The retail price for pumps similar to the chosen pump generally range from $40 to $80, but since overhead, labor, sales, and other such costs will not need to be taken into account for this product, the actual cost will be much lower than this. Cal Poly is also currently the recipient of generous donations for various parts of the air motor, and discussion of the possibility of donating the required parts for the water pump will be imperative for keeping costs low.

Cost analysis for this project will not follow the typical costing analysis for manufacturing processes in the industry, because the product being made will not be sold and the direct labor will be done without pay. However, certain modes of costing analysis will still apply. Typically, the four categories that affect the cost of a product are direct material, direct labor, tooling and equipment, and indirect costs (Kalpakjian 1984, 760). For the purpose of this project, only direct material and tooling and equipment costs will be taken into account.

Direct material cost is the cost of raw material for the product. The cost of direct material will fluctuate with time, a factor that must be understood and taken into account. Another factor in the calculation of direct material cost is loss due to waste and defectives during the process. Waste may be estimated through calculation, but defectives must be estimated through

prior experience or experimentation. Also included in the direct material cost is the price of any component that is purchased partially or totally completed.

Tooling and equipment costs are the costs involved in making fixtures, purchasing tools, and upkeep of the machines. Fixture costs will only be affected by the type and amount of material used, seeing as students will be creating the fixtures with no pay. Calculation of the cost of tooling will depend on tool wear, which can be estimated once cutting conditions are selected, and tool breakage. The hardest sum to estimate will be the cost of machine upkeep, because the machines are also used by other classes for other purposes. An effective way of allocating this cost is the use of direct labor hours, in which the cost of machine upkeep for each month is averaged over the number of hours each machine is used in said month. The sum of tooling and equipment costs will seem high, but the cost of the tooling can be spread out over a projected amount of time.

Seeing as this project is a non-profit process, the overall goal with regards to finances is to break even. The unit cost of each completed pump can be calculated using a unit cost analysis chart, and the total cost for all of the students performing the project in a given quarter can be extrapolated from this. With this number and more detailed information about the economic resources and income available for this project, the economic feasibility of the water pump as a final project could be determined.

Computer Numerical Control (CNC)

An important advance in machining technology in the 1940s was the introduction of numerical control for machines, which more recently has developed into computer numerical control, or CNC. This project will incorporate CNC machining in several ways. CNC machining will be used

for tool and fixture making, any necessary mold making, and as a step in the process carried out by IME 143/144 students.

NC is defined as "the control of operation of machine tools by a series of coded instructions (El Walik 1989, 369). An NC machine is made up of two main components: the machine tool and the machine control unit, or MCU. The MCU contains the data processing unit and the control unit, which sends the instructions to the machine (Lal and Choudhury 2005, 305). There are several ways of generating the NC code, whether by hand or using computer software such as Pro/Manufacturing, the software used at Cal Poly. Numerical control is important because it makes it possible to pass the limits of human operators, automatically generating complex machine motions with precise accuracy. Using NC also reduces machining time through savings in setup time and tool changing time.

Machines set up with a CNC program are actually simpler to use than a manually operated machine, because all that is required of the operator is proper fixturing of the workpiece and pressing the "start" button. For this reason, it will be in the interest of time and accuracy to plan for one or more machining steps in the IME 143/144 final project to be machined using CNC.

Geometric Dimensioning and Tolerancing

In manufacturing, tighter tolerances almost always lead to higher cost. One major goal of a manufacturing engineer is to keep the tolerances as loose as possible without sacrificing product function or quality. Using the regular system of dimensioning and toleracing, some dimensions have unnecessarily tight tolerances due to tolerance accumulation. This is where the tolerance from one dimension builds up on subsequent dimensions. A common occurrence is in the

tolerancing of holes and guide pins. The tolerance on the hole position and size must be strict in order to ensure a fit with the pin. Unlike traditional dimensioning, the tolerance zone is not fixed but can be extended based on the position of other features. GD&T is bound by only two rules:

1. Perfect form at Max Material Condition (MMC)
2. Bonus tolerances

Rule 1 means that if the part is produced at MMC, there can be no variation in the form. For example, a long cylindrical rod is difficult to make absolutely straight. Rule 1 requires that if the rod is at the maximum diameter, then it must also be perfectly straight. However, if the diameter is less than the maximum, the rod is allowed to vary slightly in straightness within the "envelope" of MMC.

Rule 2 is a special case of GD&T. For certain tolerances, the deviation from MMC of one tolerance can be added to another tolerance making it less restrictive. For instance, when a hole is specified to mate with a pin, a variation in the position of the pin affects the size of the tolerance zone of the hole.

The full standard of GD&T is specified in *ASME Y14.5M-1994*.

Tool Design

Another important aspect of this process will be designing fixtures for several steps in the manufacturing process. The main functions of a fixture are: locating, holding, supporting. In designing a fixture, all degrees of freedom must be taken into account, measured, and held. A-symmetric pieces have six degrees of freedom, changing their orientation when spun in either direction along each of the x-, y-, and z-axes. To accurately locate a part, movement must be

restricted in all six degrees of freedom, all twelve directions. Avoiding redundant locators and angled locators will increase the effectiveness and accuracy of a fixture, as will allowing for easy chip and burr removal. Another useful feature to include in the design of a fixture is a fool-proofing feature, such as a pin or block that will prevent the piece from being inserted incorrectly into the fixture (Society of Manufacturing Engineers, 91–96, 109).

There are several different ways of locating, most of which are dependent upon the type of locating surfaces available, whether plane, concentric, radial, or a combination. A commonly used and very effective method of location is known as the 3-2-1 method, in which a workpiece is located by six pins, 3 in one axial direction, 2 in another, and 1 in the final direction. This method works best for items that are prism-like in shape. This method only locates, and once the piece is placed in the fixture, it must be clamped. Other useful methods of locating are the concentric and radial methods, both of which are used for workpieces that must be located by their center axis. This method locates the piece in such a way that it may rotate about one axis, and this axis is restricted by a clamping device. In conjunction with these methods, many different types of locators can be used, both internal and external. Examples of external locators are fixed locators, integral locators, commercial pins, assembled locators, V-type locators, locating nests, adjustable locators, sight locators, and internal locators. Examples of internal locators are machined internal locators, relieved locators, diamond pins, floating pins, conical locators, and self-adjusting locators (Society of Manufacturing Engineers, 94–109).

There are also many different ways of holding a workpiece in a fixture. The most important factor in choosing a clamp is its ability to hold against machining forces, but also very important is the cost of the clamp. Simple clamps are generally the best, seeing as they are

cheapest and do not lose effectiveness as they wear, although they may be slower to secure. Examples of clamp types are strap clamps, screw clamps, cam-action clamps, toggle-action clamps, wedge-action clamps, and specialty clamps. Not only is the type of clamp important, but also the placement of clamps. Clamping against the supporting surface of the fixture dampens vibrations and more strongly secures the workpiece. Clamping against thin sections is to be avoided, but if it must be done, support against the clamping forces should be provided (Society of Manufacturing Engineers, 109–124).

Another type of tool that could be useful to this project is tools for inspection and gaging. Several types of go/no go gages could be used for inspection in this manufacturing process, saving students' time by removing the need for tedious measurements. Plug gages and flush-pin gages are the most likely candidates for useful gages for this specific application. Generally, gages must be made of a hard material so that they do not wear with use, and some sort of allowance must be designed into the gage to prevent the workpiece from interfering with the gage (Society of Manufacturing Engineers, 272–274, 278).

Poka-Yoke

Poka-yoke means "mistake-proofing" in Japanese. It is a principle first developed by Shigeo Shingo, the famous industrial engineer and co-developer of the Toyota Production System. Poka-yoke is intended to make a manufacturing operation simple, intuitive, and impossible to do incorrectly. This can be accomplished by a variety of means, from placing alignment pins in a fixture that prevent a part from being loaded incorrectly, to symmetrically designed parts that can be assembled in any orientation removing the possibility of assembly error.

Single Minute Exchange of Dies (SMED)

Shigeo Shingo also developed the concept of Single Minute Exchange of Dies, or SMED, which aims to reduce the changeover time to be less than 10 minutes. When he implemented the process at Toyota in the 1970's, the changeover time for switching out the large dies that stamp automobile body panels was about four hours. After his recommendations were completed, the setup time was reduced to just three minutes. The fundamental breakthrough for Shingo was the classification of internal and external setup time. He separated the steps that could be done before or after the exchange—external—from those that had to be done during the changeover—internal. He also found that internal setup could sometimes be converted to external setup to further reduce machine down time while exchanging dies.

The main benefit of SMED is the ability to run small lot production and keep low inventory. Using SMED and other techniques, engineers at Toyota were able to get the economic lot size to be below one automobile, meaning that it was practical for their assembly line to produce different models in any order.

Design

In this section, the design details of the water pump will be discussed including some of the DFM changes we incorporated into the design.

Selection of the Pump

The first step in designing a solution for this project was to select a suitable product for the students to manufacture. After speaking with several people and narrowing down a long list of possibilities, a rotary water pump was finally chosen. The pump is not too complicated, yet simple enough to be of a reasonable scope for the IME143/144 classes. This specific pump was chosen because it was previously used for a project for the Appropriate Technologies for Developing Countries class. The Cal Poly students involved in this project designed a simple method for modifying the pump to be bicycle powered. As discussed in the literature review of this report, their tests of the pump showed satisfactory results. It was determined that the pump has sufficient power to be used in deep wells, which would be especially helpful in rural areas of developing nations.

The pump design is based on two rotary barrel pumps manufactured by Advanced Tool Design, Inc. The ATD 5009, which is made out of cast iron, was a preliminary resource that aided in the selection of this particular design. The ATD 5019, which is made of various types of plastic, was the pump primarily used for reference in the final pump design. Throughout the course of the project, many changes were made to increase the educational value of the pump as well as to increase manufacturability and cost-effectiveness. However, because this project is a not a fluid dynamics and pump design project, the critical dimensions of the pump that are

related to its performance were not altered. For the parts listing of each of the pumps, see the Appendix B: Bill of Materials on page 57.

Preliminary Process Plan

The redesign of the selected pump for the final project of the material removal classes began with a preliminary process plan. This plan was used as a basis for making decisions regarding such tasks as material selection, re-design for manufacturing, and geometric dimensioning and tolerancing. To create this plan, it was first decided which components would be purchased and which would be manufactured in the class. The current processes used for the Air Motor project were taken into account, and an inventory was made of all of the machines and methods available to the students. Unlike in a typical manufacturing setting, the goal of this project is to use as many machines and process types as possible so that the students may be exposed to many different methods of material removal. Therefore, many seemingly unnecessary steps were included in the plan, purely for the sake of education. The preliminary process plan was then formed based on all these factors. Following is the basic preliminary process plan.

Table 2: Preliminary Process Plan

Part	Material	Process	Machine
Fins (2)	Acetal Plastic (bars)	1. Face to size	Kent Vertical Mill
		2. Mill slot, drill hole	Kent Vertical Mill
		3. Mill angled faces	Kent Vertical Mill
Handle Arm	Aluminum (Possibly zinc alloy?) (bar)	1. Drill Hole	Kent Vertical Mill
		2. Broach Hole	Broacher
		3. Drill set screw hole w/ countersink	Kent Vertical Mill
Handle Grip	Acetal Plastic (rod)	1. Centerless grind to diameter	Centerless Grinder
		2. Drill and tap end hole	Drill press
		3. Chamfer ends	Lathe
Face Plates (2)	Zinc-Aluminum Alloy (casting)	1. CNC machine back side: Face, mill o-ring slot, mill out center holes	Haas Mini Mill
		2. CNC machine front side:Cut top "cake" shape, drill 5 holes	Haas Mini Mill
Center Shaft	Acetal Plastic (rod)	1. Face to length	LeBlonde Lathe
		2. Turn varying diameters	LeBlonde Lathe
		3. Mill flat	Kent Vertical Mill
		4. Mill slot through	Kent Vertical Mill
Pump Body	Zinc-Aluminum Alloy (casting)	1. Face both sides	LeBlonde Lathe
		2. Drill pipe holes?, thread inner holes	Lathe?
		3.Turn center hole to size	CNC Lathe
		4. CNC machine: Drill bolt holes, Mill o-ring groove	Haas Mini Mill

Materials Selection

The part of the preliminary process design creation was dictating the materials that would be used for each component of the pump. The three parts that would be donated as castings of near net shape would be a zinc-aluminum alloy dictated by the generous donors of the castings. For the handle arm, standard 6061 aluminum was chosen based on its machinability and strength. For the other four components a plastic called Delrin was selected. Delrin has many desirable characteristics, including the fact that it is easily machinable due to its self-lubricating properties. Delrin is also FDA approved for use with ingested goods, and is relatively strong and durable. Finally, the purchase parts needed to be selected. Springs, steel pins, and two sizes of rubber O-rings were ordered to fit the specifications of the pump.

DFM, DFA, DFE Considerations

Once materials for each component of the pump were selected, the pump needed to be slightly re-designed to fit certain needs and parameters. As previously mentioned, possibly the most important aspect of the pump is the educational value that it has. Therefore, Design for Education was a very important consideration when re-designing the pump: certain features were added or changed that allowed for use of a variety of the tools in the materials removal lab. Also considered for each part were design for manufacturing, design for assembly, and design for cost. Following is a list of the modifications made and justifications for each.

Modifications of each component:

Here the specific changes will be listed in bullets for each part of the water pump.

Main Body

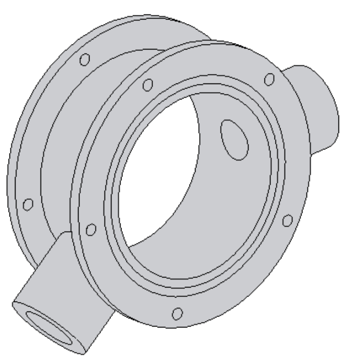

Figure 1: Main Body

- Material selected: 6061 Aluminum
- Name changed from "Pump Casting"
- Part cast to near net shape, with machining only necessary for purposes of precision and surface finish.

- Connecting pipe shafts oriented radially as opposed to parallel to each other. This promotes ease of design and ease of hole locating.
- Outer feature on connecting pipe shafts removed. For a zinc-aluminum pump, these features would be primarily aesthetic. Removing them decreases amount of material used and increases ease of mold design.
- Small slot added for O-ring.

Face plates

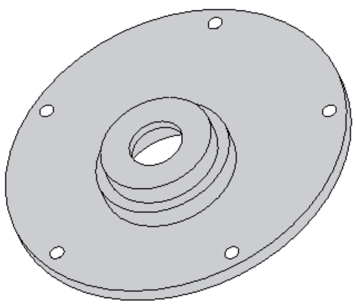

Figure 2: Face Plate

- Material selected: 6061 Aluminum
- Name changed from "Cover Plates"
- Cast to somewhat near net shape. While finished part had features that are off center, the casting would be a symmetrical part. This increases ease of mold design and ease of location for machining purposes, as well as decreases possibility of part being loaded incorrectly into the machine.
- Changed so that the face plates are the same design, as opposed to two different designs. This increases the efficiency of the process as well as decreases the chance of incorrect loading of the part

- Number of holes for bolting to main body decreased from 10 to 5. This decreases cycle time, decreases assembly time, and requires that less bolts be purchased, decreasing costs.
- Small slot added for O-ring. This replaces a full gasket, which is more expensive to purchase and would need to be modified for use with this pump.
- Thickness of plates decreased. Because zinc-aluminum is stronger, more expensive, and heavier than plastic, it would be beneficial to use less material for each plate.
- Webbing originally for plastic molding purposes removed.

Center Shaft

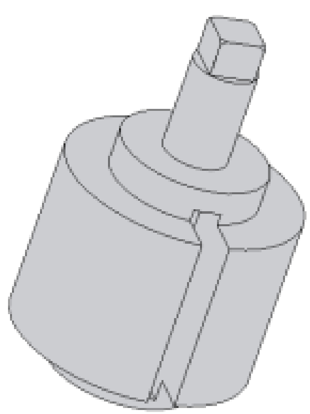

Figure 3: Center Shaft

- Material Selected: Delrin
- Name changed from "Shaft"
- Dimension change made to accommodate fins.
- Redesigned connection to handle arm

Fins

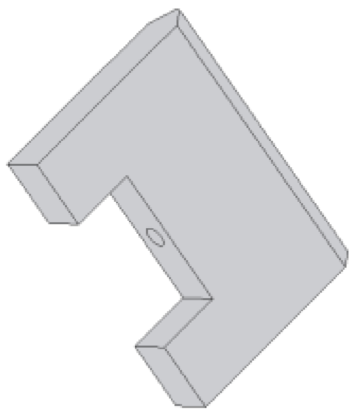

Figure 4: Fin

- Material Selected: Delrin
- Name changed from "Impellers"
- Slight dimension change made. This allows for purchase of a standard size of stock material.

Handle Arm

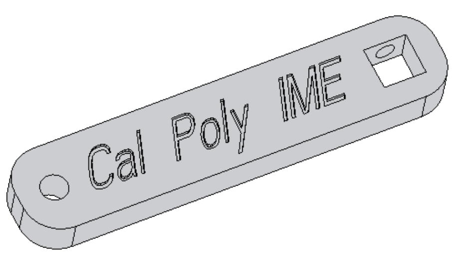

Figure 5: Handle Arm

- Material selected: 6061 aluminum
- Name changed from "Handle"
- Shape changed to a rectangle. This is simpler to cut on a mill.
- Broached hole selected to include broacher in process.

- Method of attachment to handle grip changed.

Handle Grip

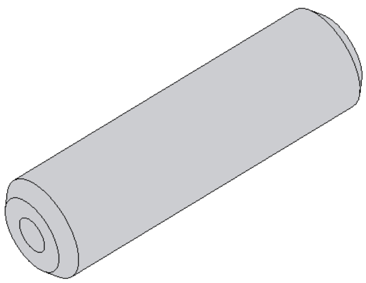

Figure 6: Handle Grip

- Material selected: Delrin
- Name changed from "Plastic Grip"
- Made cylindrical for use with centerless grinder.
- Chamfers added to include hand-lathing in process.
- Method of attachment to handle arm changed. Eliminates need for special boring tool.

O-rings

- Material selected: Silicone
- Size selected to be between core diameter and bolt holes on main body
- Original design had no O-rings, used packing instead (thin plastic gasket)
- Silicone selected due to good chemical resistance and resistance to ozone cracking

Rubber Bushing

- Material selected: Aramid/Buna-N composite
- Bushing seals hole in face plate where center shaft protrudes
- Material exhibits good abrasion resistance and excellent sealing properties

Handle Grip Bolt

- Material selected: 18-8 Stainless Steel
- Size selected based on handle grip and handle arm.
- Material selected as trade-off between cost and corrosion resistance

Small Bolts

- Material selected: 18-8 Stainless Steel
- Bolt for securement of handle arm to center shaft selected to be same as all other small bolts used

Small Nuts

- Material selected: 18-8 Stainless Steel

Spring

- Material selected: 302 Stainless Steel

Guide Rod

- Material selected: Aluminum wire

Modeling the Pump in Pro/Engineer, GD&T

After making modifications of the pump design, the part was modeled using the computer aided design (CAD) software Pro/ENGINEER. The modeling was done based on the dimensions of the pre-manufactured pump that was originally chosen for the subject of the project, and the aforementioned design changes were included. Also taken into account while modeling the parts was geometric dimensioning and tolerancing. The parts were modeled based on the planned processes, with features created in a similar way to the processes in actual production. For example, if a diameter is going to be turned on the lathe, the component was originally modeled to a larger diameter and then a sweep cut was performed to model the part to size. This technique will help future students who are working on the project in the design and modeling process of special tooling and fixturing for the component. It was also a crucial component of this project because it enabled the creation of intermediate part drawings for all of the operation sheets.

Once the parts were modeled, technical drawings were created of each part. These drawings can be seen in Appendix C: Engineering Drawings beginning on page 55. GD&T was applied to the part designs to identify the most important datums and part features. When tooling is designed for the parts, the GD&T specifications will enable an easy transition from the part drawing to a functional fixture that properly locates the part. In this project, the tolerancing component of GD&T was not fully implemented on each part due in to the use of an existing design and consequently being unfamiliar with the required tolerances. Nevertheless, applying GD&T to identify the important datums is still a valuable and necessary step in this project.

Methodology

Speaking with Stakeholders

An important resource for the research and background for this project was the people who are currently involved with the class project itself. Much of the needed information was gathered by talking one-on-one with a variety of stakeholders in the project, including professors, donors, and people involved in the department's finances. Rod Hoadley, who has been teaching the IME 144 lab for several years, and who is very involved in the project's evolution and success, was the primary resource for information on the class itself. For economic information regarding the class and student enrollment, Stephanie Allen was an important resource.

Some of the parts for the air motor are donated by a die-casting company owned by an alumnus. Through Martin Koch, the company was contacted and expressed their willingness to help out however they could. It was originally intended that they could assist with designing molds for some of the water pump parts. Due to time conflicts throughout the project, that never came to fruition.

Contacting Lifewater International

Another important aspect of making this project relevant is building a relationship with a non-profit organization. If the pump cannot be donated to people who will use it, then making the change from the Air Motor Project will be irrelevant. Preliminary contact was made with Lifewater International, and an interest was expressed in the pumps. Because these pumps can easily be modified for use with a bicycle, they have potential to be powerful enough to be used for deep wells in developing nations. It is hoped that future Cal Poly students will create a

simple plan for modification of the pump, making the pump even more appealing to a non-profit organization. However, no concrete plans to donate the pumps can be discussed until the proposal to implement the project is accepted.

Student Survey

One of the assumptions that led to the development of this project was that the air motor served as nothing but a trophy for students, maybe even less. To verify this assumption, a short survey was created and distributed via an email link to students in Industrial & Manufacturing, Aerospace, and Mechanical Engineering.

The survey consisted of three questions:

1. Have you taken IME 143 or IME 144?
   a. Yes
   b. No
2. If so, where is your Air Motor now?
   a. On my desk / in my office
   b. In my closet or garage
   c. In the trash
   d. Who knows?
3. What is your major?
   a. IE/Mfg
   b. Aero
   c. Mechanical

The answers in the first two questions were presented to the respondents in random order to mitigate the effect of the order on the selection of a particular answer. The survey received 384 responses, although a limitation of the survey service allowed only the first 100 responses to be viewed. Of the first 100 responses, 56 respondents have the air motor on display in their office or on their desk. That means almost half have done something else with their air motor like the

three respondents who have thrown away their air motor, and admitted it. A pie chart of the results of the survey is shown below in Figure 7.

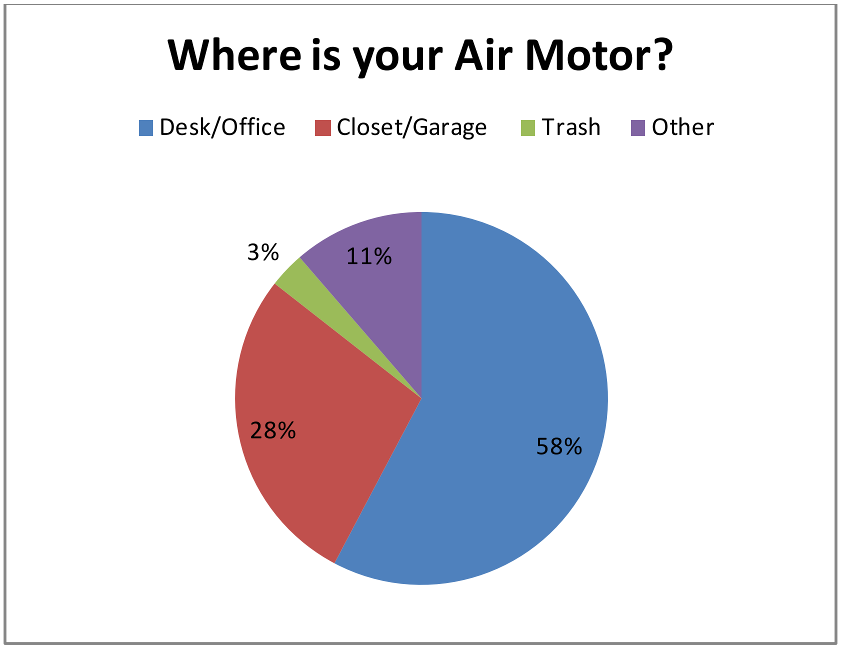

Figure 7: Survey Results

The survey was created on SurveyMonkey.com and can be found at https://www.surveymonkey.com/MyCollector_Detail.aspx?sm=ZquiMWAZL1e00pBUSEoufsIQOhywm4bIWuW3hquS7tDwTNT4nif9DLNtD4frET8Y.

Creating the Prototype

Following the preliminary process plan to create the first prototype of the proposed water pump was an integral part of this project. Actually manufacturing the prototype aided in the understanding of the various processes used and helped identify any large problems with the preliminary process plan. The steps in this process included ordering stock material, writing computer numerical control (CNC) code, and machining the various features of each component.

Ordering Stock Material

One challenge posed by this project was the need to create a prototype from different stock material than is proposed for the classes. The scope and time limits on the project did not allow for the creation of molds with which to cast the needed stock material, and so it was decided that bar stock aluminum and bar stock Delrin would be used for creating the prototypes. The barstock material was first machined to be close to the shape expected from molds so that the process plan could be followed as closely as possible. The purpose of the prototype was to test the process plan, so it would have been meaningless to just complete a pump using other means.

Additionally, there were other materials that needed to be purchased for the prototype. This included O-rings and bushings, which have to be purchased in specific lot sizes. All of these factors drove the cost of the prototype up, although in the quantities that could be expected in the IME 143/144 classes, the unit cost would be substantially lower. A complete cost analysis can be found on page 43 in the Methodology section.

Writing CNC Code

The procedure of writing CNC code was also affected by the difference between the prototype and the actual proposed pump. Several features had to be machined that in the proposed plan would be cast. Also, the rectangular fins had to be machined out of round bar stock. Nonetheless, much valuable and applicable code was created in the process. A computer aided manufacturing (CAM) software called Pro/Manufacturer was used to design the CNC programs for machining the face plates, main body, and handle arm. All three of these parts were made out of stock 6061 aluminum, and the machine settings (such as speeds and feeds) were calculated based on the equations in the literature review section of this report. Once the CNC code was

created, a post-processor was used to translate it into G-code, which is compatible with all Haas machines. Alterations were made and notes were included. For the full G-code used for each of the parts, see Appendix G: CNC Code on page 102.

The CNC machines found in both the undergraduate lab as well as in the advanced machining lab—where most of the prototype was fabricated—are all manufactured by Haas, Inc. Manufacturers of CNC machines often adapt the set of CNC codes for their particular brand. Before running the CNC code contained in this project, verify that all G and M-Codes match with those of the specific manufacturer, or else some adaptation will be necessary.

CNC Machining

Several factors made the actual machining processes for the prototype different from the proposed processes. However, the main goal of creating the prototype was achieved: understanding different difficulties with the process and the design of the pump. Each component of the pump posed its own challenges, but the final prototype was successful.

The first components to be machined were the face plates. This was particularly challenging without the benefit of a specialized fixture, because the face plates are round and designed to be located with the use of a customized tool. After a few trials, the parts were located and secured successfully enough to create finished components within tolerance. Various methods were used, including soft jaws and modular fixturing. For the prototype, the two face plates are different, but in the final process plan they are the same. This difference was due to several factors, including the availability of raw materials.

Next, the main body of the pump was machined. This was the component with a machining process that varied most from the proposed process. Because the stock material was

nowhere near the net shape of the final part, much machining time was needed to cut away unnecessary material. The proposed process would be performed on a near net shape casting, with only minimal machining to give the part specific dimensions and surface finish on critical features. Another challenge was locating the part in the machine without a specialized feature. Creating a specialized fixture would have been too time-consuming, especially because the fixture would not have been used again. The location of the part had to be approximate, and this resulted in a part that was far from perfect, but served its purpose.

The last feature to be machined for the main body was the outside profile. Once again, this is a process that would be unneeded in the proposed project, but in order to make a working prototype, these features had to be machined. The best method for doing this would have included the use of the 4th axis in the CNC mill, but this was not possible due to several factors, and so the features were machined with a standard 3-axis mill. The unique code needed for this shape was challenging to produce, but was finally successfully created. Fixturing the part for machining posed several challenges, and resulted in an unfortunate gash in the outside of the part, but in the end the main body was acceptably machined. Finally, the handle arm was machined. Because of this component's simplicity, the standard vice and a very short CNC program produced a near perfect part.

Other Machining Processes

For some of the prototype parts, it was impossible or impractical to use the process that is intended for the class project. One case was with the handle grip, which is expected to use a centerless grinder to remove a very thin layer from the diameter of Delrin barstock. The stock purchased for the prototype was 3" in diameter while the handle grip is to be 1.5". The stock

was much too large to fit into the grinder, and due to how the grinder functions, it would have to be re-setup for every change in diameter. The setup is a long complicated process, and the grinder had to remain in service for the ongoing classes. So, the Delrin stock was turned on a lathe to the required dimensions with no further processing.

Another instance where this was the case was with the square hole in the handle arm. To make perfectly square holes requires the use of a broach, which the project specifies using. However, a broaching tool presented a significant cost that could not be justified for a prototype run. Instead, the square shape will be approximated as closely as possible with a small diameter end mill.

Finalizing the Process Design

Once the production of the prototype was under way, the process plan began to be finalized. Many needed changes to the preliminary plan were recognized, and the necessary adjustments began to be formed and solidified. Following is the summarized proposed process plan. The expanded proposed process plan can be seen in Appendix D: Process Plan on page 66 while a condensed version appears below.

Table 3: Final Process Plan

Part #	Part Name	Material	Process	Machine
1	Fins (2)	Acetal Plastic (bar)	1. Face to size	Kent Vertical Mill
			2. Mill slot, drill hole	Kent Vertical Mill
			3. Mill angled faces	Kent Vertical Mill
2	Handle Arm	60-61 Aluminum (bar)	1. CNC mill back side	Kent Vertical Mill
			2. CNC mill front side	Kent Vertical Mill
			3. Broach Hole	Broacher
			4. Drill set screw hole w/ countersink	Kent Vertical Mill
3	Handle Grip	Acetal Plastic (rod)	1. Cut to length	Bandsaw
			2. Centerless grind to diameter	Centerless grinder
			3. Drill and tap end hole	Drill press
			4. Chamfer ends	Lathe
4	Face Plates (2)	Zinc-Aluminum Alloy (casting)	1. CNC machine back side: Face, mill o-ring slot, mill out center holes, drill 5 holes	Haas Mini Mill
			2. CNC machine front side: Cut top "cake" shape, face plate to thickness	Haas Mini Mill
5	Center Shaft	Acetal Plastic (rod)	1. Face to length	LeBlonde Lathe
			2. Turn varying diameters (side 1)	LeBlonde Lathe
			3. Turn varying diameters (side 2)	LeBlonde Lathe
			4. Mill flats	Kent Vertical Mill
			5. Mill slot through (both sides)	Kent Vertical Mill
6	Pump Body	Zinc-Aluminum Alloy (casting)	1. Face both sides	LeBlonde Lathe
			2. Drill pipe holes to size, thread holes	Lathe?***
			3.CNC Lathe (both sides): Turn center hole to size	CNC Lathe
			4. CNC Mill (both sides): Drill 5 holes, cut o-ring groove	Kent Vertical Mill

Operation and Routing Sheets

Once the process plan was relatively set, the development of operation and routing sheets was the next step. An operation sheet lists all of the machining parameters for a specific operation and provides an engineering drawing that shows how a part will look once that step is completed. The operation sheet also contains time estimates for setup and cycle times. The routing sheet lists all the operations for a specific part in order. It lists the setup and cycle times from the operation sheets, but also incorporates the accumulated cost at each operation. The operation and routing sheets for all the manufactured parts of the pump can be found beginning on page 68 in Appendix E: Operation and Routing Sheets.

Cost Analysis

Since this project presents an alternative to an existing case, the cost analysis is conducted to show the additional savings or expense compared to the base case. Since this is essentially a subtraction, all the cost factors that remain unchanged will cancel out of the equations. With this in mind, some assumptions were made to simplify the cost analysis. Next, a bill of materials (BOM) was compiled that listed, among other things, each part that is needed for the water pump, the quantity required, and the unit cost.

Assumptions

One of the biggest assumptions that was made with respect to cost is that the castings for the water pump--the main body and face plates--would be donated by the company that donates some of the air motor parts. This may not be an entirely valid assumption due to the difference in size and the need for expensive molds. Nevertheless, the company did express their willingness to help with the project.

One of the factors that is expected to remain unchanged is the operating overhead of running the machining lab. This includes electricity, maintenance, and administrative costs. Since the class meets a specific number of times per quarter, the overhead is basically fixed. This project cannot take any more time than is allotted by the class schedule. Similarly, the cost of the professor will remain unchanged regardless of which project the class undertakes.

The final assumption in the cost analysis is that the cost of tools (except fixtures) will be similar between the two projects. While the projects do not necessarily use the same tools, the cost of tooling can be roughly estimated by the run time of the machines. Since the class period is fixed, this is likely to be very similar.

Costs Not Considered

Some costs, such as the cost of fixtures have been generally ignored in this cost analysis. The reason is that the fixtures will have a long life and overtime, the fraction of fixture cost to number of parts produced becomes smaller. Since there was no fixture design conducted in this project, the initial cost of the fixtures, nor the expected life, can be estimated.

Bill of Materials

The BOM for the water pump is shown in Table 4 below. What is strikingly evident is the overwhelming disparity between the cost of the center shaft to every other part. Over half of the purchased material cost is attributed to the center shaft. This is one area that could benefit most from a redesign. An expanded BOM can be found in Appendix B: Bill of Materials on page 57; it additionally lists product numbers and order quantities from McMaster-Carr.

Table 4: Bill of Materials

Part	Units	Unit Cost	Total Cost	Material
Main Body	1	$-	$-	Aluminum 6061
End Plate A	1	$-	$-	Aluminum 6061
End Plate B	1	$-	$-	Aluminum 6061
Center Shaft	1	$17.05	$17.05	Delrin Copolymer
Fin	2	$1.49	$2.99	Delrin
Handle Arm	1	$2.70	$2.70	Aluminum 6061
Handle Grip	1	$0.60	$0.60	Delrin
Grip Bolt	1	$0.36	$0.36	18-8 Stainless Steel
Bolt	11	$0.10	$1.05	18-8 Stainless Steel
Nut	10	$0.04	$0.43	18-8 Stainless Steel
Spring	1	$0.30	$0.30	302 Stainless Steel
Guide Rod	1	$0.06	$0.06	Aluminum Wire
O-Ring	2	$1.55	$3.09	Silicone
Seal	1	$1.67	$1.67	Aramid/Buna-N
		Total	$30.28	

Current Costs

In the 2009–2010 school year, 355 students enrolled in IME 143 and 258 in IME 144. To take the class, each student in IME 143 is charged a $10 lab fee on top of tuition, and each student in IME 144 is charged $50. This generated a total revenue stream of $16,450 for the year, which equates to about $26 per student. The air motor project takes place over the last two weeks or so of the quarter, however it cannot be assumed that the cost is spread evenly. While it is not exactly known how much is spent specifically on the air motor, it can be safely assumed that at least half of the lab fees are spent on the air motor.

Cost Comparison

By comparing the average lab fee to the material cost from the water pump BOM, it is clear that producing one pump per student is not financially viable. However, it can be contended that since the water pump is larger and more complicated than the air motor, the water pumps could be made one per two students, perhaps even one to three. In these cases, the per-student cost is at least in the range of the air motor materials.

Results

Creation of the prototype was crucial to understanding the difficulties involved in creating a system of mass production for students to perform. The preliminary process plan did not take into account many unforeseen factors and challenges. The final proposed process plan is more feasible, however there still is room for improvement. While the scope of this project did not encompass implementation of the proposed project into the classes, it nevertheless had to take into account the limitations of the classroom and present a usable process plan. The final process plan fulfills all of the requirements set at the beginning of the project:

- It revolves around a product that is relatively simple to manufacture, assemble, and operate.
- It revolves around a product that is useful and has potential to be donated to a nonprofit organization for use in developing nations.
- It involves almost all of the machining processes available in the IME 143/144 lab.
- It has a reasonable number of operations that can be learned and performed by students in approximately 12 hours of laboratory time.
- It involves a variety of materials.

Pictures of the prototype and its creation can be found in Appendix F: Pictures on page 97.

The plan, however, is not perfect. Changing the final project for these classes will be a much bigger undertaking than originally estimated, and the number of details involved in planning the process for "classroom production" could not be adequately addressed in this project.

Problems Encountered

The biggest problem encountered in this project was scope creep. The original scope of the project was much too large, and as time passed, it underwent several modifications before reaching a reasonable state. It was originally intended that this project would include research, process design, tool and fixture design, mold design, implementation proposal, and actual implementation of the new product into the IME 143/144 curriculum. It soon became evident that this was not a practicable amount of work for two people to perform over the course of two quarters, and the scope of the project had to be reduced significantly.

The primary challenge related to the subject matter of the project itself was the educational aspect of the manufacturing process. As mentioned previously, the requirements for the process design are almost the opposite of what is normally desired in a production line. As many machining processes as possible had to be included in the production, yet there is a time limit on the process. Balancing the limited amount of time that students have to complete this project with the high number of necessarily simplistic operations was a very large challenge. Another limiting factor that will affect the future of this project is the cost effectiveness of both the proposed design and the proposed change. Implementation of this new product will itself be very time-consuming and expensive, and since the proposed project is not significantly less costly than the current project, the chance of implementation may be low.

Creating the first prototype also posed a variety of problems. The most prominent was the infeasibility of using the same stock materials being proposed for the final project performed by IME 143/144 students. Custom cast parts and a variety of sizes and shapes of aluminum and Delrin were not readily available to us due to cost and time constraints. Thus, the

process of creating the prototype was not only very different from the proposed method, it was more time-consuming and required creative methods of machining to complete. Another downside of this challenge is that much of the CNC code created will not be very useful for machining in the actual project. It was also more challenging and time-consuming than expected to write the CNC code for each of the individual components, and many adjustments had to be made at the machine during the machining process.

The prototype, while not perfect, gives a good enough understanding of the manufacturing processes required to create the pump. Several challenges, such as fixturing the prototype, led to a realization of how important appropriate fixturing and tooling are for a good manufacturing process. The pump itself is a more complicated item than the current air motor, and thus would take more time to create. However, with some changes to the structure of the class and the organization of students into teams, creating this pump in the IME 143/144 class is very feasible. The biggest problems encountered while creating the prototype had to do with features that, due to the different stock material being used, will not be a concern in the actual class. Also, the prototype is not 100% within the specified tolerances, yet it can still be assembled and is functional. This is a very important discovery, because students in the class will not be producing perfect parts every time.

Conclusion

For over many years, hundreds of students each year have manufactured an air motor in IME 143 or IME 144, the freshman-level machining courses for undergraduate engineers. While the air motor has been a useful tool to demonstrate a wide variety of machining processes, it finishes its useful life at the end of the quarter. Besides its use in the class, the air motor is arguably a waste of valuable machining time. Time which could be spent manufacturing products that may have an impact on the lives of people in developing countries, without sacrificing any of the educational benefit of the class project. This was the ultimate purpose of this project.

From the onset, two main goals were set. The project was intended primarily to select an appropriate alternative product, and design a basic process plan for its manufacture. Both of these goals had to be framed by the capabilities and limitations of both the machines available in the machining lab and the students who will operate them. During the product selection phase, additional consideration was given to products that could be donated to people in need.

After selecting a rotary barrel pump, the next step was to break down the product into not only its subsequent parts, but to assign a specific manufacturing process to each part feature. Due to the time limitation, and educational intention of the class, the optimal process may or may not have been selected for each feature. In many cases creative work-arounds and slight design changes had to be made to ensure certain processes would be included in the final process plan.

After the development of a preliminary process plan, research into different materials was conducted. The materials had to balance cost with functionality, machinability, and

reliability. Recognizing the potential for bad seals between the face plates and main body of the pump, the decision was made to include O-rings in the design. Under normal circumstances, O-rings are very standardized and some materials are very cheap. However, considering that the pumps may be sent to a developing country, O-rings made of silicone were ultimately selected for the final product. Silicone, unlike most other rubbers, is not susceptible to ozone cracking, and should not require replacement, but this convenience comes at a slight premium.

With a basic process plan and the selected materials, a prototype was manufactured to test the process plan, discover any design flaws, and to have a physical representation of the product to garner support.

The completion of the prototype was a validation of all the work that has been done up to this point. The final product meets all of the criteria that were set. It has few parts (8 manufactured), is simple to assemble and operate, can incorporate both metal and plastic machining, and can be manufactured almost exclusively by machining.

After analyzing the cost of the project in comparison to the air motor, the water pump is significantly more costly. However, it is recommended that rather than making one product per student like the air motor, the water pump should be made one pump for every two students. This cuts the per-student cost in half allowing the project to be cost competitive with the air motor and allocates more time per unit to manufacturing.

Based on the results of this project, it is recommended that the department investigates this alternative and encourages continued student effort to implement the project into the IME 143 and 144 classes. A formal proposal is included in Appendix A: Proposal to Implement on page 55.

Before the water pump can be integrated into the classroom, there are some additional tasks that must be completed. It is hoped that this project will be continued to bring it to completion. Some of the remaining tasks are:

- Tooling and fixture design
- Development of quality limits and appropriate gaging
- Mold design
- Writing production CNC code
- Rewriting the class lab manual
- Petitioning the IME Department to update the class
- Development of a relationship with a non-profit organization

There is certainly enough work left for students to do as a senior project. It is hoped that someone continues to develop this project to facilitate the project switch.

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Appendix A: Proposal to Implement

The IME 143/144 Class (Materials Removal) is class taken by most engineers at Cal Poly, and is critical to forming a basic understanding of the manufacturing process. For many of these students, the final project in this class is the most hands-on post-design experience that they will receive in their college career. The current final project, an air-powered motor, has little use beyond the classroom. While creating the air motor is a learning experience for students, 43% of survey respondents stated that after they receive their grade the motor ends up in storage or in the trash. Even those who display their motor primarily use it as a paperweight.

The final project of the materials removal classes at Cal Poly is a greatly untapped resource. At a standard of 6 to 8 classes per quarter and an average of 20 students per class, up to 500 final projects are made each year. Imagine the good that could be done if each of these projects was a useful item that could be utilized by the student or, better yet, donated to a nonprofit organization.

This proposal will summarize and describe the process to change the air motor final project to a hand-crank water pump. This particular pump was selected for several reasons. One, it is a standard pump that is efficient and commonly used with 50 gallon tanks. Two, it can be modified to be used with a bicycle for more pumping power, and thus can be used to pump water from deep wells. Three, the pump fits the basic criteria for the needs of the class:

- Has a manageable number of components (6 distinct components, 8 total)
- Is simple to assemble and operate
- Requires machining to manufacture
- Can be fabricated out of a combination of metal and plastics

- Is not too large, simply for logistical reasons
- Does not require welding to manufacture

Once the basic pump design was selected, several alterations were made, taking into account geometric dimensioning and tolerancing as well as design for manufacturing, education, assembly, and cost. A unique aspect of the design of this pump is that a large variety of processes must be used to manufacture it. The students in the class should be exposed to as many of the machines and processes available to them as possible to enhance their learning experience. Thus, while design for manufacture generally focuses on decreasing the number of processes necessary, in this setting design for manufacture meant that all the components of the pump combined should use all fourteen types of processes available in the IME143/144 lab.

Beginning with a preliminary process plan and creating a prototype based on this plan was the next step in the process. The prototype was of course not created with exactly the same processes that are being proposed for the class, but going through the necessary steps helped determine flaws in the plan and assisted in creating a greater overall understanding of the process itself.

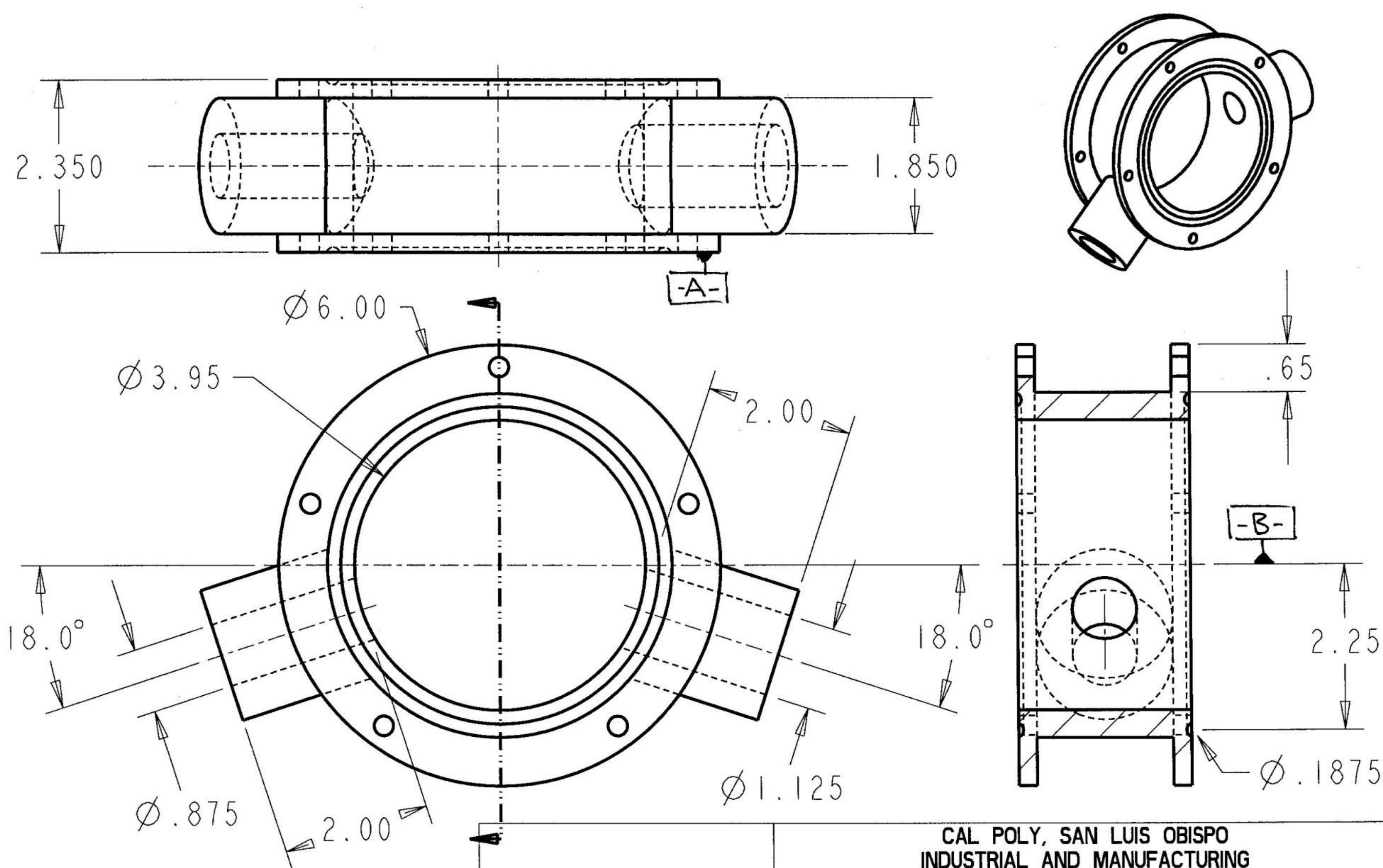
From a cost perspective, the water pump as specified in this report will cost about $15 per student and yield one pump for every two students. There is not a direct cost breakdown that shows how much the department spends on the air motor, but based on the class fees and enrollment levels, the actual cost of the air motors is in the range of $10–$20. Therefore, the water pump project should be competitive with the air motor on cost.

Appendix B: Bill of Materials

Part	Units	Unit Cost	Total Cost	Order Quantity	SKU	Material
Main Body	1	$ -	$ -			Aluminum 6061
Face Plate A	1	$ -	$ -			Aluminum 6061
Face Plate B	1	$ -	$ -			Aluminum 6061
Center Shaft	1	$ 17.0450	$ 17.0450	1	8497K491	Delrin Copolymer
Fin	2	$ 1.4938	$ 2.9875		8739K87	Delrin
Handle Arm	1	$ 2.6950	$ 2.6950	6	4490T21	Aluminum 6061
Handle Grip	1	$ 0.5967	$ 0.5967	15	8572K25	Delrin
Grip Bolt	1	$ 0.3568	$ 0.3568	25	92198A628	18-8 Stainless Steel
Bolt	11	$ 0.0959	$ 1.0549	100	92240A540	18-8 Stainless Steel
Nut	10	$ 0.0431	$ 0.4310	100	91845A029	18-8 Stainless Steel
Spring	1	$ 0.2962	$ 0.2962	50	9663K15	302 Stainless Steel
Guide Rod	1	$ 0.0567	$ 0.0567	316.8	8904K75	Aluminum Wire
O-Ring	2	$ 1.5460	$ 3.0920	5	9396K235	Silicone
Seal	1	$ 1.6660	$ 1.6660	5	93303A111	Aramid/Buna-N
Total			$ 30.2778			

Appendix C: Engineering Drawings

The following are engineering drawings of the manufactured parts of the water pump with GD&T datums.



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES IN ACCORDANCE WITH ASME Y14.5M-1994

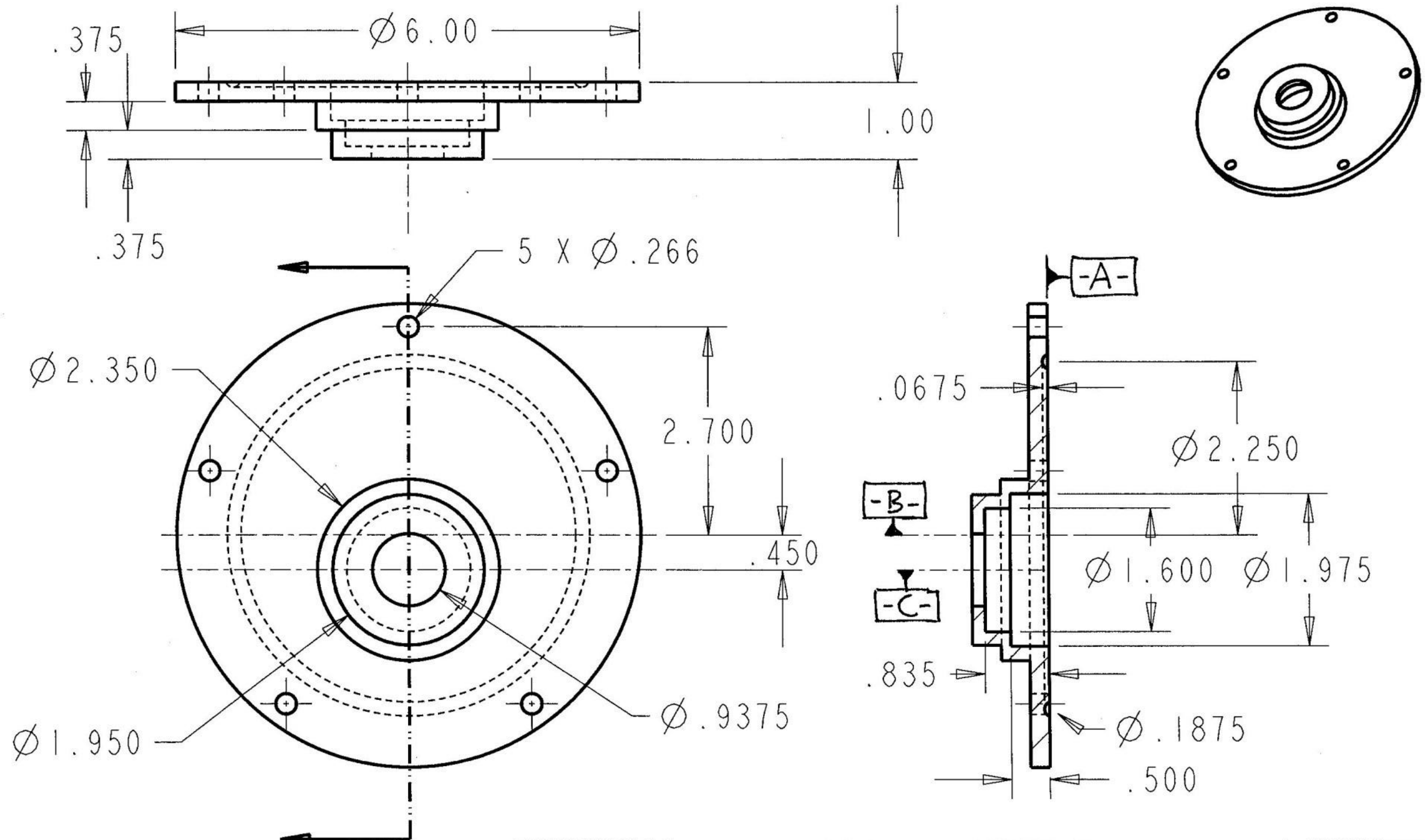
TOLERANCES:
.X ± .1
.XX ± .01
.XXX ± .005
ANG ± 1°

DRAWN BY: Shackelford
APPROVED BY:
DATE: 4/26/10

CAL POLY, SAN LUIS OBISPO
INDUSTRIAL AND MANUFACTURING
ENGINEERING DEPARTMENT

Main Body

SIZE	FSCM NO	DWG NO	REV
A	N/A	1	1.0
SCALE .5	AL ALLOY	SHEET 1	



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TOLERANCES:
.X ± .1
.XX ± .01
.XXX ± .005
ANG ± 1°

DRAWN BY: Shackelford

APPROVED BY:

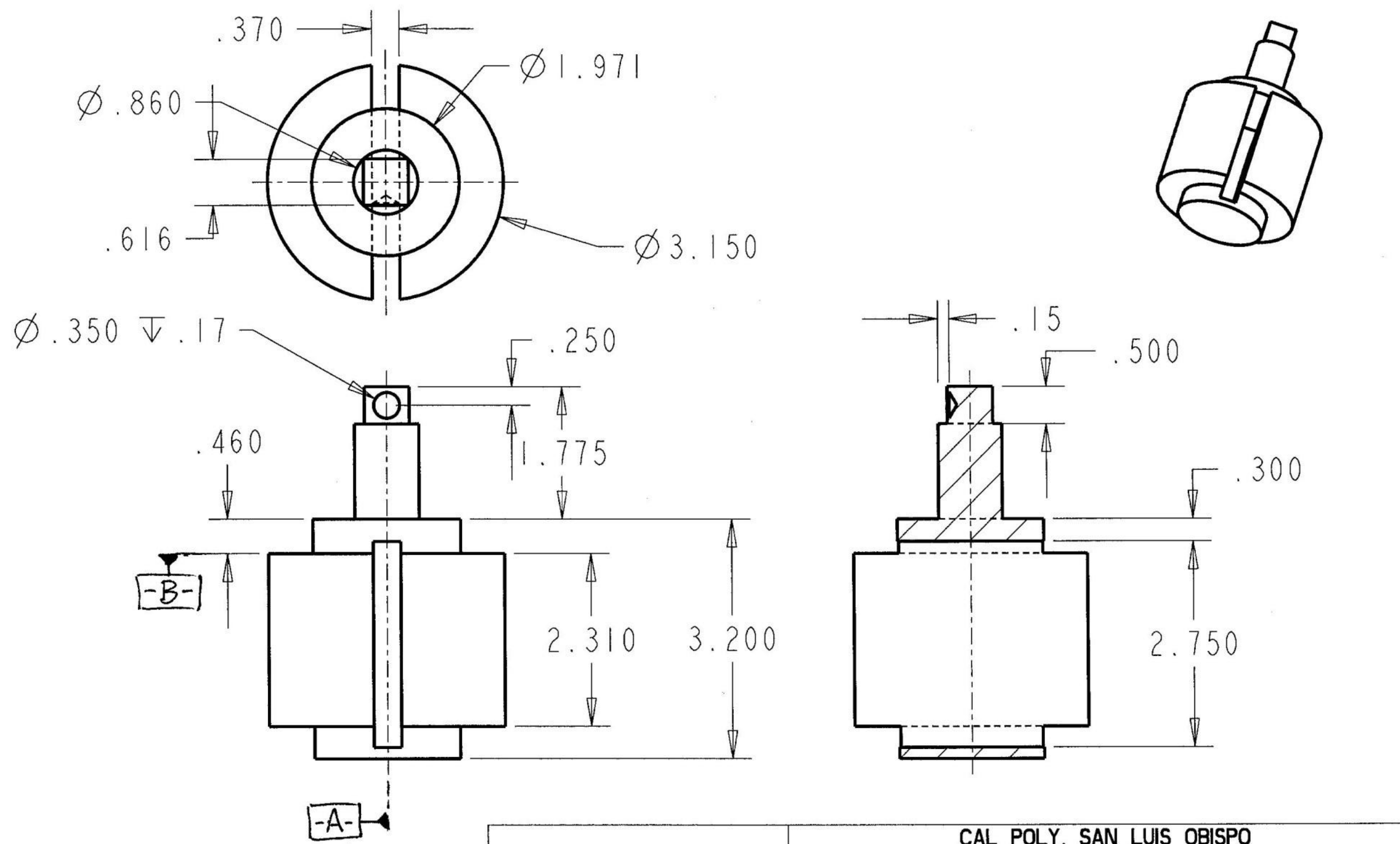
DATE: 4/23/10

CAL POLY, SAN LUIS OBISPO
INDUSTRIAL AND MANUFACTURING ENGINEERING DEPARTMENT

Face Plate

SIZE	FSCM NO	DWG NO	REV
A	N/A	1	1.0

SCALE .5 | AL ALLOY | SHEET 1



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TOLERANCES:
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DRAWN BY: Shackelford	CAL POLY, SAN LUIS OBISPO INDUSTRIAL AND MANUFACTURING ENGINEERING DEPARTMENT			
	Center Shaft			
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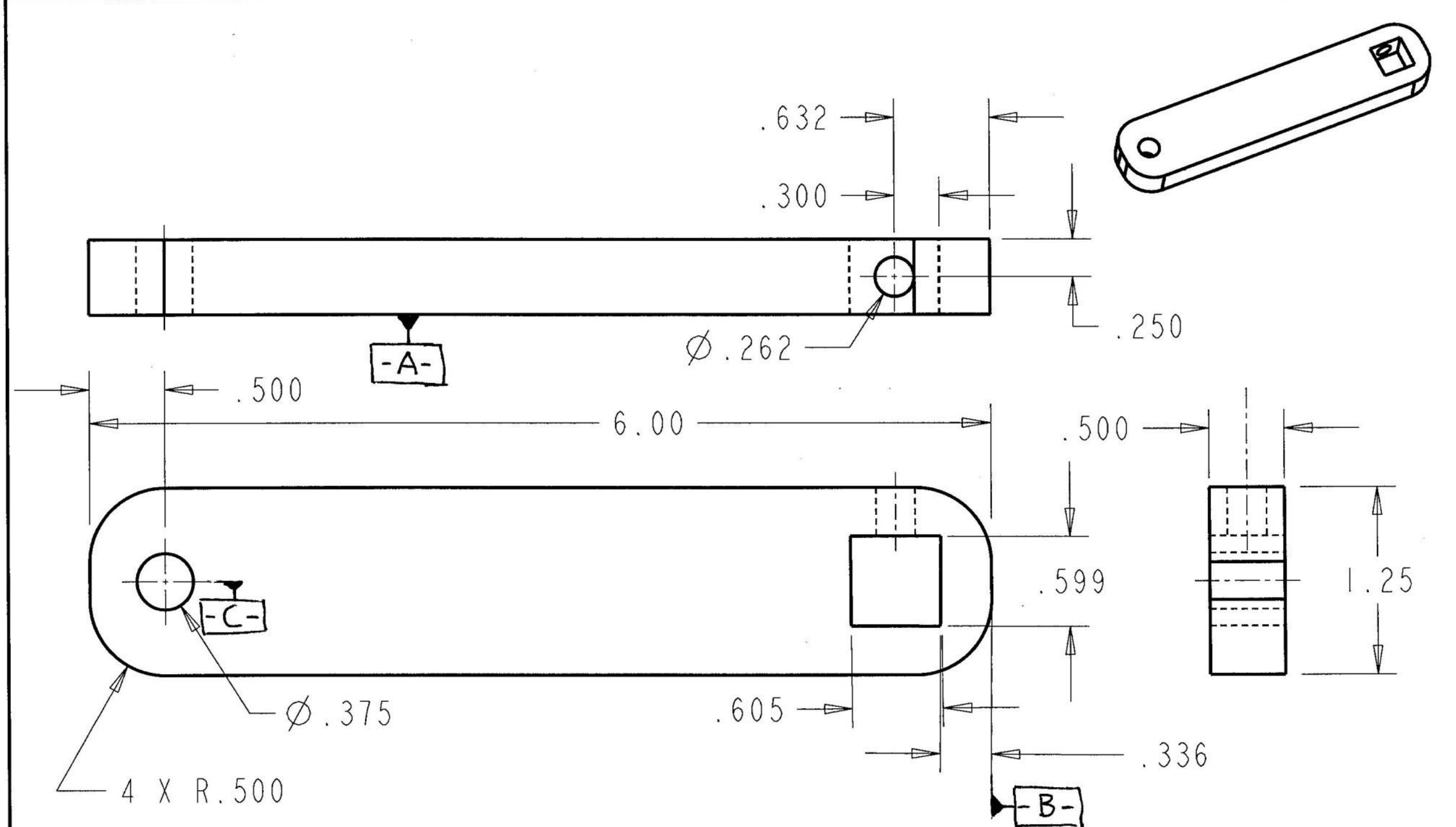
DATE: 4/23/10	SCALE .5	DELRIN	SHEET 1	



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TOLERANCES:
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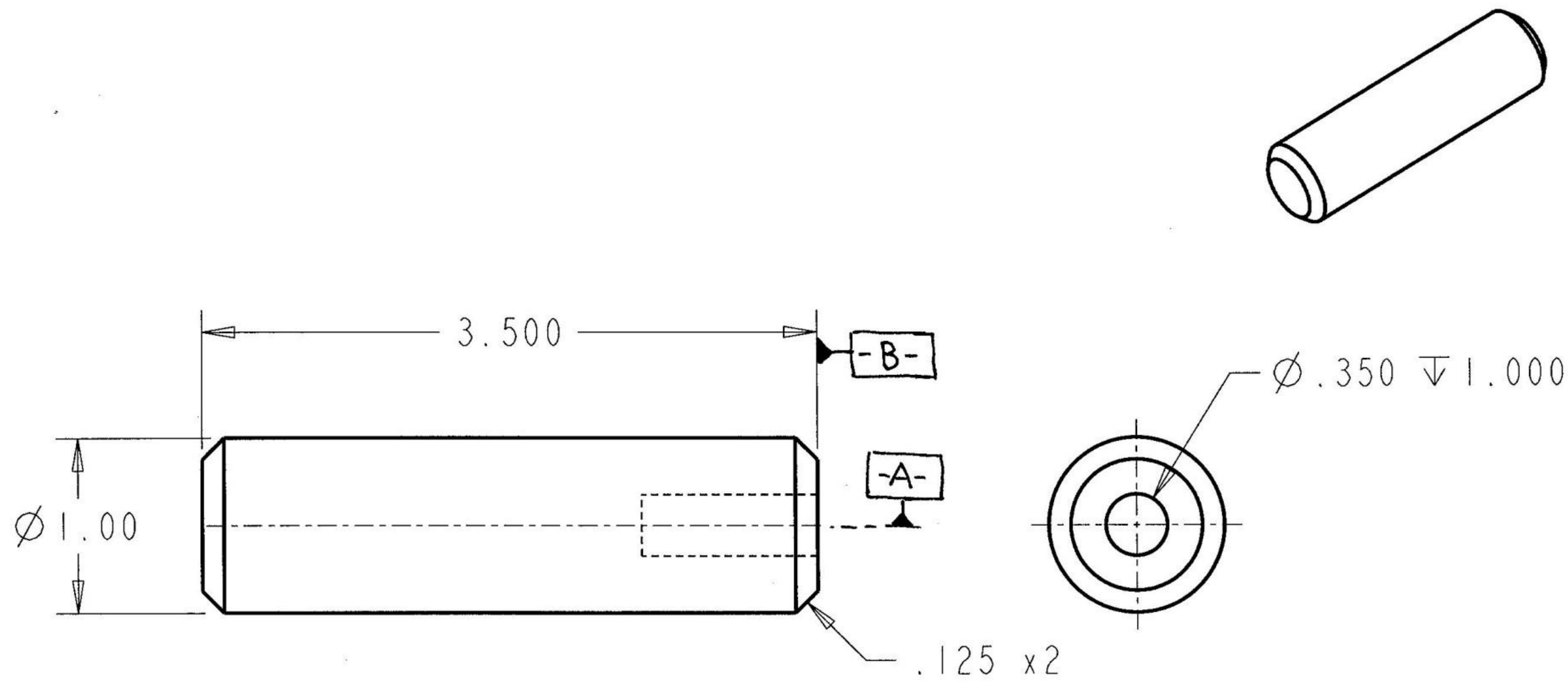
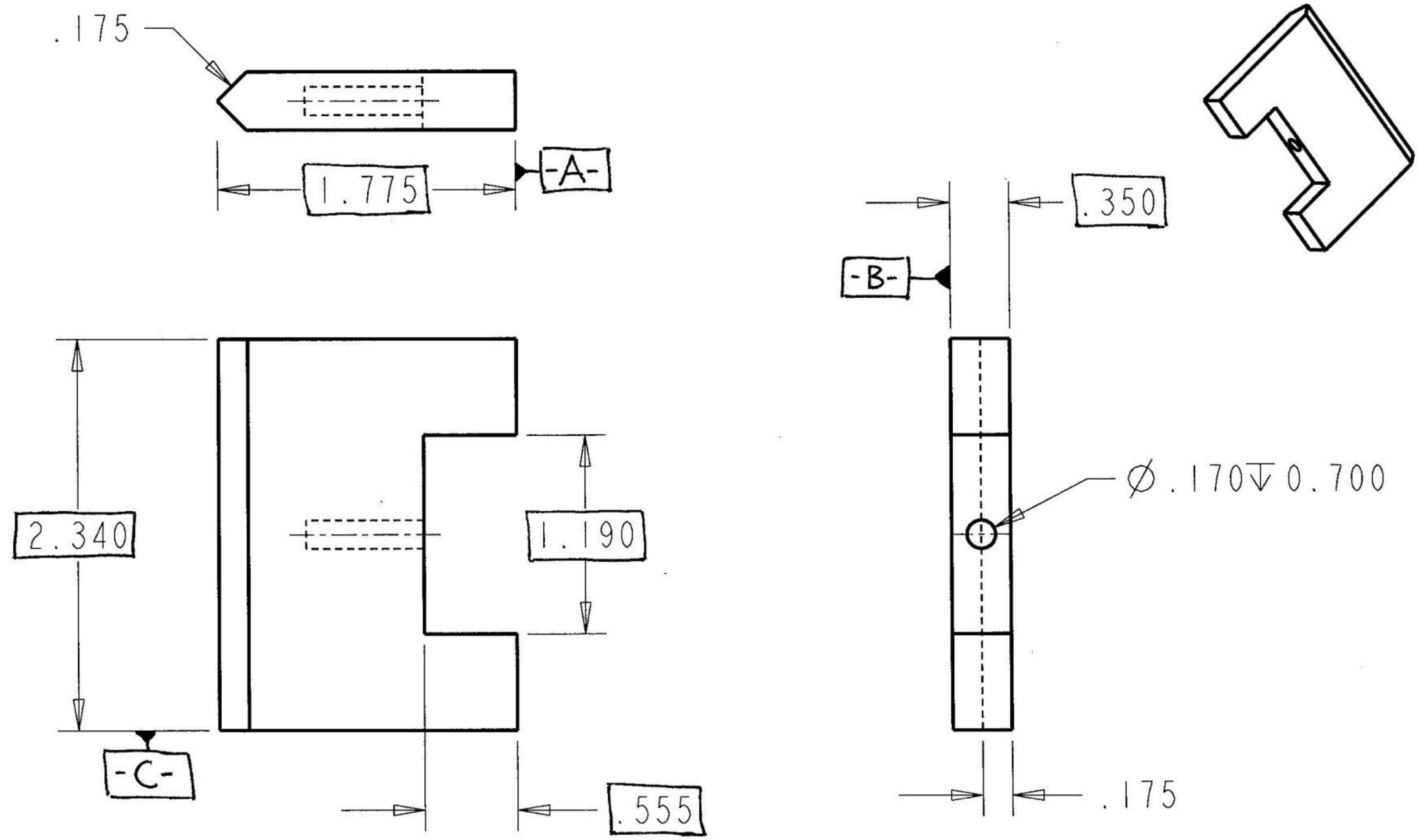
DRAWN BY: Shackelford	CAL POLY, SAN LUIS OBISPO INDUSTRIAL AND MANUFACTURING ENGINEERING DEPARTMENT			
	Handle Arm			
APPROVED BY:	SIZE A	FSCM NO N/A	DWG NO 1	REV 1.0
DATE: 4/26/10	SCALE 1	6061 AL	SHEET 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES IN ACCORDANCE WITH ASME Y14.5M-1994	TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 ANG ± 1°	DRAWN BY: Shackelford	CAL POLY, SAN LUIS OBISPO INDUSTRIAL AND MANUFACTURING ENGINEERING DEPARTMENT
		APPROVED BY:	Handle Grip
		DATE: 4/26/10	SIZE A · FSCM NO N/A · DWG NO 1 · REV 1.0
			SCALE .5 · DELRIN · SHEET 1



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TOLERANCES:
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.XX ± .01
.XXX ± .005
ANG ± 1°

DRAWN BY: Shackelford

APPROVED BY:

DATE: 4/25/10

CAL POLY, SAN LUIS OBISPO
INDUSTRIAL AND MANUFACTURING
ENGINEERING DEPARTMENT

Fin

SIZE	FSCM NO	DWG NO	REV
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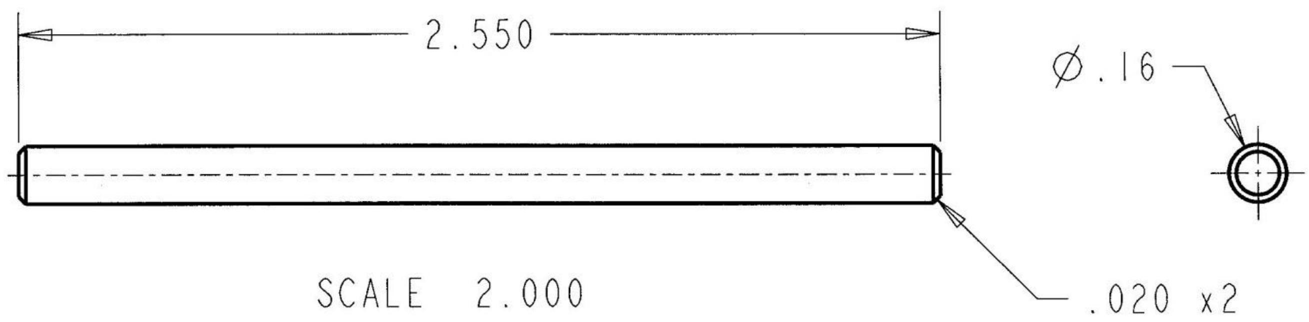
SCALE .5	DELRIN	SHEET 1	



SCALE 2.000

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ACCORDANCE WITH ASME Y14.5M-1994

TOLERANCES:
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.XX ± .01
.XXX ± .005
ANG ± 1°

DRAWN BY: Shackelford	CAL POLY, SAN LUIS OBISPO INDUSTRIAL AND MANUFACTURING ENGINEERING DEPARTMENT			
	Rod			
APPROVED BY:	SIZE A	FSCM NO N/A	DWG NO 1	REV 1.0
DATE: 4/26/10	SCALE 2:1	AL WIRE	SHEET 1	

Appendix D: Process Plan

An expanded version of the finalized process plan follows.

Part #	Part Name	Material	Process	Machine	Tooling	Fixture	Notes
1	Fins (2)	Acetal Plastic (bar)	1. Face to size	Kent Vertical Mill	1/2" HSS 2 fluted end mill	Vice, end stop	Thickness is most critical dimention.
			2. Mill slot, drill hole	Kent Vertical Mill	1/2" HSS 2 fluted end mill	Vice, end stop	
			3. Mill angled faces	Kent Vertical Mill	1/2" HSS 2 fluted end mill	Vice, angled fixture	
2	Handle Arm	60-61 Aluminum (bar)	1. CNC mill back side	Kent Vertical Mill	1/2" HSS 2 fluted end mill	Vice, end stop	
			2. CNC mill front side	Kent Vertical Mill	1/2" HSS 2 fluted end mill, 1/8" HSS ball end mill	Vice, end stop	
			3. Broach Hole	Broacher	.6" square broaching tool	--	
			4. Drill set screw hole w/ countersink	Kent Vertical Mill	Size H drill, countersink tool	Vice, end stop	
3	Handle Grip	Acetal Plastic (rod)	1. Cut to length	Bandsaw	Bandsaw blades	End stop	Dimensions on this component are not critical.
			2. Centerless grind to diameter	Centerless grinder	--	--	
			3. Drill and tap end hole	Drill press	***size drill, tapping tool	Custom fixture	
			4. Chamfer ends	Lathe	Chamfer tool	Three jaw chuck	
4	Face Plates (2)	Zinc-Aluminum Alloy (casting)	1. CNC machine back side: Face, mill o-ring slot, mill out center holes, drill 5 holes	Haas Mini Mill	1" HSS 2 fluted end mill, 3/16" HSS ball end mill, center drill, 1/8" drill, size H drill	Custom vaccuum fixture	Loading of these parts correctly is critical: custom fixture must be foolproof. 5 holes should be used to locate part in fixture.
			2. CNC machine front side: Cut top "cake" shape, face plate to thickness	Haas Mini Mill	1" HSS 2 fluted end mill	Custom vaccuum fixture	
5	Center Shaft	Acetal Plastic (rod)	1. Face to length	LeBlonde Lathe	Facing tool	3 jaw chuck	Flats and bottom end should be used to locate center slot.
			2. Turn varying diameters (side 1)	LeBlonde Lathe	Turning tool	3 jaw chuck	
			3. Turn varying diameters (side 2)	LeBlonde Lathe	Turning tool	3 jaw chuck	
			4. Mill flats	Kent Vertical Mill	1/2" HSS 2 fluted end mill	Custom v-block fixture	
			5. Mill slot through (both sides)	Kent Vertical Mill	*** HSS 2 fluted end mill	Custom v-block fixture	
6	Pump Body	Zinc-Aluminum Alloy (casting)	1. Face both sides	LeBlonde Lathe	Facing tool	Custom fixture	Diameter of center hole and location of 5 holes are very important. Pipe shafts should be used to locate part in CNC Lathe
			2. Drill pipe holes to size, thread holes	Lathe?***	***	Custom fixture	
			3.CNC Lathe (both sides): Turn center hole to size	CNC Lathe	Turning tool	Custom fixture	
			4. CNC Mill (both sides): Drill 5 holes, cut o-ring groove	Kent Vertical Mill	3/16" HSS ball end mill, center drill, 1/8" drill, size H drill	Custom fixture	

Appendix E: Operation and Routing Sheets

This section contains the routing sheets for each part and the operation sheets for each operation. It is organized according to part with the routing sheet for the part first, followed by the operation sheets in order of operation.

Routing Sheet

Date:____________
Sheet ____ of ____

Part Name:______Main Body______
Part #:______________________
Lot Size: ___________

Material: _Cast Aluminum_
Team Name:_________________

Op#	Operator	Machine	Feature	Operation/Notes	Actual Setup Time (min)	Actual Run Time (min)
10		Kent Vertical Mill		Face contact areas		
20		Turret Drill		Tap input and output connections		
30		Haas CNC Lathe		Bore interior cavity		
40		Kent Vertical Mill		Mill O-ring slot Drill bolt holes		
				Total Time		

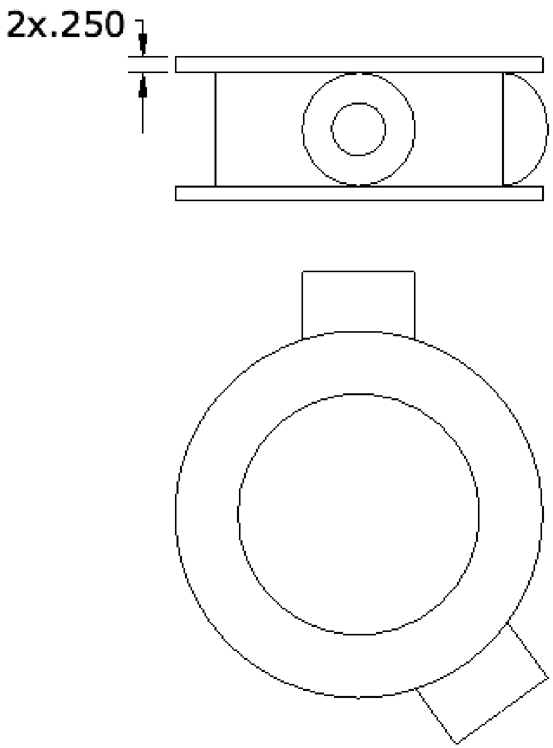
Total Actual Run Time:_____________________

Operation Sheet

Machine ___Kent Vertical Mill___

Operation # __010___

Operation Name: ___Face Top and Bottom________



Part Name __Main Body_____

Part # _______________

Operation Name: ____Face Top and Bottom________

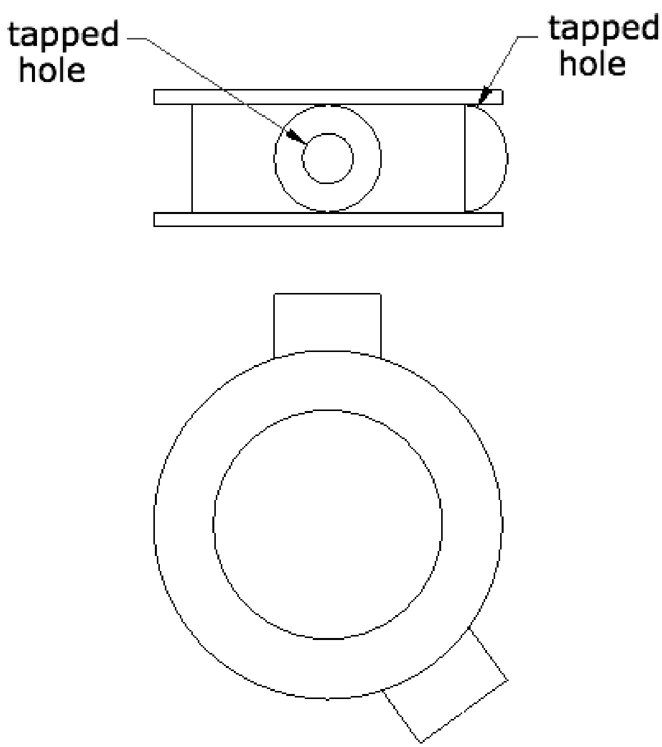
Operation Steps:

1. Fixture part to mill
2. Make finishing pass across top surface
3. Turn part over in fixture and reclamp
4. Face the remaining side

Notes:

Operation Sheet

Machine ____Turret Drill____
Operation # __020____
Operation Name: ____Tap Input and Output_________



Part Name __Main Body_____
Part # _______________

Operation Name: _____Tap Input and Output________

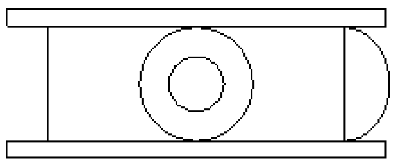
Operation Steps:

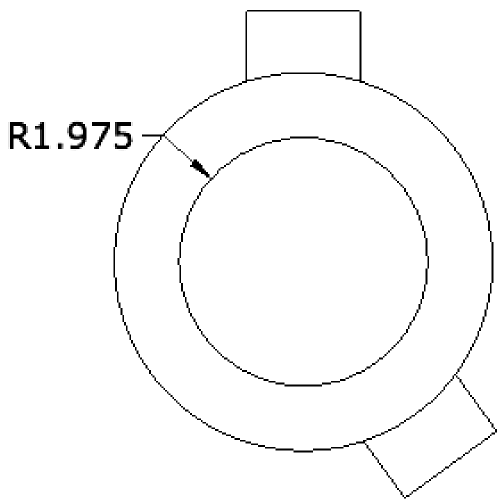
5. Clamp part in turret drill vice with one connection facing upwards
6. Index turret to large diameter tap
7. Tap hole
8. Reposition the part with other connection facing upwards
9. Tap the remaining hole

Notes:

Operation Sheet

Machine ___Haas CNC Lathe___
Operation # __030____
Operation Name: ___Bore Inner Cavity_________





Part Name __Main Body_____
Part # _______________

Operation Name: ____Bore Inner Cavity________

Operation Steps:

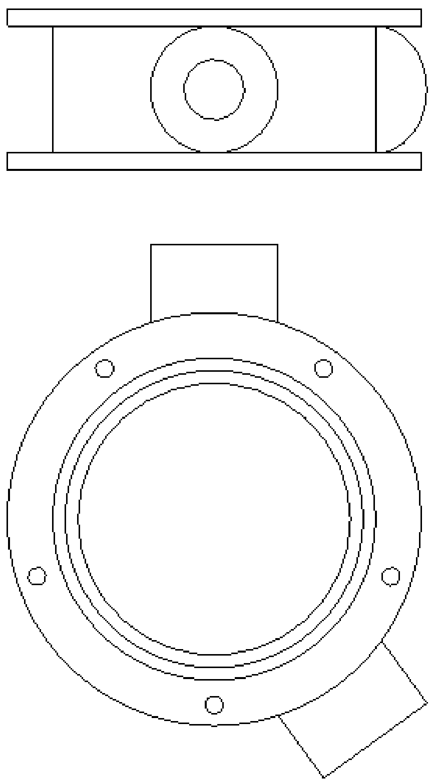
10. Secure part in lathe fixture
11. Run the CNC program
12. Leave part fixture in lathe for next operation

Notes:

Make sure the lathe is set to the correct program

Operation Sheet

Machine____Haas CNC Lathe____
Operation # __040____
Operation Name: ____Cut O-ring Slots__________



Part Name ___Main Body______
Part # ________________

Operation Name: _____Cut O-ring Slots________

Operation Steps:

13. Part should be in lathe from previous operation
14. Change lathe to run second program
15. Run CNC program
16. Turn part around in fixture
17. Run the CNC program again

Notes:

Make sure the lathe is set to the correct program

Routing Sheet

Date:____________
Sheet ____ of ____

Part Name:__________Face Plate__________
Part #:_______________________
Lot Size: ___________

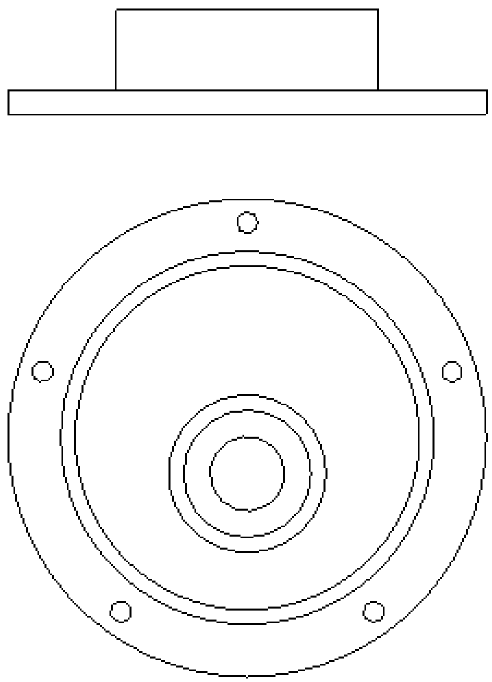
Material: _6061 Aluminum__
Team Name:___________________

Op#	Operator	Machine	Feature	Operation/Notes	Actual Setup Time (min)	Actual Run Time (min)
10A		Haas Mini Mill		Mill interior shaft guides		
10B		Haas Mini Mill		Mill center shaft through hole (Only on half of the face plates)		
20		Haas Mini Mill		Mill outer side of face plate		
				Total Time		

Total Actual Run Time:_______________________

Operation Sheet

Machine: Haas CNC Mill
Operation #: 010
Operation Name: Mill Interior of Face Plate



Part Name: Face Plate
Part # ________________

Operation Name: Mill Interior of Face Plate

Operation Steps:

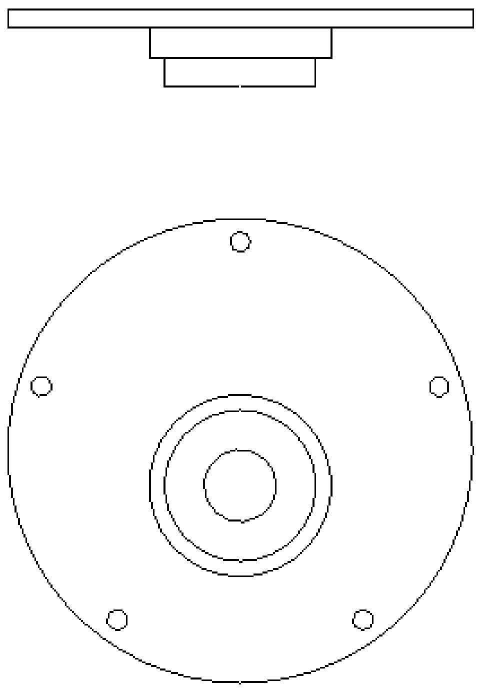
18. Place part in mill fixture
19. Run the CNC code

Notes:

The fixture has spots for two parts, one is for Operation 010 and one for Operation 020. There should be parts in both positions for each run.

Operation Sheet

Machine____Haas CNC Mill____
Operation # __020____
Operation Name: ____Mill Exterior of Face Plate_________



Part Name __Face Plate_____
Part # ________________

Operation Name: _____Mill Exterior of Face Plate_________

Operation Steps:

20. Turn part over and place in second fixture spot
21. Run the CNC code

Notes:

The fixture has spots for two parts, one is for Operation 010 and one for Operation 020. There should be parts in both positions for each run.

Routing Sheet

Date:____________

Sheet ___ of ___

Part Name:_____Center Shaft__________

Part #:______________________

Lot Size: ___________

Material: _______Delrin_____

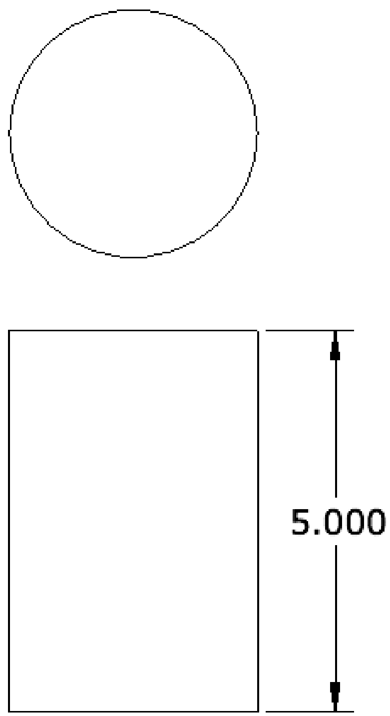
Team Name:_________________

Op#	Operator	Machine	Feature	Operation/Notes	Actual Setup Time (min)	Actual Run Time (min)
10		Cut-off Saw		Rough cut to length		3
20		LeBlonde Lathe		Face one side Turn large diameter and bottom		
30		LeBlonde Lathe		Face other side Turn small shaft		
40		Kent Vertical Mill		Mill square head on shaft Mill set screw contact spot		
50		Kent Vertical Mill		Mill slot through base		
				Total Time		

Total Actual Run Time:_____________________

Operation Sheet

Machine ____Cut-Off Saw____
Operation # __010____
Operation Name: ____Rough Cut to Length_________



Part Name ___Center Shaft_____
Part # _______________

Operation Name: _____Rough Cut to Length________

Operation Steps:

22. Clamp rod into vice
23. Cut through slowly with slight pressure at the high speed setting

Notes:

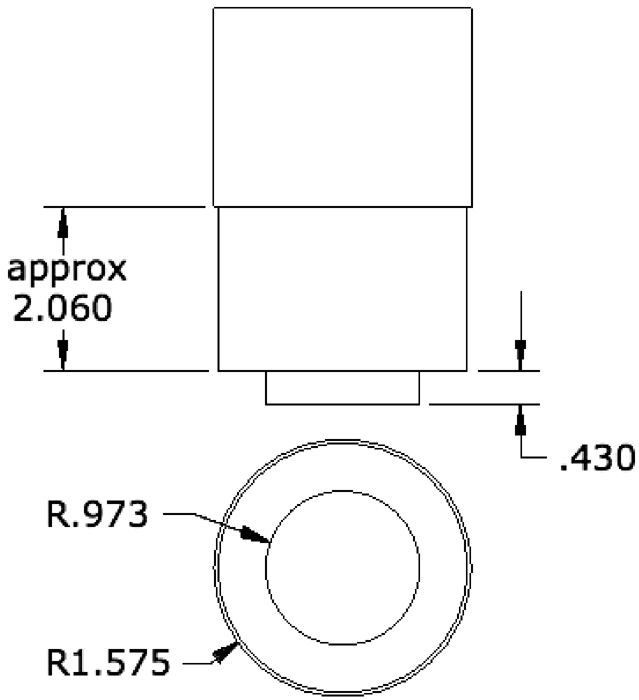
Make sure coolant is running

Operation Sheet

Machine ____LeBlonde Lathe____

Operation # __020____

Operation Name: ____Face and Turn Bottom_________



Part Name ___Center Shaft_____

Part # _______________

Operation Name: _____Face and Turn Bottom________

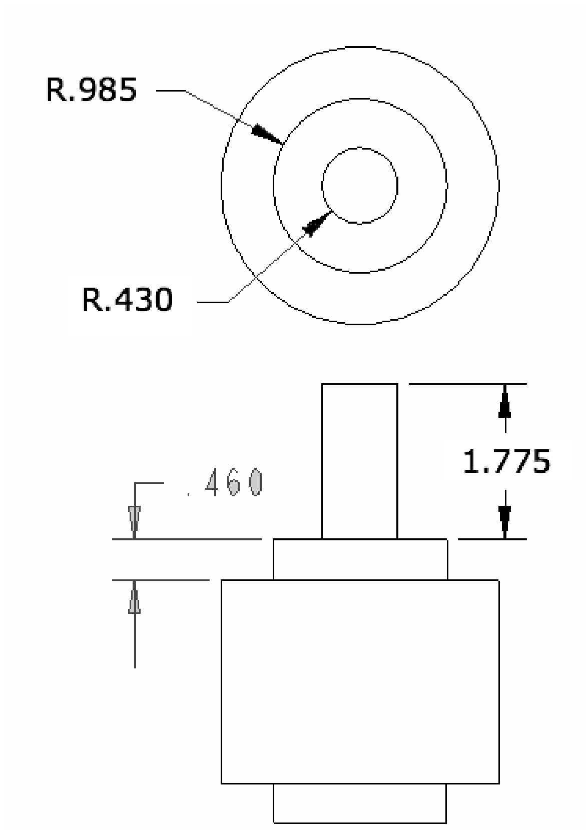
Operation Steps:

24. Clamp tightly in chuck with about 3" sticking out
25. Face end
26. Turn to large diameter
27. Turn small diameter and draw tool straight outwards with cross slide

Notes:

Operation Sheet

Machine ____LeBlonde Lathe____
Operation # __030____
Operation Name: ____Face and Turn Handle Shaft__________



Part Name __Center Shaft_____
Part # ______________

Operation Name: _____Face and Turn Handle Shaft________

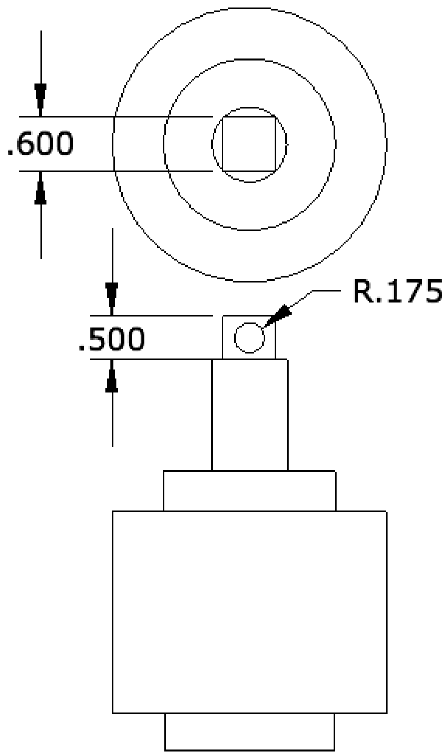
Operation Steps:

28. Clamp tightly in chuck with about 2.5” sticking out
29. Face end
30. Turn to large diameter
31. Turn shaft diameter and draw tool straight outwards with cross slide

Notes:

Operation Sheet

Machine____Kent Vertical Mill____
Operation # __040____
Operation Name: ____Mill Square on Shaft End__________



Part Name __Center Shaft_____
Part # _______________

Operation Name: _____Mill Square on Shaft End________

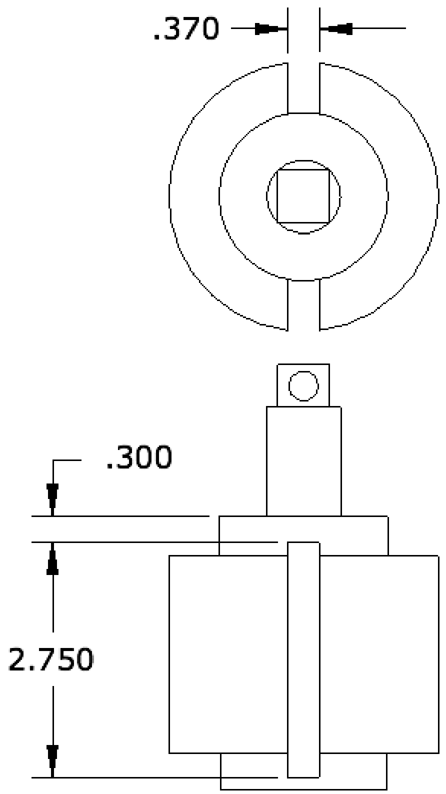
Operation Steps:

32. Fixture sideways in mill vice on v-block with shaft sticking out of the vice to the right side
33. Mill a flat on the top of the shaft
34. Turn the shaft 90° along its axis and repeat until all four sides have been cut
35. After milling the last flat, mill the set screw spot

Notes:

Operation Sheet

Machine ____Kent Vertical Mill____
Operation # __050____
Operation Name: ____Mill Slot Through Base_________



Part Name __Center Shaft_____
Part # _______________

Operation Name: _____Mill Slot Through Base_________

Operation Steps:

36. Fixture the center shaft in the mill vice on a v-block, alignment with the square head is not crucial
37. Make cutting passes back and forth along the part axis at a DOC of 0.150” until at least halfway through part.
38. Turn part over and align as closely as possible.
39. Continue milling slot at 0.150” DOC until slot is completed

Notes:

Routing Sheet

Date:____________

Sheet ____ of ____

Part Name:_________Fin________________

Part #:______________________

Lot Size: ___________

Material: ______Delrin________

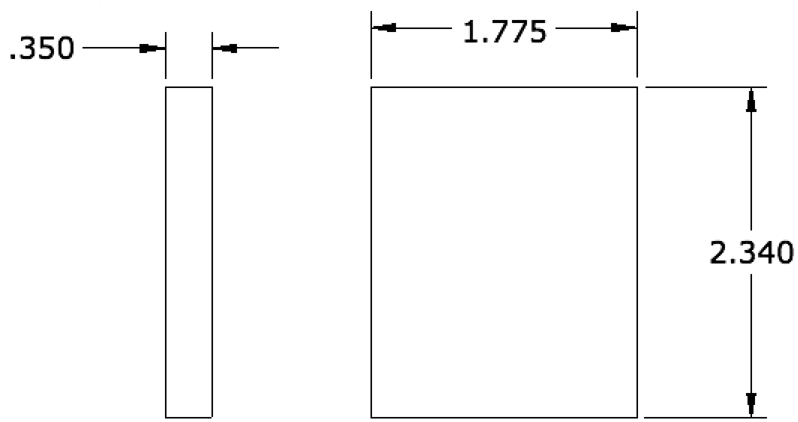
Team Name:_________________

Op#	Operator	Machine	Feature	Operation/Notes	Actual Setup Time (min)	Actual Run Time (min)
10		Kent Vertical Mill		Mill Fin to size		
20		Drill press Kent Mill		Drill through hole Mill slot		
30		Kent Vertical Mill		Chamfer		
				Total Time		

Total Actual Run Time:_____________________

Operation Sheet

Machine____Kent Vertical Mill____
Operation # __010____
Operation Name: ____Mill Fins to Size_________



Part Name ____Fin_____
Part # ________________

Operation Name: _____Mill Fins to Size________

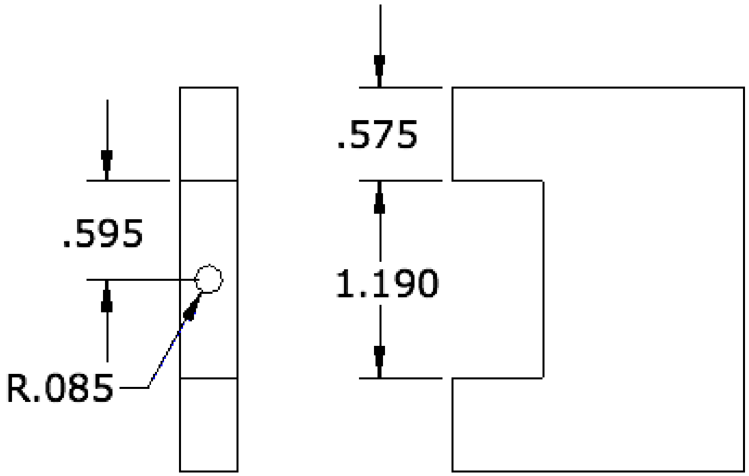
Operation Steps:

40. Fixture block into vice
41. Face .020” off top

Notes:

Operation Sheet

Machine____Kent Vertical Mill____
Operation # __020____
Operation Name: ____Drill Through Hole and Mill Slot__



Part Name ____Fin_____
Part # _______________

Operation Name: _Drill Through Hole and Mill Slot

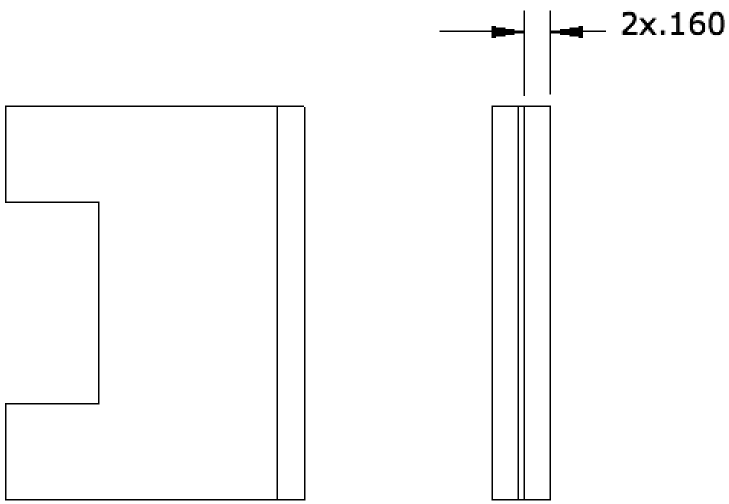
Operation Steps:

42. Fixture block into vice
43. Mill slot with 0.100" DOC passes to a depth of 0.600"
44. Fixture into drill press vice with slot facing downwards
45. Drill through with #44 drill bit making sure to frequently retract the drill to clear chips

Notes:

Operation Sheet

Machine ____Kent Vertical Mill____
Operation # __030____
Operation Name: ____Chamfer__________



Part Name ____Fin______
Part # _______________

Operation Name: ____Chamfer________

Operation Steps:

46. Fixture in mill vice with slot facing downward
47. Using a drill end mill bit, chamfer both top edges in one pass each

Notes:

Routing Sheet

Date:____________

Sheet ___ of ___

Part Name:_________Handle Arm_______

Part #:______________________

Lot Size: ___________

Material: _6061 Aluminum__

Team Name:_________________

Op#	Operator	Machine	Feature	Operation/Notes	Actual Setup Time (min)	Actual Run Time (min)
10		Kent Vertical Mill		Mill contour of handle Engrave text		
20		Drill Press		Drill through holes		
30		Broacher		Broach square hole		
40		Drill Press		Drill and Tap Set Screw hole		
				Total Time		

Total Actual Run Time:_____________________

Operation Sheet

Machine ____Kent Vertical Mill____
Operation # __010____
Operation Name: ____Mill Contour of Handle_________

Part Name __Handle Arm_____
Part # _______________

Operation Name: _____Mill Contour of Handle_________

Operation Steps:

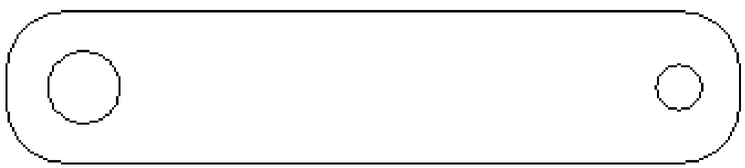
48. Fixture part in vice
49. Run CNC code

Notes:

The mill is programmed to make the contour of the handle and engrave "Cal Poly SLO Manufacturing Engineering" onto the handle

Operation Sheet

Machine____Drill Press____
Operation # __020____
Operation Name: ____Drill Through Holes_________



Part Name ___Handle Arm_____
Part # ________________

Operation Name: _____Drill Through Holes________

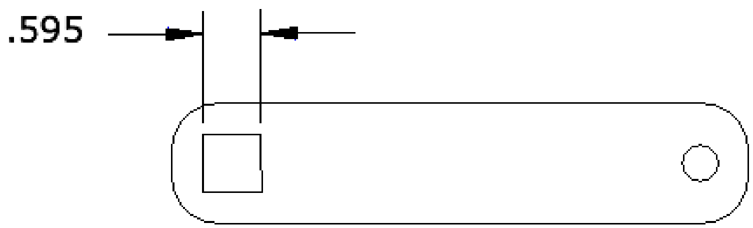
Operation Steps:

50. Clamp into drill press vice
51. Drill both through holes

Notes:

Operation Sheet

Machine____Broacher____
Operation # __030____
Operation Name: ____Broach Square Hole_________



Part Name __Handle Arm_____
Part # ________________

Operation Name: _____Broach Square Hole________

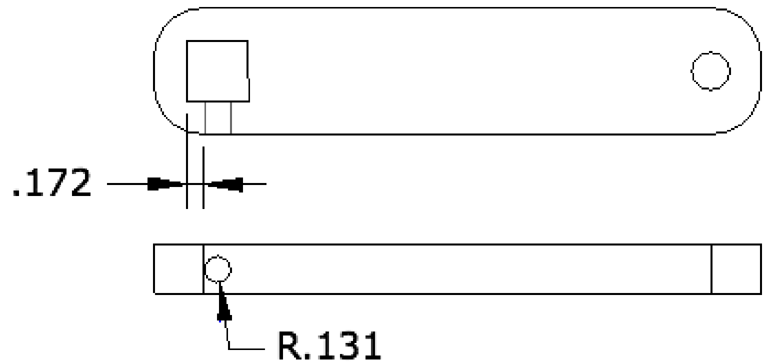
Operation Steps:

52. Secure part on broacher and attach broaching bar to machine through the large hole
53. Run the broacher

Notes:

Operation Sheet

Machine____Drill Press____
Operation # __040____
Operation Name: ____Drill and Tap Set Screw Hole_________



Part Name ___Handle Arm_____
Part # ________________

Operation Name: _____Drill and Tap Set Screw Hole________

Operation Steps:

54. Clamp into drill press vice
55. Drill through the side of the handle arm into to square hole

Notes:

Routing Sheet

Date:____________

Sheet ____ of ____

Part Name:______Handle Grip_________

Part #:______________________

Lot Size: ___________

Material: ______Delrin __ _____

Team Name:__________________

Op#	Operator	Machine	Feature	Operation/Notes	Actual Setup Time (min)	Actual Run Time (min)
10		Cut-off Saw		Rough cut to length		
20		Centerless Grinder		Grind to diameter		
30		Turret Drill		Drill and tap hole		
40		LeBlonde Lathe		Chamfer edges		
				Total Time		

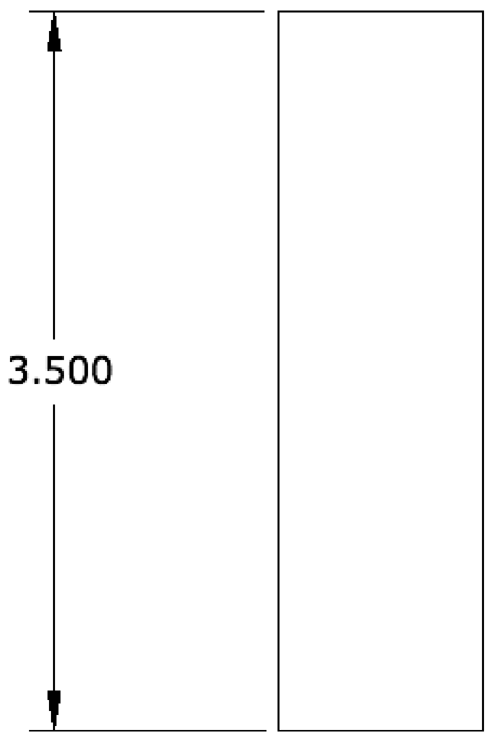
Total Actual Run Time:______________________

Operation Sheet

Machine____Cut-Off Saw____

Operation # __010____

Operation Name: ____Rough Cut to Length_________



Part Name ___Handle Grip_____

Part # ________________

Operation Name: _____Rough Cut to Length_________

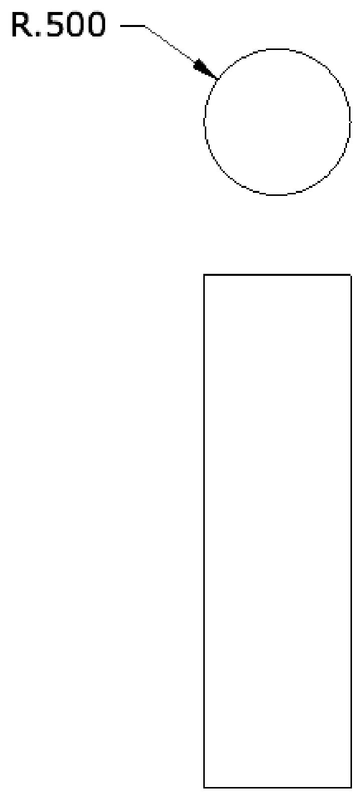
Operation Steps:

56. Clamp into saw vice
57. Cut slowly with the coolant on

Notes:

Operation Sheet

Machine____Centerless Grinder____
Operation # __020____
Operation Name: ____Grind to Diameter_________



Part Name ___Handle Grip_____
Part # ________________

Operation Name: ____Grind to Diameter________

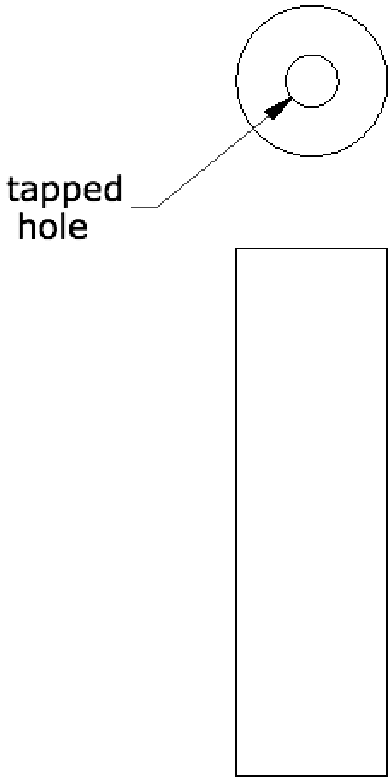
Operation Steps:

58. Place part into centerless grinder
59. Retrieve finished part as it exits the machine

Notes:

Operation Sheet

Machine____Turret Drill____
Operation # __030____
Operation Name: ____Drill and Tap Hole_________



Part Name __Handle Grip_____
Part # _______________

Operation Name: _____Drill and Tap Hole________

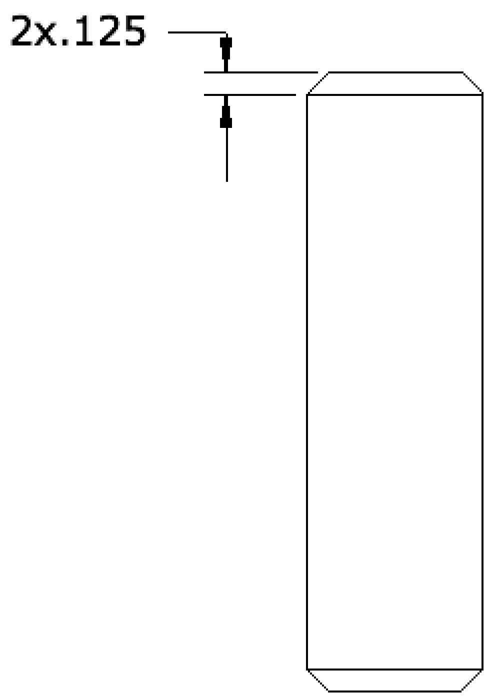
Operation Steps:

60. Clamp part into vice on turret drill
61. Index turret to drill bit
62. Drill hole to specified depth
63. Index turret to tapping bit
64. Tap hole

Notes:

Operation Sheet

Machine____LeBlonde Lathe____
Operation # __040____
Operation Name: ____Chamfer Edges_________



Part Name ___Handle Grip______
Part # _______________

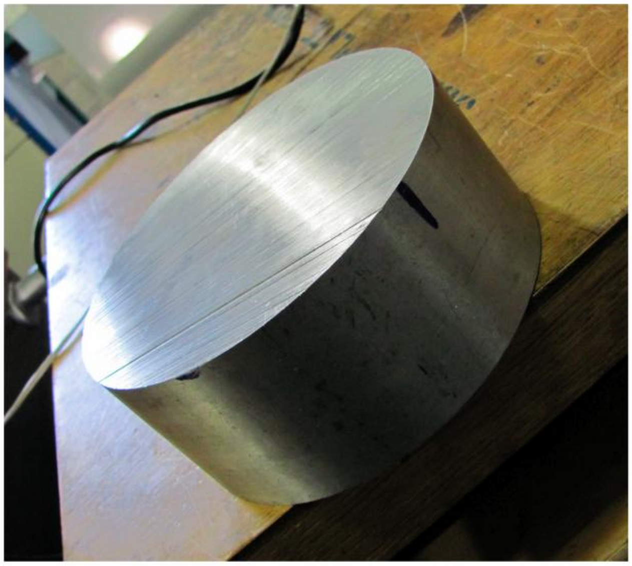
Operation Name: _____Chamfer Edges________

Operation Steps:

65. Clamp part into lathe chuck
66. Cut chamfer in first side
67. Turn part over and reclamp in chuck
68. Cut final chamfer

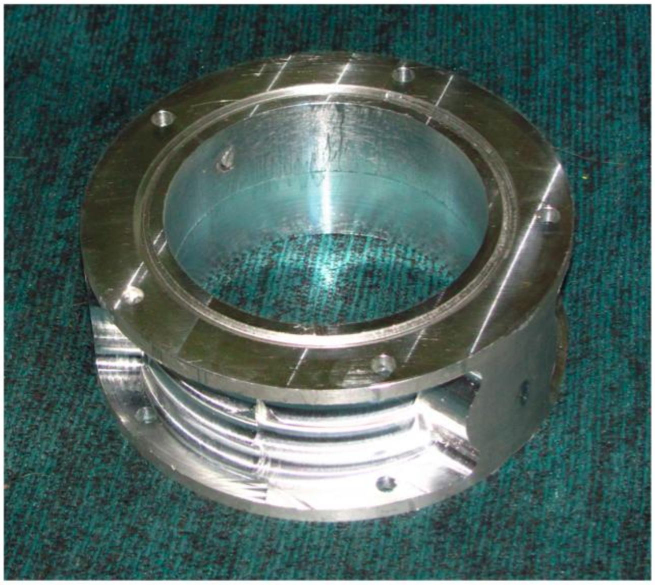
Notes:

Appendix F: Pictures

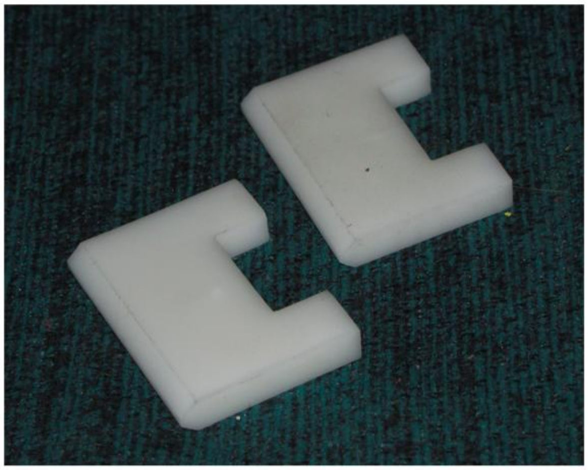


Top Left: Stock aluminum
Top Right: Stock Delrin
Center: Pin locating fixture (used for machining Face Plates and Main Body)
Bottom: Sarah Shackelford

Top Left: Cutting the stock material
Top Right: Milling the Fins
Bottom Left: Purchase parts
Bottom Right: Original pump (basis for design)



Top Left: Main Body
Center Right: Center Shaft
Bottom: Face Plates



Top Left: Fins
Top Right: Handle Grip
Center: Handle Arm
Bottom: Partially assembled pump

The completed pump (front and back)

Appendix G: CNC Code

This CNC code is intended to be used specifically and exclusively on the Haas mills and lathes available in both the undergraduate machining lab where the IME 143 and IME 144 classes meet for lab and the advanced machining lab where the prototype for this project was fabricated. Using this code on other machines should be done with caution. At minimum, the G- and M-codes used by the machine should be cross-referenced to Haas's system to verify compatibility.

It should also be noted that this code is not finalized due to the uncertainty in the exact shape of the face plate castings. This code was used to produce the prototype parts from an approximation of the casting shape.

Face Plate Interior

```
%
O1440
(Face Plate Back New)
(Coordinate System: center of
circle on top face)
(program will face at z=0)
G90 G80 G40 G54
(Facing Top Surface)
T1M06 (2" face mill, 4 flutes, WC)
S2400M03
G00X-2.75Y-4.25
G43Z.5H01M08
G01Z0.F8.
X-2.25
X-1.Y-3.
X1.
X2.5987Y-2.
X-2.5987
X-2.958Y-1.
X2.958
X3.Y0.
X-3.
X-2.958Y1.
X2.958
X2.5987Y2.
X-2.5987
X-1.Y3.
X1.
Z.5
(Milling slot for o-ring)
T2M06 (3/16" ball end mill, 2
flutes, HSS)
S6400M03
G00X-2.2538Y0.
G43Z.5H02M08
Z.4325
G01Z-.0675F10.
G02X-2.2538Y0.I2.2538J0.F30.
G01Z.5
M00
(Milling Pocket)
T3M06 (1" end mill, 2 flutes, HSS)
S1200M03
G00X-.6875Y0.
G43Z.5H03M08
G01Z-.075F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01X-.6875
Z-.15F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01X-.6875
Z-.225F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
```

```
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01X-.6875
Z-.3F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01X-.6875
Z-.375F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01X-.6875
Z-.45F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01X-.6875
Z-.5F5.
G03X-.6875Y0.I.2375J0.F20.
G01X-.9375
G03X-.9375Y0.I.4875J0.
X-.9375Y0.I.4875J0.
G01Z.5
(Drilling 5 Holes)
T10 M06 (Center drill)
S3000 M03
G00 x0.8343 y-2.5679
G43 Z1. H10 M08
G81 x0.8343 y-2.5679 Z-0.1 R0.5 F5.
y-1.587 x-2.1843
y1.587
y2.5679 x0.8343
y0. x2.7
G80
G00 Z1.
T15 M06 (1/8" Drill HSS)
S9000 M03
G00 y-2.5679 x0.8343
G43 Z1. H15 M08
G81 y-2.5679 x0.8343 z-0.45 R0.5
F10.
y-1.587 x-2.1843
y1.587
y2.5679 x0.8343
y0. x2.7
G80
G00 Z1.
T16 M06 (1/4" Drill HSS)
S4800 M03
G00 y-2.5679 x0.8343
G43 Z1. H16 M08
G81 y-2.5679 x0.8343 Z-0.45 R0.5
F10.
y-1.587 x-2.1843
y1.587
y2.5679 x0.8343
y0. x2.7
G80
G00 Z1.
M30
%
```

Face Plate Exterior

```
%
O1444
(Face Plate Front Flat/New)
(Part is located at bottom and
center of hole opposite pocket)
G90 G80 G40 G54
(Facing)
T3M06 (1" end mill, 2 flutes, HSS)
S1200M03
G00X1.325Y-.866
G43Z1.H03M08
G01Z.65F5.
Y.866F20.
G03X1.325Y-.866I1.375J-.866
G01X1.7
Y1.7321
G03X1.7Y-1.7321I1.J-1.7321
G01Y-.866
X2.45
Y2.7386
G03X2.45Y-2.7386I.25J-2.7386
G01Y-.866
X3.2
Y3.5
X2.7
G03X2.7Y-3.5I0.J-3.5
G01X3.2
Y-.866
X1.325
Z.625F5.
Y.866F20.
G03X1.325Y-.866I1.375J-.866
G01X1.7
Y1.7321
G03X1.7Y-1.7321I1.J-1.7321
G01Y-.866
X2.45
Y2.7386
G03X2.45Y-2.7386I.25J-2.7386
G01Y-.866
X3.2
Y3.5
X2.7
G03X2.7Y-3.5I0.J-3.5
G01X3.2
Y-.866
X.4813Y-.8472
Z.525F5.
G02X.4813Y.8472I2.6687J.8472F20.
G03X.4812Y-.8472I2.2187J-.8472
G01X.8387Y-.7337
G02X2.45Y2.3218I2.3113J.7337
G01Y2.7386
G03X2.45Y-2.7386I.25J-2.7386
G01Y-2.3218
G02X.8387Y-.7337I.7J2.3218
G01X1.5535Y-.5068
G02X3.2Y1.6743I1.5965J.5068
G01Y3.5
X2.7
G03X2.7Y-3.5I0.J-3.5
G01X3.2
Y-1.6743
G02X1.5535Y-.5068I-.05J1.6743
G01X.4813Y-.8472
Z.425F5.
G02X.4813Y.8472I2.6687J.8472F20.
G03X.4812Y-.8472I2.2187J-.8472
G01X.8387Y-.7337
G02X2.45Y2.3218I2.3113J.7337
G01Y2.7386
G03X2.45Y-2.7386I.25J-2.7386
G01Y-2.3218
G02X.8387Y-.7337I.7J2.3218
G01X1.5535Y-.5068
G02X3.2Y1.6743I1.5965J.5068
G01Y3.5
X2.7
G03X2.7Y-3.5I0.J-3.5
G01X3.2
Y-1.6743
G02X1.5535Y-.5068I-.05J1.6743
G01X.4813Y-.8472
Z.325F5.
G02X.4813Y.8472I2.6687J.8472F20.
G03X.4812Y-.8472I2.2187J-.8472
G01X.8387Y-.7337
G02X2.45Y2.3218I2.3113J.7337
G01Y2.7386
G03X2.45Y-2.7386I.25J-2.7386
G01Y-2.3218
G02X.8387Y-.7337I.7J2.3218
G01X1.5535Y-.5068
G02X3.2Y1.6743I1.5965J.5068
G01Y3.5
X2.7
G03X2.7Y-3.5I0.J-3.5
G01X3.2
Y-1.6743
G02X1.5535Y-.5068I-.05J1.6743
G01X.4813Y-.8472
Z.25F5.
G02X.4812Y.8472I2.6687J.8472F20.
G03X.4812Y-.8472I2.2188J-.8472
G01X.8387Y-.7337
G02X2.45Y2.3218I2.3113J.7337
```

```
G01Y2.7386
G03X2.45Y-2.7386I.25J-2.7386
G01Y-2.3218
G02X.8387Y-.7337I.7J2.3218
G01X1.5535Y-.5068
G02X3.2Y1.6743I1.5965J.5068
G01Y3.5
X2.7
G03X2.7Y-3.5I0.J-3.5
G01X3.2
Y-1.6743
G02X1.5535Y-.5068I-.05J1.6743
G01Z.75
X1.5536Y-.5069
G03X1.8783Y-1.0901I1.5964J.5069
G01X3.2Y-3.4641
Z.15F5.
G02X2.7784Y-3.4996I-
.5104J3.5445F20.
G01X3.2Y-3.5
Y-3.4641
Z.05F5.
G02X2.9368Y-3.492I-.5J3.4641F20.
G01X2.7782Y-3.4991
X2.6995
X2.7Y-3.5
X3.2
Y-3.4641
G02X2.9368Y-3.492I-.5J3.4641
G01X2.7782Y-3.4991
X2.7125
X2.7Y-3.5
Z0.F5.
X3.2F20.
Y-3.4641
G02X2.7Y-3.5I-.5J3.4641
G01Z.75
X2.7125Y-1.6168
G02X2.7341Y1.6225I.4375J1.6168
G01X2.7466Y3.4998
Z.15F5.
G02X3.2Y3.4641I-.048J-3.5116F20.
G01Y3.5
X2.7466Y3.4998
X3.2Y3.5
Z.05F5.
X2.7383Y3.4999F20.
G02X3.2Y3.4641I-.0404J-3.5172
G01Y3.5
Y3.4641
Z0.F5.
Y3.5F20.
X2.7
G02X3.2Y3.4641I0.J-3.5
G01Z1.
M00
T3M06
```

```
S1200M03
G00X4.02Y-.8125
G43Z1.H03M08
G01Z.825F5.
G03X4.02Y.8125I-1.32J.8125F20.
G01Y-.8125
X4.4458Y-1.0746
G03X3.52Y1.8789I-1.7458J1.0746
G01Y-1.8789
G03X4.4458Y-1.0746I-.82J1.8789
G01X4.8716Y-1.3366
G03X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
G01X4.02Y-.8125
Z.775F5.
G03X4.02Y.8125I-1.32J.8125F20.
G01Y-.8125
X4.4458Y-1.0746
G03X3.52Y1.8789I-1.7458J1.0746
G01Y-1.8789
G03X4.4458Y-1.0746I-.82J1.8789
G01X4.8716Y-1.3366
G03X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
G01X4.02Y-.8125
Z.725F5.
G03X4.02Y.8125I-1.32J.8125F20.
G01Y-.8125
X4.4458Y-1.0746
G03X3.52Y1.8789I-1.7458J1.0746
G01Y-1.8789
G03X4.4458Y-1.0746I-.82J1.8789
G01X4.8716Y-1.3366
G03X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
G01X4.02Y-.8125
Z.675F5.
G03X4.02Y.8125I-1.32J.8125F20.
G01Y-.8125
X4.4458Y-1.0746
G03X3.52Y1.8789I-1.7458J1.0746
G01Y-1.8789
G03X4.4458Y-1.0746I-.82J1.8789
G01X4.8716Y-1.3366
G03X3.02Y2.5298I-2.1716J1.3366
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G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
X3.02Y2.5298I-2.1716J1.3366
G01Y-2.5298
G03X4.8716Y-1.3366I-.32J2.5298
G01X4.02Y.8125
Z.625F5.
Y-.8125F20.
G03X4.02Y.8125I-1.32J.8125
G01X3.52
Y-1.8789
G03X3.52Y1.8789I-.82J1.8789
G01Y.8125
X3.02
Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y.8125
X4.6854Y-1.1611
Z.575F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.525F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.475F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.425F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.375F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
```

```
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.325F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.275F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01X4.6854Y-1.1611
Z.25F5.
G02X3.27Y-1.9213I-1.5354J1.1611F20.
G01Y-2.2283
G03X4.6854Y-1.1611I-.57J2.2283
G01X4.486Y-1.0103
G02X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X4.9012Y1.2873I-.32J2.5298
G01X4.6854Y1.1611
G03X3.27Y2.2283I-1.9854J-1.1611
G01Y1.9213
G02X4.6854Y1.1611I-.12J-1.9213
G01X4.9012Y1.2873
G03X3.02Y2.5298I-2.2012J-1.2873
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
X3.02Y-1.6699I-1.336J1.0103
G01Y-2.5298
G03X3.02Y2.5298I-.32J2.5298
G01Y1.6699
G02X4.486Y-1.0103I.13J-1.6699
G01Z1.
M30
%
```

Handle Arm Front

```
%
O1446
(handle_arm_front)
G90G80G54G40
(Facing top)
T1M06 (1/2" HSS 2 flute end mill)
S2400M03
G00X-.201Y.201
G43Z.25H01M08
G01Z-.05F5.
X6.301
Y-.237
X-.201
Y-.675
X6.301
Y-1.113
X-.201
Y-1.551
X6.301
Y.201
X-.201
Y-1.551
X6.301
Z.25
(Profiling)
G00X-.201Y.201
Z.2
G01Z-.35
X6.301
X-.201
Y-.237
X-.1316
G03X-.2Y-.55I.6816J-.313
G01Y-.675
X-.201
Y-1.113
X-.1316
X-.201
Y-1.551
X6.301
Y-1.113
X6.2316
G03X6.3Y-.8I-.6816J.313
G01Y-.675
X6.301
Y-.237
X6.2316
G02X6.3Y-.55I-.6816J-.313
G01Y-.8
G02X5.55Y-1.55I-.75J0.
G01X.55
G02X-.2Y-.8I0.J.75
G01Y-.55
G02X.55Y.2I.75J0.
G01X5.55
G02X6.3Y-.55I0.J-.75
G01Z.25
G00X6.301Y.201
Z.2
G01Z-.35
X-.201
Y-1.551
X6.301
Y.201
Z.25
(Drill sequence)
T3M06 (center drill)
S6000M03
G00X.55Y-.675
G43Z.25H03M08
G81X.55Y-.675Z-.2157R.2F10.
X5.1129Y-.375
X5.1171Y-.9744
X5.7122Y-.9756
X5.7179Y-.375
G80
G00Z.25
T4M06 (1/8" drill)
S9600M03
G00X.55Y-.675
G43Z.25H04M08
G81X.55Y-.675Z-.6376R.2F10.
X5.1129Y-.375
X5.1171Y-.9744
X5.7122Y-.9756
X5.7179Y-.375
G80
G00Z.25
T5M06 (1/4" drill)
S4800M03
G00X.55Y-.675
G43Z.25H05M08
G81X.55Y-.675Z-.6751R.2F10.
X5.1129Y-.375
X5.1171Y-.9744
X5.7122Y-.9756
X5.7179Y-.375
G80
G00Z.25
T6M06 (3/8" drill)
S3200M03
G00X.55Y-.675
G43Z.25H06M08
G81X.55Y-.675Z-.7127R.2F10.
G80
G00Z.25
```

```
(Profiling)
T1M06 (1/2" HSS 2 flute end mill)
S2400M03
G00X5.3647Y-.625
G43Z.25H01M08
Z.2
G01Z-.15F20.
X5.4655
X5.4645Y-.7251
X5.3653
Y-.7249
X5.4645Y-.7251
X5.4655Y-.625
X5.3647
X5.3653Y-.7249
Y-.7251Z-.25
X5.4645
X5.4655Y-.625
X5.3647
X5.3653Y-.7249
X5.4645Y-.7251
X5.4655Y-.625
X5.3647
Z-.35
X5.4655
X5.4645Y-.7251
X5.3653
Y-.7249
X5.4645Y-.7251
X5.4655Y-.625
X5.3647
X5.3653Y-.7249
Y-.7251Z-.45
X5.4645
X5.4655Y-.625
X5.3647
X5.3653Y-.7249
X5.4645Y-.7251
X5.4655Y-.625
X5.3647
Z-.55
X5.4655
X5.4645Y-.7251
X5.3653
Y-.7249
X5.4645Y-.7251
X5.4655Y-.625
X5.3647
X5.3653Y-.7249
Y-.7251Z-.6
X5.4645
X5.4655Y-.625
X5.3647
X5.3653Y-.7249
X5.4645Y-.7251
X5.4655Y-.625
X5.3647
```

```
Z.25
(cutting words)
T7M06 (1/8" HSS 2 flute ball end
mill)
S4800M03
G00X5.4643Y-.8501
G43Z.25H07M08
Z.2
G01Z-.15F40.
X5.5883Y-.8503
X5.5895Y-.7263
X5.4643Y-.8501
Z-.25
X5.5883Y-.8503
X5.5895Y-.7263
X5.4643Y-.8501
Z-.35
X5.5883Y-.8503
X5.5895Y-.7263
X5.4643Y-.8501
Z-.45
X5.5883Y-.8503
X5.5895Y-.7263
X5.4643Y-.8501
Z-.55
X5.5883Y-.8503
X5.5895Y-.7263
X5.4643Y-.8501
Z-.6
X5.5883Y-.8503
X5.5895Y-.7263
Z.25
G00X5.2404Y-.7327
Z.2
G01Z-.15
X5.2412Y-.8497
X5.3651Y-.8499
X5.2404Y-.7327
Z-.25
X5.2412Y-.8497
X5.3651Y-.8499
X5.2404Y-.7327
Z-.35
X5.2412Y-.8497
X5.3651Y-.8499
X5.2404Y-.7327
Z-.45
X5.2412Y-.8497
X5.3651Y-.8499
X5.2404Y-.7327
Z-.55
X5.2412Y-.8497
X5.3651Y-.8499
X5.2404Y-.7327
Z-.6
X5.2412Y-.8497
X5.3651Y-.8499
```

```
Z.25
G00X5.3647Y-.5
Z.2
G01Z-.15
X5.2388
X5.2397Y-.6259
X5.3647Y-.5
Z-.25
X5.2388
X5.2397Y-.6259
X5.3647Y-.5
Z-.35
X5.2388
X5.2397Y-.6259
X5.3647Y-.5
Z-.45
X5.2388
X5.2397Y-.6259
X5.3647Y-.5
Z-.55
X5.2388
X5.2397Y-.6259
X5.3647Y-.5
Z-.6
X5.2388
X5.2397Y-.6259
Z.25
G00X5.5905Y-.6194
Z.2
G01Z-.15
X5.5917Y-.5
X5.4655
X5.5905Y-.6194
Z-.25
X5.5917Y-.5
X5.4655
X5.5905Y-.6194
Z-.35
X5.5917Y-.5
X5.4655
X5.5905Y-.6194
Z-.45
X5.5917Y-.5
X5.4655
X5.5905Y-.6194
Z-.55
X5.5917Y-.5
X5.4655
X5.5905Y-.6194
Z-.6
X5.5917Y-.5
X5.4655
Z.25
N0080T2M06
S9600M03
G00X4.4765Y-.9119
G43Z.25H02M08
Z.1
G01Z-.15F5.
X4.4831Y-.9344F30.
X4.4976Y-.9552
X4.5211Y-.9741
X4.5536Y-.99
X4.5952Y-1.0013
X4.6327Y-1.0064
X4.6725Y-1.006
X4.7094Y-.9986
X4.742Y-.9847
X4.7692Y-.9651
X4.7888Y-.9418
X4.8041Y-.9115
X4.8197Y-.8653
X4.8318Y-.8172
X4.8377Y-.7615
X4.8365Y-.6983
X4.8284Y-.6268
X4.8198Y-.5824
X4.8059Y-.545
X4.7862Y-.5127
X4.7661Y-.4917
X4.7414Y-.4765
X4.7077Y-.4653
X4.6633Y-.4591
X4.6113Y-.4593
X4.575Y-.4631
X4.5442Y-.4721
X4.5193Y-.4871
X4.5001Y-.5074
X4.4845Y-.5353
X4.4765Y-.5556
Z.25
G00X4.0552Y-.5465
Z.1
G01Z-.15F5.
X4.0749Y-.5309F30.
X4.0964Y-.5047
X4.1132Y-.4841
X4.1332Y-.4674
X4.1595Y-.4555
X4.1947Y-.4478
X4.2283Y-.4473
X4.2594Y-.4541
X4.2868Y-.4675
X4.3086Y-.4862
X4.3225Y-.5075
X4.3295Y-.5328
Y-.5628
X4.3221Y-.5935
X4.3077Y-.6209
X4.2868Y-.6439
X4.2619Y-.6605
X4.2327Y-.6707
X4.1946Y-.6752
X4.1426Y-.6738
```

```
X4.0993Y-.6717
X4.0626Y-.6736
X4.0505Y-.676
Z.25
G00X4.041Y-.4539
Z.1
G01Z-.15F5.
X4.051Y-.4868F30.
X4.0547Y-.5269
X4.0531Y-.5808
X4.0501Y-.6549
X4.0531Y-.7147
X4.0584Y-.7464
X4.0659Y-.7691
X4.0783Y-.7869
X4.0987Y-.8019
X4.1284Y-.8137
X4.166Y-.8199
X4.2023Y-.8216
X4.2372Y-.819
X4.2675Y-.8107
X4.2932Y-.796
X4.3138Y-.7758
X4.3236Y-.7603
Z.25
G00X3.8937Y-1.0125
Z.1
G01Z-.15F5.
Y-.4535F30.
Z.25
G00X3.6379Y-.7347
Z.1
G01Z-.15F5.
X3.4179F30.
X3.3975Y-.7342
X3.3751Y-.7417
X3.3506Y-.7563
X3.3318Y-.7734
X3.3179Y-.7958
X3.3091Y-.8257
X3.3058Y-.8654
X3.3086Y-.899
X3.3183Y-.9324
X3.3345Y-.9614
X3.3555Y-.984
X3.3807Y-.9999
X3.4082Y-1.0083
X3.4298Y-1.0101
X3.6391
X3.6379Y-.4507
Z.25
G00X3.1581Y-.6425
Z.1
G01Z-.15F5.
X3.1574Y-.5996F30.
X3.1495Y-.5624
X3.1346Y-.5255
X3.1189Y-.4965
X3.1018Y-.4754
X3.0805Y-.4606
X3.0507Y-.4498
X3.017Y-.4452
X2.9811Y-.4478
X2.9468Y-.4577
X2.9207Y-.4724
X2.9028Y-.4906
X2.8896Y-.5149
X2.8769Y-.5529
X2.8677Y-.5937
X2.8644Y-.624
G03X3.1578Y-.6425I.1445J-.0442
G01Z.25
G00X2.7242Y-1.0125
Z.1
G01Z-.15F5.
Y-.4535F30.
Z.25
G00X2.5702Y-.8187
Z.1
G01Z-.15F5.
X2.4211Y-.4778F30.
Z.25
G00X2.3035Y-.8187
Z.1
G01Z-.15F5.
X2.5035Y-.2388F30.
Z.25
G00X2.0889Y-1.0125
Z.1
G01Z-.15F5.
Y-.4535F30.
Z.25
G00X1.4801Y-.4539
Z.1
G01Z-.15F5.
Y-1.0129F30.
X1.7067Y-.4539
X1.941Y-1.0125
Y-.4535
Z.25
G00X1.0132Y-1.0129
Z.1
G01Z-.15F5.
X1.3333F30.
Y-.4539
X1.0132
Z.25
G00X1.3333Y-.7501
Z.1
G01Z-.15F5.
X1.0586F30.
Z.25
M30
%
```

Handle Arm Back

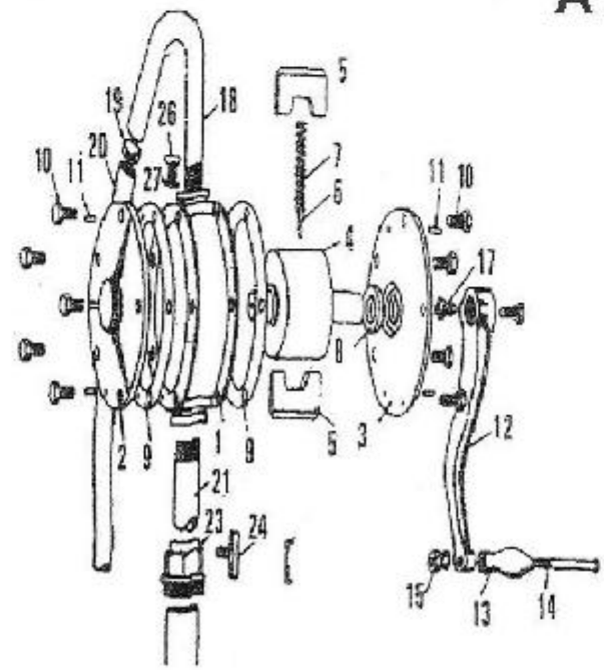
```
%
O1447
(handle_arm_back)
(Part is located at back side and
right side of already cut side, top
of finished part)
G90G80G54G40
(Facing top)
T1M06 (1/2" HSS 2 flute end mill)
S2400M03
G00X-.251Y.251
G43Z.5H01M08
Z.35
G01Z0.F20.
X6.251
Y.032
X-.251
Y-.187
X6.251
Y-.406
X-.251
Y-.625
X6.251
Y-.844
X-.251
Y-1.063
X6.251
Y-1.282
X-.251
Y-1.501
X6.251
Y.251
X-.251
Y-1.501
X6.251
Z.5
(Profiling)
G00X-.251Y.251
Z.34
G01Z-.21
X6.251
X-.251
Y-.187
X-.1816
G03X-.25Y-.5I.6816J-.313
G01Y-.625
X-.251
Y-1.063
X-.1816
X-.251
Y-1.501
X6.251
Y-1.063
X6.1816
G03X6.25Y-.75I-.6816J.313
G01Y-.625
X6.251
Y-.187
X6.1816
G03X5.5Y.25I-.6816J-.313
G01X.5
X5.5
G02X6.25Y-.5I0.J-.75
G01Y-.75
G02X5.5Y-1.5I-.75J0.
G01X.5
G02X-.25Y-.75I0.J.75
G01Y-.5
G02X.5Y.25I.75J0.
G01Z.5
G00X6.251Y.251
Z.25
G01Z-.21
X-.251
Y-1.501
X6.251
Y.251
Z.5
M30
%
```

Appendix H: ATD Pump Designs

ORDERING PART#	ITEM#	PART DESCRIPTION
PRT5019-01	1	3 Piece Suction Tube
PRT5019-02	2	Drum Nut
PRT5019-03	3	Plastic Discharge Outlet
PRT5019-04	4	Handle Assembly [illegible]

Figure 8: ATD Pump

ATD-5009



ITEM Nr.	DESCRIPTION	QTY.
1	PUMP CASTING	1
2	COVER PLATE	1
3	COVER PLATE	1
4	SHAFT	1
5	IMPELLER	1
6	IMPELLER PIN	1
7	SPRING	1
8	OIL SEAL	1
9	COVER PACKING	1
10	HEXAGONAL BOLT	10
11	TAPER PIN	1
12	HANDLE	1
13	PLASTIC GRIP	1

ITEM Nr.	DESCRIPTION	QTY.
14	GRIP SHAFT	1
15	NUT	1
17	HEXAGONAL BOLT	1
18	DISCHARGE SPOUT	1
19	HOSE BAND	1
20	VINYL HOSE (Accessory)	
21	SUCTION PIPE ASSEMBLY	1
23	BUNG NUT	1
24	TIGHTENING BOLT	1

ORDERING PART#	ITEM#	PART DESCRIPTION
[illegible]	18	[illegible]
[illegible]	12,13,14,15	HANDLE ASSY [illegible]
[illegible]	[illegible]	IMPELLER SET [illegible]
[illegible]	[illegible]	OIL SEAL [illegible]
[illegible]	21	[illegible]
[illegible]	[illegible]	DRUM NUT [illegible]

Figure 9: ATD Pump Exploded View