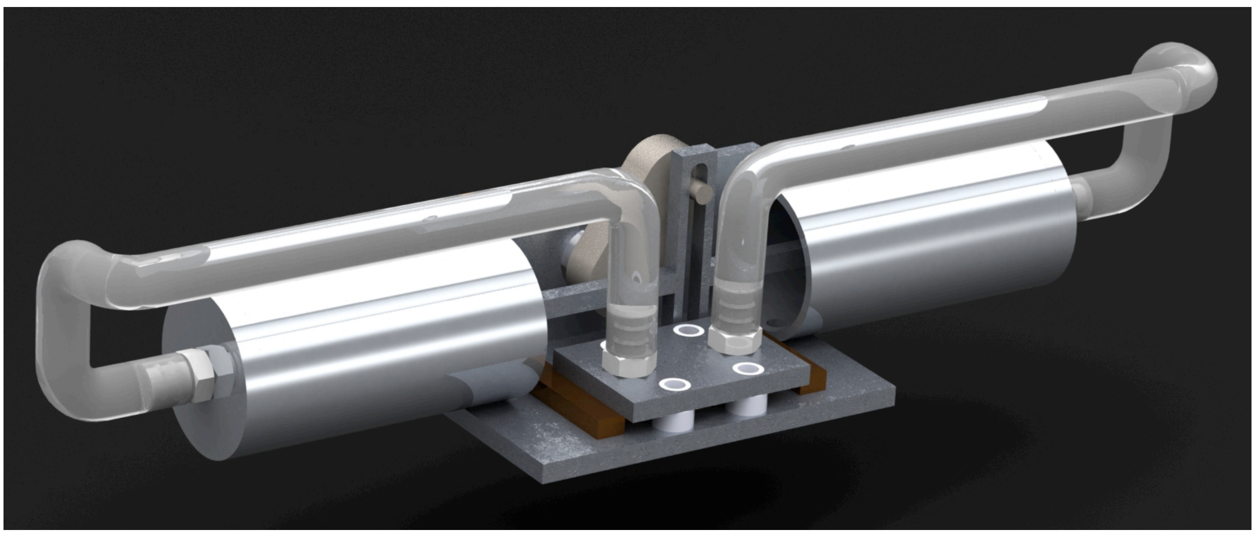
MAE 2250 Spring 2014

Section 406

Air Motor Design Report



Updated: April 14th, 2014

Group 6D:

Trevor Alexander
Sarah Angle
Maggie Bradley
Orlando Farias

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# Section 1: Team Overview

**Team Contact Information:**

Trevor Alexander - tsa37 - 858.414.4652
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Maggie Bradley - mbb242 - 207.807.8426
Orlando Farias - of39 - 956.827.8872

**Meeting Minutes:**

Meeting 1 - March 22nd, 2014 - Libe Cafe, Olin Library. All members attending.

At our initial meeting, we first wanted to go over everyone's strengths and weaknesses, preferences, goals for the project, and other items of interest that would really change the effectiveness of our group. Sarah mentioned that she was pretty good at putting together reports, and was a decent machinist, however, CAD was not her forte. Orlando said that he really liked machining, and would like to focus on hands on work. Trevor stated that he was not good at machining, but that he was willing to put time into it as long as he had help and guidance in Emerson. Finally, Maggie mentioned that she really likes machining and CAD, but that she was not great with marketing and initial decision work. We then talked a bit about our project goals. Everyone agreed that simplicity was key - we all knew groups who had struggled to put together a functioning motor, and that our key goal was making something that worked, and that we understood each part of. After this, we also talked about our preferences for work strategies, and mostly came to the conclusion that we'd like to have shorter meetings, and try to split up the work as much as possible, rather than all doing it together. For this, we agreed that everyone being prepared with their assignments was key to our progress.

Net, we moved into talking specifics about the first week's deliverables. We discussed that we needed a PDR presentation, where we had basically decided the general design of our motor. We discussed a bit the types of motors (piston, rotary, Tesla) but came to the conclusion that we all needed to do a little online research. The items we identified needed to be created were: Gantt chart, Specification chart, Morph chart, and designs / decision matrix. Maggie agreed to create the specification chart, Sarah the Gantt chart, and all, the morphological chart. We would meet on Thursday, March 27th, everyone having done these assignments, to review each other's work, create three motor designs, and then use a decision matrix to choose which of these designs to pursue.

Meeting 2 - March 24th, 2014 - Taylor Design Studio. All members attending.

We got some impromptu meeting time in during Monday night lab this week. So, our group started going over some categories we would need in our morphological chart, as well as some general motor designs we had found while going researching motors. We mentioned the three general motor types we could choose from, piston, rotary, and Tesla turbine. Maggie mentioned that it would be important to keep tolerances in mind when choosing a motor, as this would greatly affect our ability to machine it, and the time it would take to do so. We found that two large cons of rotary and turbine designs were cost (of large cylindrical housing) and tight tolerancing of airtight pieces. Tesla turbines also had the con of figuring out how to gear rotations down, as McMaster did not have a good selection. Piston cylinder motor designs have the pros of being cheap, and having pre-made parts from Emerson, but the cons of finding a timing mechanism and designing a few more pieces of housing, timing, and motion conversion. Finally, we identified the following as potential rows of our Morphological chart: general type, timing mechanism, enclosure, linear to circular motion conversion, and materials.

Meeting 3 - March 27th, 2014 - Duffield Atrium. All members attending.

To start this meeting, we went over the work that everyone had done on their own. Sarah's Gantt chart was pretty straightforward. Maggie hadn't finished the Specification chart yet, but promised to do so in time for the PDR and design report due date. Then, we went over the Morphological charts everyone had worked on. We were happy with the breadth of options we covered, and had good drawings/descriptions of each ready to be compiled into the chart.

Then it came time to create three designs to analyze. We really liked the concept of piston cylinder motors, based on the variety of options and understandability of the thermodynamics and such that go into the design, so we chose to make two different designs of this type. Then we included a rotary motor design, because they are fairly simple, and we had seen groups execute these types of design successfully in the past. Our first design was a two cylinder piston motor, with opposed cylinder layout, scotch yoke conversion, and timing based on intake/exhaust placement. The second design has two cylinders acting in parallel, turning a bent crankshaft. Finally, our third design is a rotary motor, basically the simplest version of its type. To choose between these, we put together a decision matrix that took many categories, based on feasibility and performance, into account. Using this tool, we found design one to be the most optimal. Finally, we split up responsibilities for the next week. Maggie and Trevor would make PDR slides, and Sarah and Orlando would formalize the report.

Meeting 4 - April 7th, 2014 - Taylor Design Studio. All Members Attending.

Once again, after presenting in lab, we got about an hour of time to work on the next week's tasks. It was pretty clear to our group what the focus was for week two - the CAD model. But, we still had things to do before we could start the model. First, we wanted to talk about timing. After talking to other groups who had done the motor project previously, it was clear that the cause of failure for piston-cylinder designs was the timing mechanism. Placement of the intake and exhaust ports would not be enough. Sarah suggested a sort of bumper design. That is, the linear motion of the scotch yoke hits a metal piece back and forth. This metal piece, when hit one way or the other, opens the intake for one of the pistons. A couple other designs were brought up, all using about the same basic concept to take advantage of scotch yoke motion to control timing. In the end, we chose Sarah's design because of it's simplicity. We also agreed to meet the following afternoon in Duffield Atrium to do the brunt of the week's work, really honing in on the specifics of our design and assigning responsibilities for the week.

Meeting 5 - April 8th, 2014 - Duffield Atrium. All Members Attending.

We had a lot of work to do this week, so we tried to meet early on to start taking on tasks. The big goal we had for the meeting was to define most of the geometries of our motor down, so that way we could begin making a CAD model. To do this, we drew a large picture of our design, and discussed the different pieces we still needed to figure out. Our first challenge was deciding timing, and we chose the bumper system, because of its simplicity. The second issue was intake and exhaust. We wanted the intake to be run through the timing mechanism. Then, we decided to make several exhaust ports along the body of the cylinder, which we could then test by plugging certain ports with aluminum tape to decide on the most optimal exhaust location. The third problem was how to attach the separate pieces to a base. We discussed a few options, using screws, welding, and metal tabs to hold pieces securely, but we ultimately decided to wait to make this decision until we saw the CAD and the pieces in place. Finally, we discussed the flywheel, and having an output shaft that held our crank and the 2kg flywheel securely. We decided the shaft should likely be steel, but may be solid shaft or tubing depending on price and availability. We also started compiling a parts list, to be completed once we saw the CAD model as well. Lastly, we split up tasks for the week. Orlando was to begin costing the pieces we knew we were purchasing, look into intellectual property domains, and begin preparing CDR slides. Sarah was to CAD the timing mechanism she had suggested, and do all hand calculations and analyses for the motor. Maggie was in charge of CAD-ing the piston heads with cones, since she had experience with those, and was also to put together the assembly of the separately CAD-ed parts. Finally, Trevor was to CAD the other parts. These assignments were to be done on Friday, when our next meeting was scheduled.

Meeting 6 - April 11th, 2014 - Duffield Atrium. All members attending.

When everyone met up, we identified some goals for the meeting. We needed to, primarily, look at the CAD, and see what needed to be changed, as well as design a framing system for the motor. In line with this, we needed to compile a parts list, and understand whether we fit in our budget or not. When we saw the CAD assembly, the framing method we mainly talked about was having a base plate and backplate. The cylinders would screw into both of these. Then, the output shaft would go through a bushing in the backplate. Finally, the timing mechanism would be threaded into the backplate. Then we began putting together a parts list for our cost analysis. We realized we could buy virtually everything from Emerson, with the exception of the rod ends and tube fittings (since we wanted the cheaper plastic ones.) This gave us the advantages of cost and waiting time. Still, we were over budget. To help this, we decided to try to eliminate the most costly piece of our budget - the large aluminum disk to make the flywheel our slider crank attached to. So, we decided to make more of a crankshaft arm out of much cheaper stock aluminum from Emerson. After this, we just had to take on responsibilities for the weekend. Orlando was to write up the cost analysis, and work on the CDR presentation. Trevor was to work on the CDR with Orlando, as well as make an animation and photorealistic shot of the motor assembly. Sarah was to write the design report. Finally, Maggie was going to finish the assembly with hardware and all, as well as make production drawings and instructions for each part we need to make or modify. She also was going to begin using ANSYS to analyze some of the static loadings Sarah had done by hand. Everyone had to have these tasks finished by Monday evening, and had to upload it so other group members could reference it when it was complete.

Meeting 7 - April 15th, 2014 - Libe Cafe. All members attending.

The biggest issues we identified to start the meeting were finalizing the back plate/base plate setup, affirming the scotch yoke’s dimensions, and ordering parts. We realized one big bottleneck was that editing one piece caused many other pieces in the CAD to change. Because of this, Maggie had to do a lot of work editing the CAD, and that specific work load couldn’t really be distributed. However, we realized a couple good solutions for our motor (turning the timing sideways, and using a shorter baseplate, which saved us both time and money. Using these changes, we figured out a final parts list to order, which Orlando put together and sent to our TA to be ordered, so we could begin manufacturing ASAP. We also split up parts, as in who would machine what. Maggie is taking on the piston heads, scotch yoke, cylinders, welding, and output shaft. Sarah's going to do the whole timing mechanism, that is, base plate, timing slider, timing output, and elbows. Trevor and Orlando are going to split up the final parts, the back plate, cones, crank arm, and pin. Everyone's going to try to have these parts done for the fourth week lab, that is, April 28th. Other responsibilities for the week are: Maggie and Trevor, updating CAD Model, Sarah, design report, and Orlando, ordering.

Meeting 8 - April 25th, 2014. Taylor Design Studio. Sarah, Trevor, and Orlando.

We had a sort of impromptu meeting on this day, just to talk a bit about machining. It was going sort of slowly, and we wanted everyone on the same page. Our members had a really hard time getting time slots in Emerson, so we hadn't made much progress. Still, it seemed like we were on track, and Sarah and Orlando just checked up on some measurements to make sure the back and base plates fit together. We all still had a bunch of machining work to do, but we aim to finish all our parts by next Thursday or Friday - giving us the weekend to assemble, test, and create media for our FDR. This isn't a ton of time, but should allow us enough to prepare a good FDR, and tweak the necessaries on our motor.

Week 5 - Informal messages and coincidental Emerson meetings.

This week, we really didn't have any formal meetings, as everyone was spending tons of time machining and working on other classwork. Here we summarize the main points we mentioned to each other when we were messaging or talking about our project. On Monday night in lab, Maggie basically said she needed some help getting her parts done. She had taken a lot more machining on, and had not been able to reserve enough time in Emerson. So, the steel pin and output shaft were going to be completed by others. That night in Emerson though, we were very effective. The pin and output shaft both were nearly finished, Trevor managed to make a big start on the cones, the flywheel arm was finished, as was the backplate, and Maggie was able to make a lot of progress on the piston heads. However, at the end of lab Sarah noticed that the backplate and baseplate didn't fit together to allow for the cylinders in the right way! Orlando agreed to modify the baseplate that week. Sarah would finish the pin, output shaft, and timing elbows. Trevor would finish the cones, and Maggie would finish the scotch yoke, piston heads, and cylinders.

Then, when Sarah picked up the cylinders later in the week from Joe, the inner diameter was way larger than promised on the 2250 website. Luckily, later in the week, Maggie was able to trade them for some unbored cylinders, and bore them very slightly to get a good fit on the piston heads. The modified baseplate Orlando made also fit together well.

Over message during the week we discussed some responsibilities for our report/FDR. For the FDR, Trevor said he'd make an exploded view of our motor. He would also make a user manual for our final report. Orlando was in charge of testing the quantitative functions of our motor. Maggie agreed to take pictures and videos of the motor. Finally, Sarah was to make a spec/feature chart, competitive analysis, and compile these elements into the report. We also agreed to tentatively meet over the weekend, likely Sunday, to assemble our motor and finalize things for the final deadlines.

Week 5 - May 5th, Day of FDR and Testing.

This day was sort of crazy. First, Maggie went to Emerson to finish some machining, then went to weld the cylinders to the end caps. Meanwhile, Sarah, Trevor, and Orlando spent most of the morning filing the piston head cones and assembling the piston head setups. Sarah and Orlando also decided to present the FDR, and touched up the slides so that they looked nice and were complete.

After these two tasks were done, towards the afternoon, we began trying to assemble the motor. To do this, we still need to drill our cylinders. Maggie jigged them up to the aluminum back and baseplates, so that the holes for securing the cylinders were lined up correctly, then cut the holes with a hand drill. We soon noticed a problem though. Our stroke length was too long for our cylinders! We measured the cylinders (we had assumed they were 4", as Joe said they were) and found they were really more like 3 1/4". So, we did two things. Sarah cut a new crank arm, with it's holes closer together, and Maggie cut down the scotch yoke length, so it wouldn't bottom out at the end caps. After assembling again, the stroke length was shortened again, to less than two inches, and our motor could be spun by hand. Though it was shakey, we tested, but unfortunately did not get RPM or torque out of our air motor.

**Presentation Materials:**

**PDR**

# Preliminary Design Review

Created by:
Sarah Angle
Trevor Alexander
Maggie Bradley
Orlando Farias

## Designer Goals

- Reliable Concept favored over risky designs.
- Not reinventing the Air Pump.
- Low tolerance on machined parts (+/-0.002 on lathe and +/-0.004 on mill)
- Careful Prior Analysis before any machining or ordering.
- Clear understanding of design concept for all members of group.

# Customer Needs

- The prototype is required to operate on a regulated 40 PSI outlet at 0.012 m^3/s and operate below 1000rpm.
- For testing, it must be possible to clamp the motor firmly in a vice with a maximum 4" opening.
- During testing, the motor must support a 2Kg flywheel + 10Kg maximum downward force at the tip of the axis.
- If using cylinders, the cylinder bore diameter is fixed at 1.760”, wall thickness 0.120", due to material availability
- Motor mount geometry, drive shaft and air intake must conform to the specifications below.
- Static load computations must be performed with a safety factor of 2.0
- The high operating pressure requires adequate safety and failure constraints in the event of catastrophic failure during operation

# Consumer Specification Chart

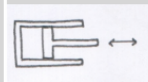
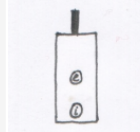
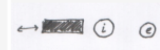
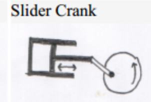
**Air Motor Preliminary Design**
**Consumer Specification Matrix**

| Prompt | Consumer Statement | Interpreted Need |
|---|---|---|
| **Use of Air Source** | The motor should work with my pressurized air source. | The prototype is required to operate on a regulated 40 PSI outlet at 0.012 m^3/s |
| | The motor cannot run too fast given air source. | Motor operates below 1000rpm. |
| **Use and Adjustment** | I should be able to secure my motor for regular shop use so it will not rattle. | Possible to clamp the motor in a vice with a 4" opening. |
| | The shaft of the motor should be strong enough to support itself and my use for it. | Must support a 10Kg downward force at the tip of the axis. |
| **Application** | I should be able to use the motor for a flywheel. | Must support a 2Kg flywheel. |
| | The price should be reasonable, as should the weight and material use. | Cylinder bore diameter is fixed at 1.760”, wall thickness 0.120". |
| | I would like the motor to meet the geometries and sizing that I need. | Motor mount geometry, drive shaft and air intake must conform to consumer specifications. |
| **Safety in Operation and Reliability** | I do not want to have to start or touch the motor after air inlet is attached. | Self-start at any state once connected to air pressure. |
| | I need the motor to not hurt me in the event of a catastrophic failure. | Adequate safety and failure constraints in the event of failure. |
| | I want the chance of failure should be mimimal (reliable). | Designed with a safety factor of 2.0. |

# Morph Chart

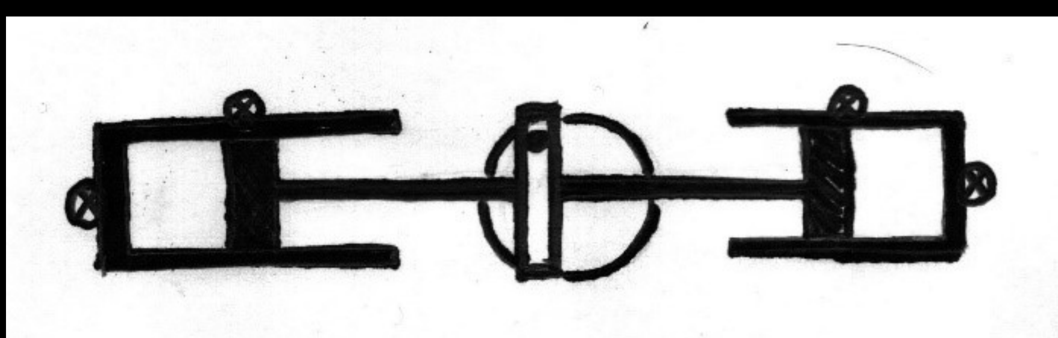
Basic design aspects given Morph Chart, Decision Matrix, and Group Brainstorming

- Piston Cylinder
- Slider Mechanism
- Aluminum Sleeves
- Scotch Yoke
- 2 Pumps
- Opposed Pumps
- Medium Pump Sizing
- Reduce Friction
- O-ring Groove
- Aluminum and Limited Acrylic in nonstructural parts

| | | | | |
|---|---|---|---|---|
| **General Motor Type** | Piston Cylinder  | Tesla Turbine  | Rotary Vane  | |
| **Timing Mechanism** | Timing Belt | In/Ex Placement  | Slider/Blocking  | |
| **Closure/ Housing** | Aluminum sleeving | PVC tubing | | |
| **Converting Motion** | Scotch Yoke  | Hinge  | Slider Crank  | |
| **Pump Layout** | Opposed (Facing) | Cross (4 Facing Inwards) | V-shaped | |
| **Sealing** | Epoxy/Glue | Nuts & Bolts | O-rings & Other Rubber Pieces | |
| **Materials** | Aluminum | Steel | Acrylic | PVC |

# Design Variation 1

Scotch Yoke Piston Cylinder



# Design Variation: Scotch Yoke Piston Cylinder

Pros

Simple, Reliable concept

External Design makes troubleshooting more efficient

Easier to source material, more means of online analysis

Machining capale in few setups.

Emerson provides base materials and parts to work from

Familiar with piston analysis and performance through Thermo and Synthesis Lectures

Easy assembly

Cons

Low tolerencing on scotch yoke.

Limited adjustability

Potentially more expensive in materials than a rotary vane concept

A "safe" option which limits innovation

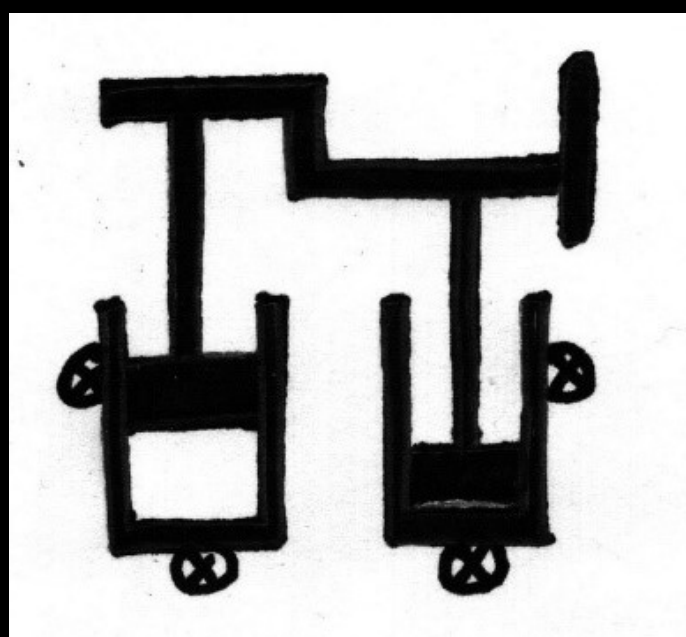
Piston limits adjustability

Machining tolerancing as well as pressure levels make a heavier design

Housing size costs more than a more compact concept

# Design Variation 2

Crank Shaft Piston Cylinder



# Design Variation: Crank Shaft Piston Cylinder

**Pros**

Lower tolerancing than Scotch Yoke

More room for analysis than other variations

Potentially more conservative housing and space needs.

Crank would be unnecessary to machine, lowering cost.

Mimics common designs in everyday items, good for analysis and sourcing

**Cons**

TIG welding crank bars would be time exhaustive, as well as hard to tolerance.

Jigging crank for welding would be expensive and potentially wasteful.

Limited examples available in old course designs, more risky.

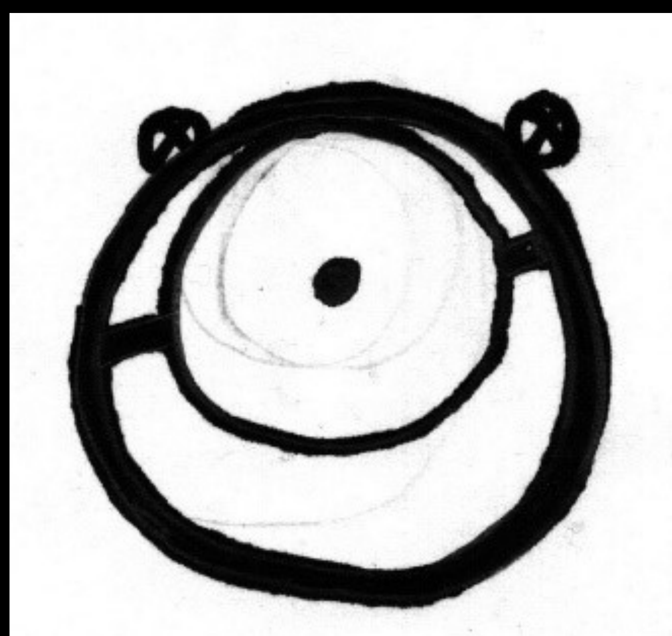
Mitering bars would also be time expensive.

Heavier in the crank than a simple scotch yoke would be.

Bar would need to withstand loading conditions that are difficult to analyze given corner welds.

# Design Variation 3

Circular Rotary Vane



# Design Variation: Circular Rotary Vane

Pros

Most likely a lighter, more compact design than a piston cylinder.

Housing more simple as pumping mechanism is internalized.

Internalized mechanism suggests potential flow analysis that piston cylinder lacks.

More nuanced design suggests the potential for more variations and optimization given analysis results.

Cons

Multiple, low tolerance setups between mill and lathe mean a more difficult and risky machining process for internals.

Internalized mechanics mean a more difficult and theoretical trouleshooting process.

Tolerancing on internal circular pump needs to be extremely low, suggesting a higher propensity for leaks and failure.

AKA less Reliable

Limited housing options and sizing suggests a less efficient design with lower air capacity .

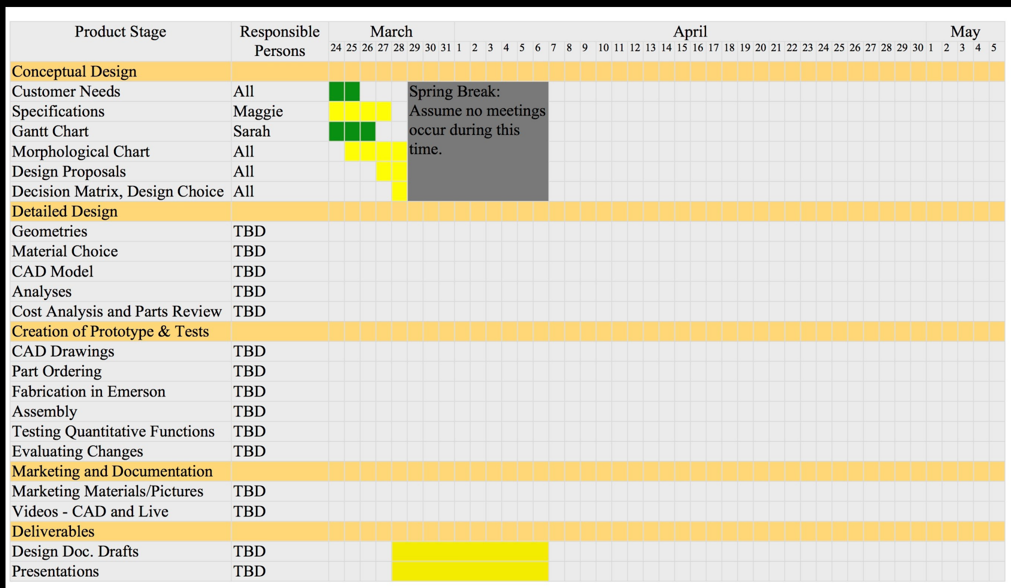
Large outer housing suggests higher structural material costs.

# Pugh Decision Matrix

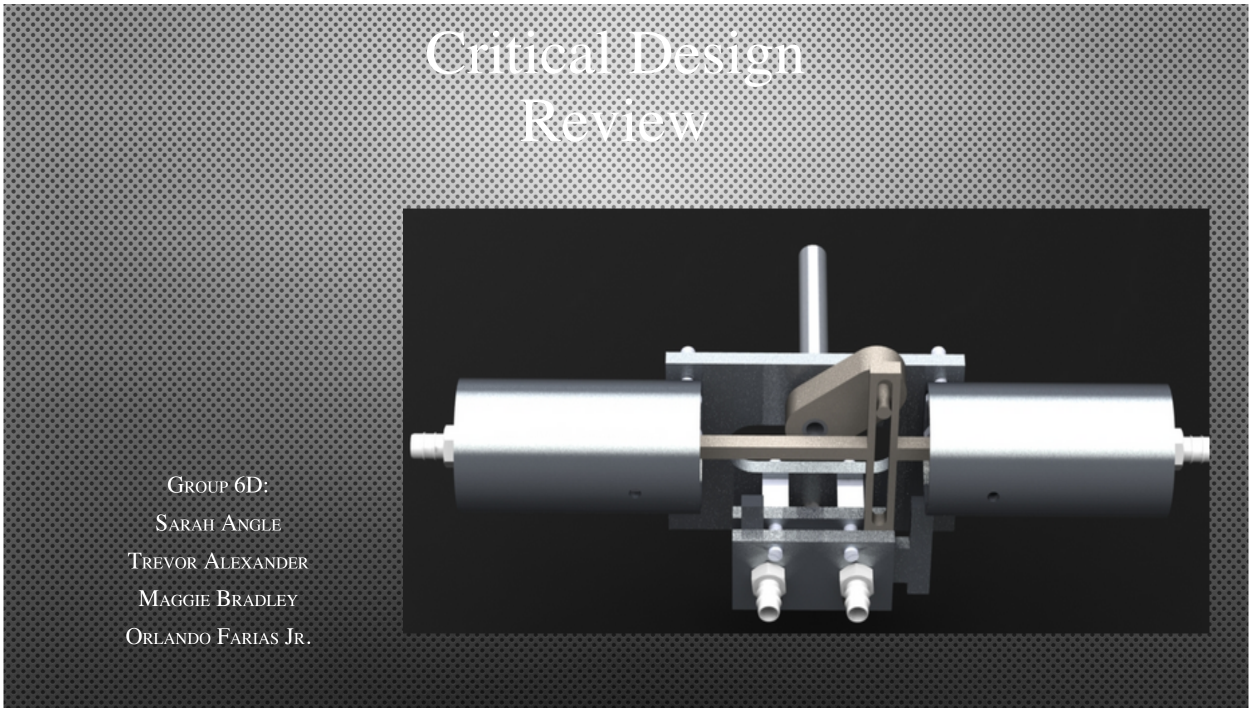
**Decision Matrix:**

| Issue | Importance Factor | Design 1 | Design 2 | Design 3 |
|---|---|---|---|---|
| Reliability | 15% | 10 | 7 | 5 |
| Ease to Manufacture | 15% | 9 | 2 | 2 |
| Tolerance | 10% | 7 | 9 | 3 |
| Cost | 10% | 9 | 9 | 5 |
| Power | 5% | 6 | 6 | 6 |
| Weight | 5% | 5 | 5 | 8 |
| Torque vs. Weight | 5% | 8 | 8 | 9 |
| Ability to Analyze | 8% | 9 | 9 | 10 |
| Testing Ease | 5% | 8 | 9 | 3 |
| Tuning/Adjustment | 5% | 10 | 5 | 4 |
| Student Understanding | 2% | 8 | 9 | 5 |
| Time | 9% | 8 | 6 | 7 |
| Stresses | 6% | 8 | 4 | 9 |
| Total: | 100% | 8.38 | 6.38 | 5.42 |

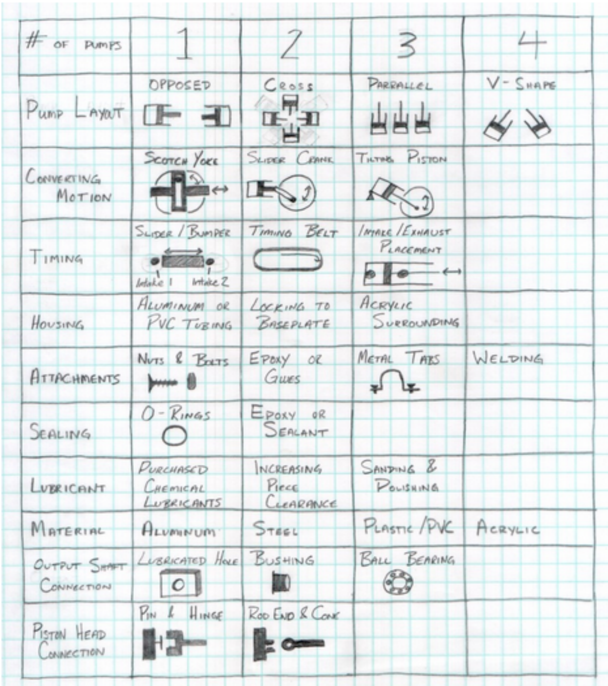
# Gantt Chart


Product Stage
Responsible Persons
March
April
May
24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 1 2 3 4 5
Conceptual Design
Customer Needs All
Specifications Maggie
Gantt Chart Sarah
Morphological Chart All
Design Proposals All
Decision Matrix, Design Choice All
Spring Break: Assume no meetings occur during this time.
Detailed Design
Geometries TBD
Material Choice TBD
CAD Model TBD
Analyses TBD
Cost Analysis and Parts Review TBD
Creation of Prototype & Tests
CAD Drawings TBD
Part Ordering TBD
Fabrication in Emerson TBD
Assembly TBD
Testing Quantitative Functions TBD
Evaluating Changes TBD
Marketing and Documentation
Marketing Materials/Pictures TBD
Videos - CAD and Live TBD
Deliverables
Design Doc. Drafts TBD
Presentations TBD

**CDR**


Critical Design Review
Group 6D:
Sarah Angle
Trevor Alexander
Maggie Bradley
Orlando Farias Jr.


OVERVIEW
Decision Matrix
Design changes since PDR
CAD Model
Pros/Cons
Hand Calculations
Assembly Plans
Cost Analysis
Updated Gantt Chart

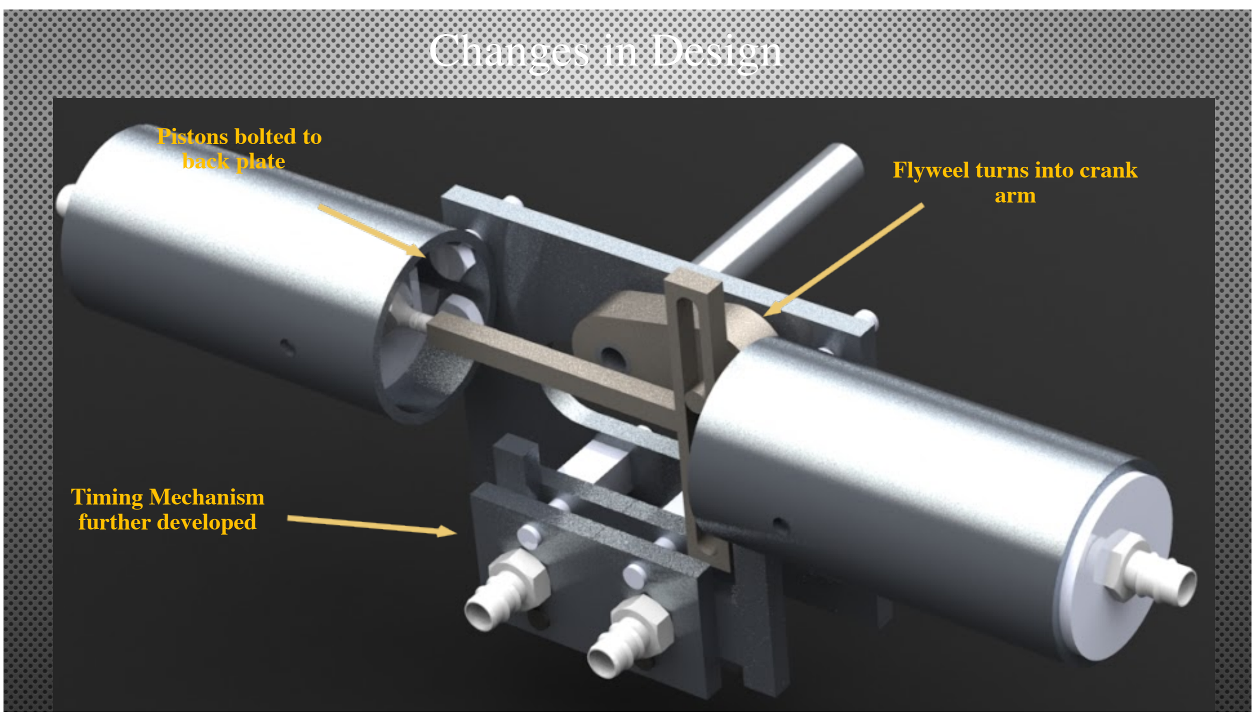


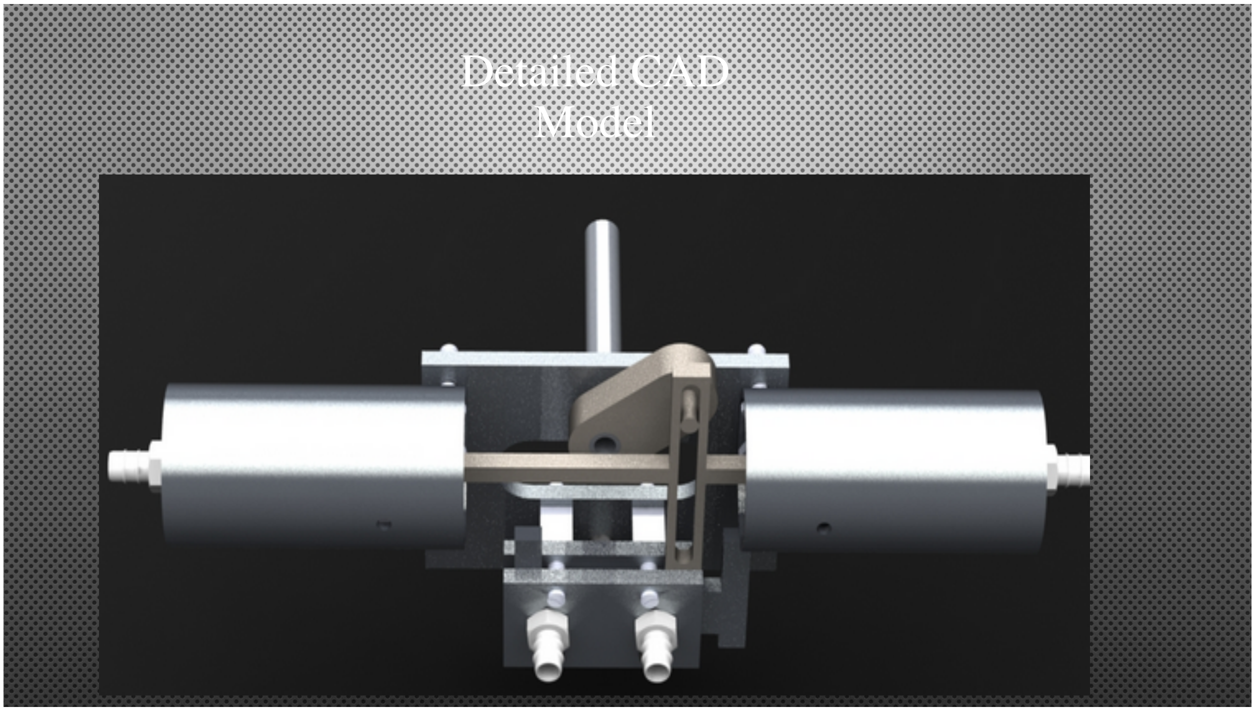
| # of Pumps | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Pump Layout | Opposed | Cross | Parrallel | V-Shape |
| Converting Motion | Scotch Yoke | Slider Crank | Tilting Piston | |
| Timing | Slider / Bumper (Intake 1, Intake 2) | Timing Belt | Intake / Exhaust Placement | |
| Housing | Aluminum or PVC Tubing | Locking to Baseplate | Acrylic Surrounding | |
| Attachments | Nuts & Bolts | Epoxy or Glues | Metal Tabs | Welding |
| Sealing | O-Rings | Epoxy or Sealant | | |
| Lubricant | Purchased Chemical Lubricants | Increasing Piece Clearance | Sanding & Polishing | |
| Material | Aluminum | Steel | Plastic / PVC | Acrylic |
| Output Shaft Connection | Lubricated Hole | Bushing | Ball Bearing | |
| Piston Head Connection | Pin & Hinge | Rod End & Cone | | |

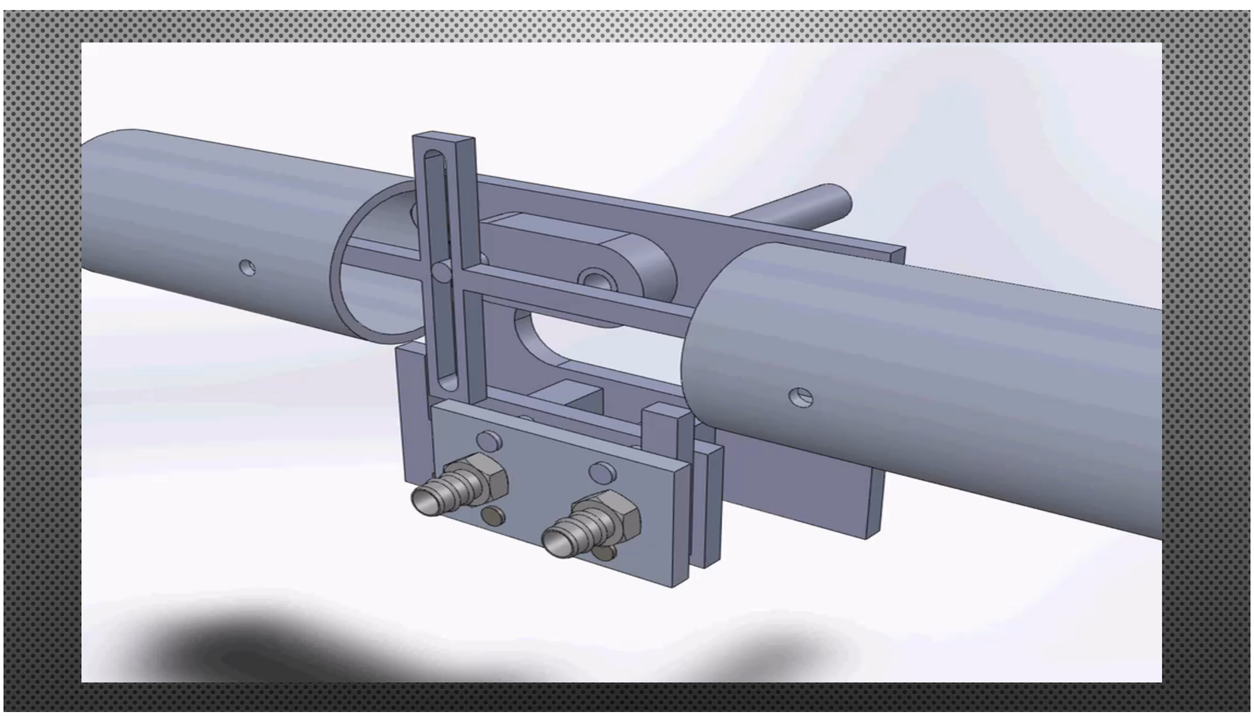
## DECISION MATRIX

Design Specifications:

- 2 Opposing Pumps
- Scotch Yoke
- Slider/Bumper for timing
- Supported by Back plate and base plate




Detailed CAD
Model



## Pros/Cons

Pros:

- Crankshaft arm = less weight and money
- 2 pistons = push back helps timing
- "Bumper" = effective, reliable

Cons:

- 2 pistons = lower power vs. weight ratio
- Bumper = lots of stock, pricey

## Hand Calculations

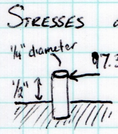
STRESSES IN SCOTCH YOKE

force from air $= (40\ \text{psi})(\pi(.88\ \text{in})^2) = 97.3\ \text{lb}$

axial stress maximum $= (97.3\ \text{lb}) \div (2(1/8\ \text{in})(1/2\ \text{in})) = 778.4\ \text{psi}$

$X = \sigma_u / 778.4\ \text{psi} = 57.8$

STRESSES ON FLYWHEEL PIN



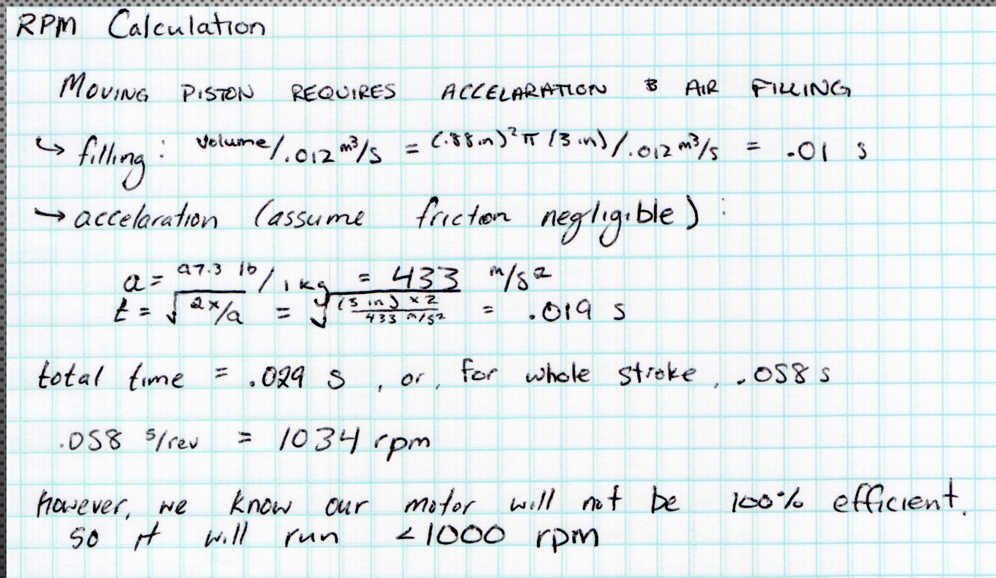

Shear $= 97.3\ \text{lb} / \pi(1/8\ \text{in})^2 = 1982\ \text{psi}$

Moment $= (97.3\ \text{lb})(.5\ \text{in}) = 48.65\ \text{lb}\cdot\text{in}$

Stress $= (48.65\ \text{lb}\cdot\text{in})(1/8\ \text{in}) \div (\pi/4 \cdot (1/8\ \text{in})^4) = 31.7\ \text{ksi}$

$X = \sigma_u / 31.7\ \text{ksi} = 4.3$

## Hand Calculations



RPM Calculation

MOVING PISTON REQUIRES ACCELARATION & AIR FILLING

↳ filling: $\text{volume}/.012\ m^3/s = (.88\ in)^2\pi(3\ in)/.012\ m^3/s = .01\ s$

→ accelaration (assume friction negligible):

$a = 97.3\ lb / 1\ kg = \underline{433}\ m/s^2$

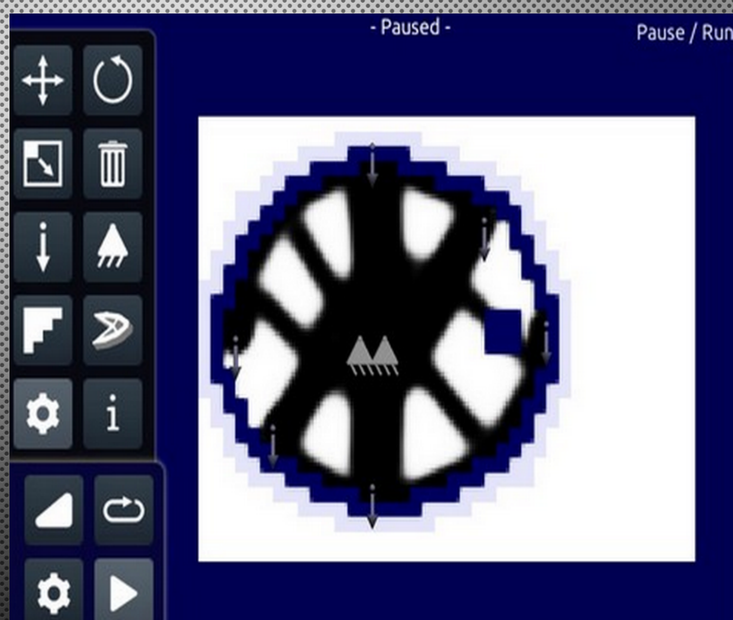
$t = \sqrt{2x/a} = \sqrt{\frac{(3\ in) \times 2}{433\ m/s^2}} = .019\ s$

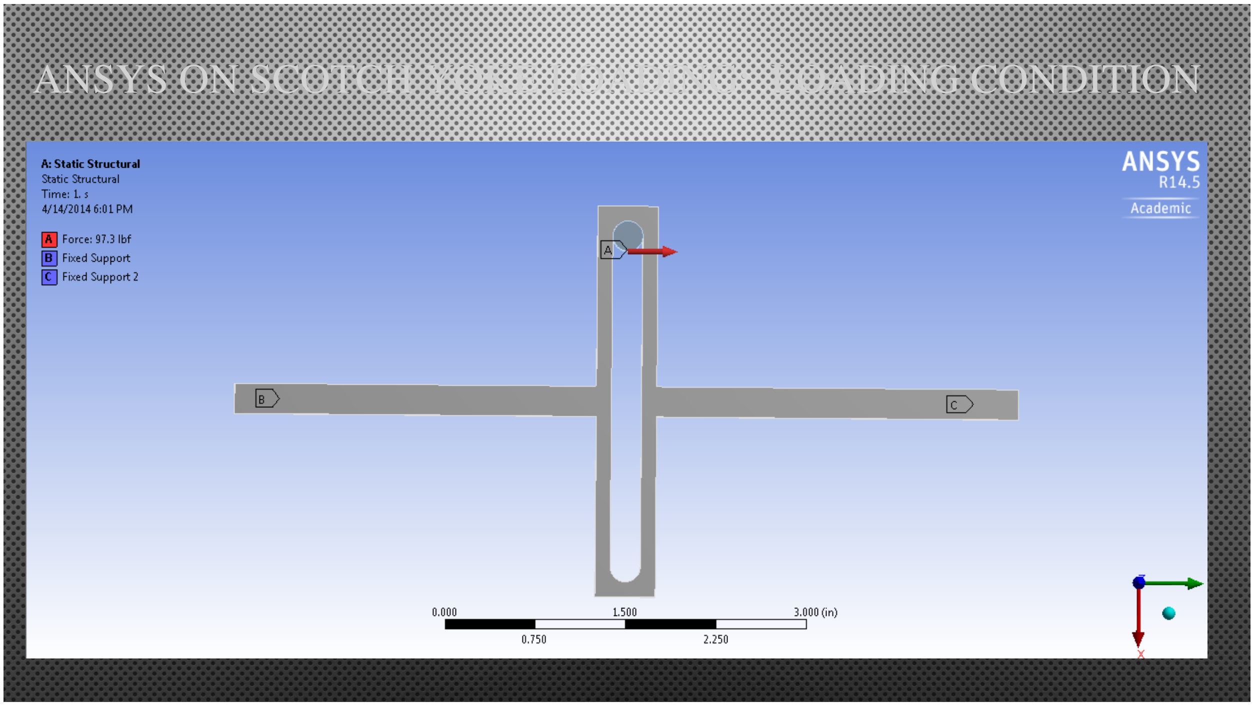
total time = .029 s, or, for whole stroke, .058 s

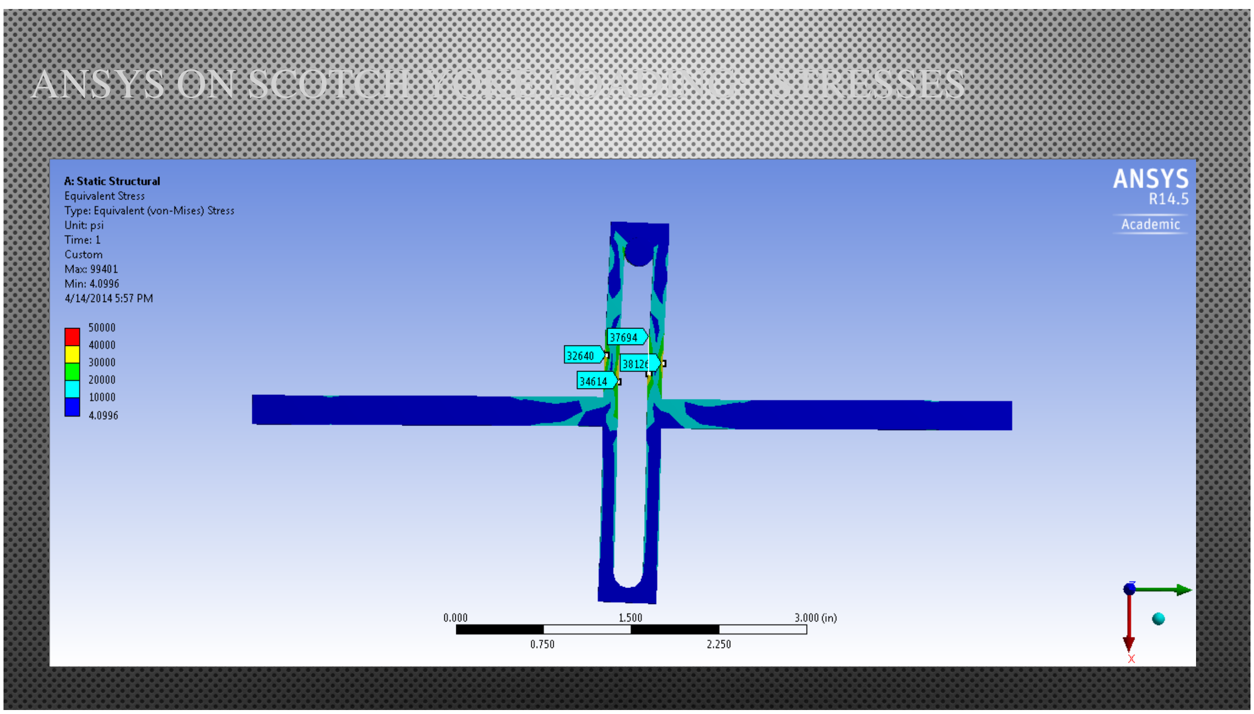
.058 s/rev = 1034 rpm

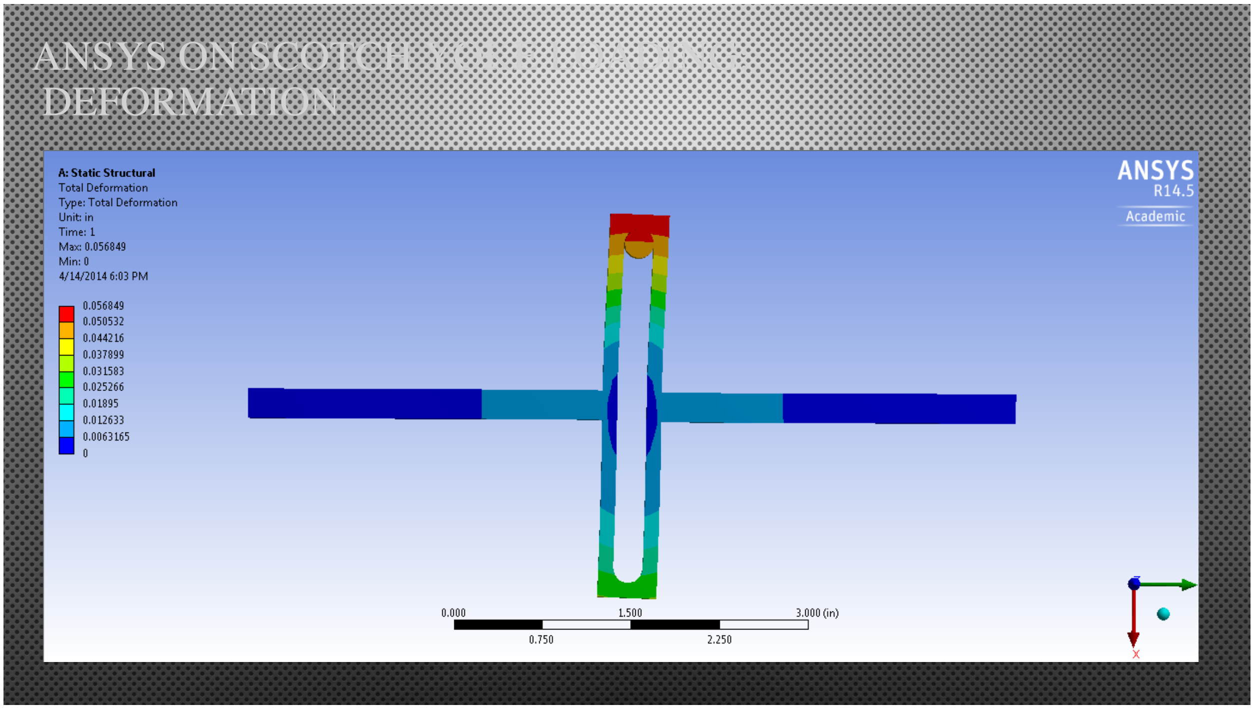
However, we know our motor will not be 100% efficient, so it will run <1000 rpm

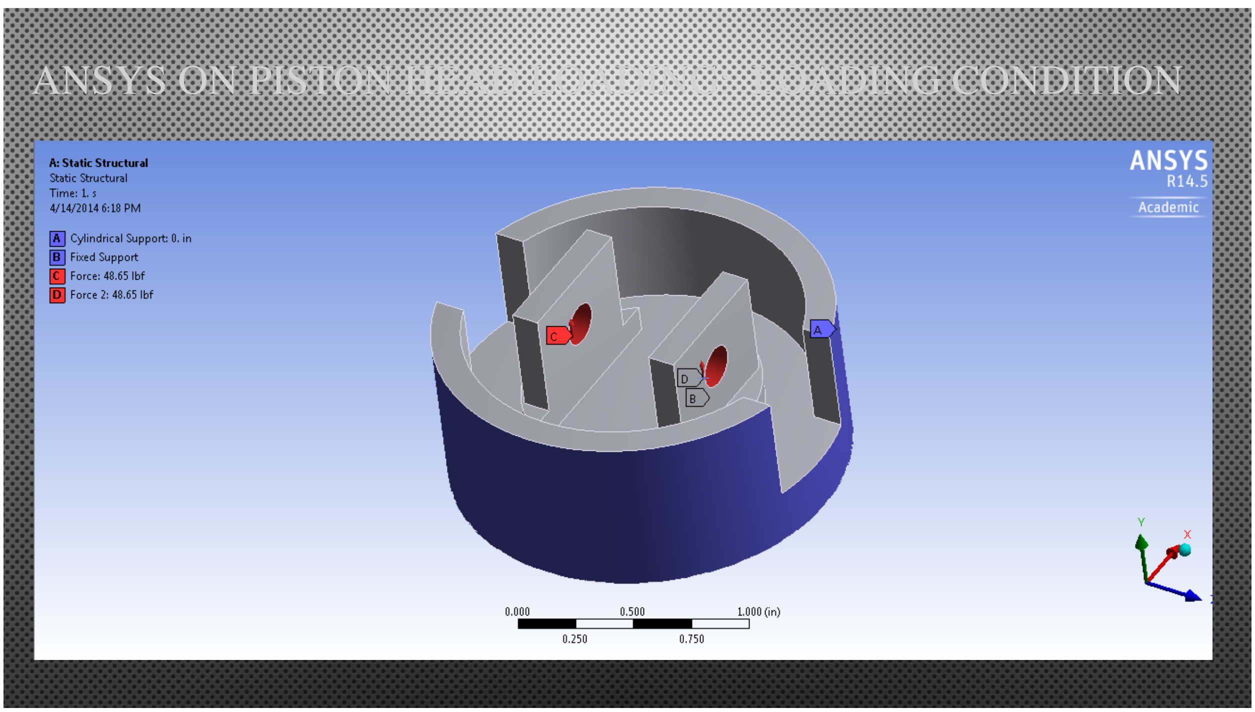
## Topological Optimization

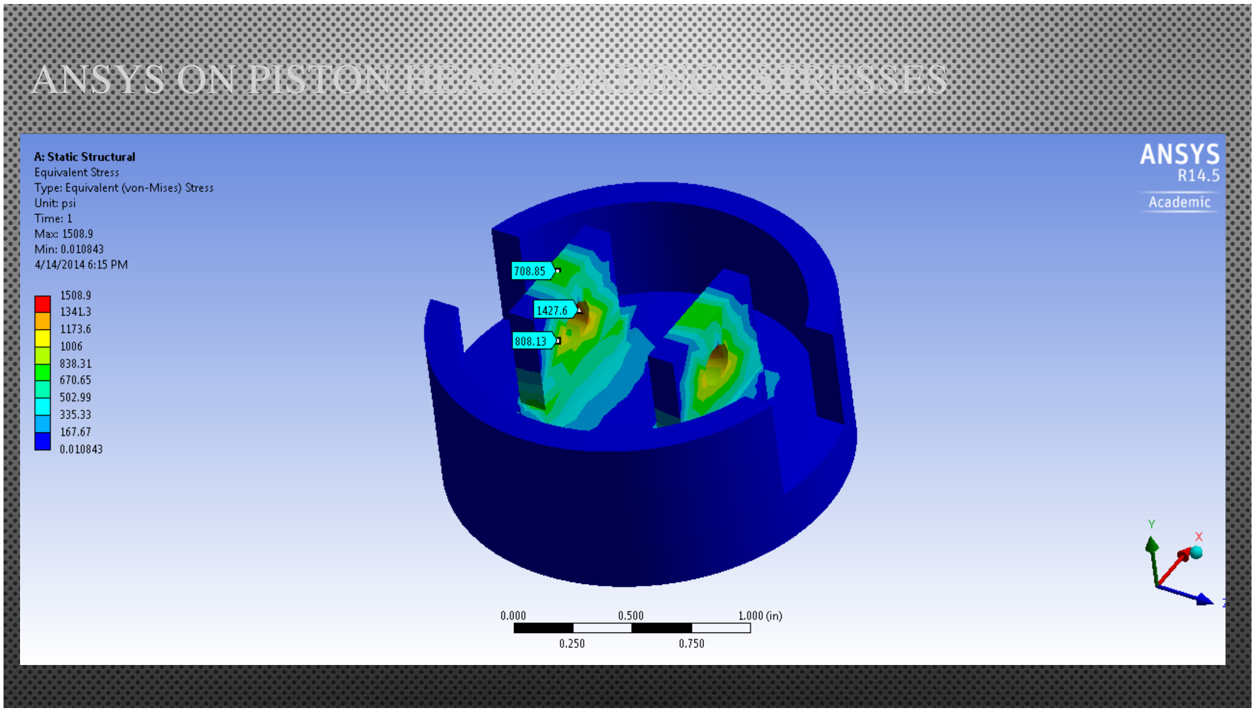


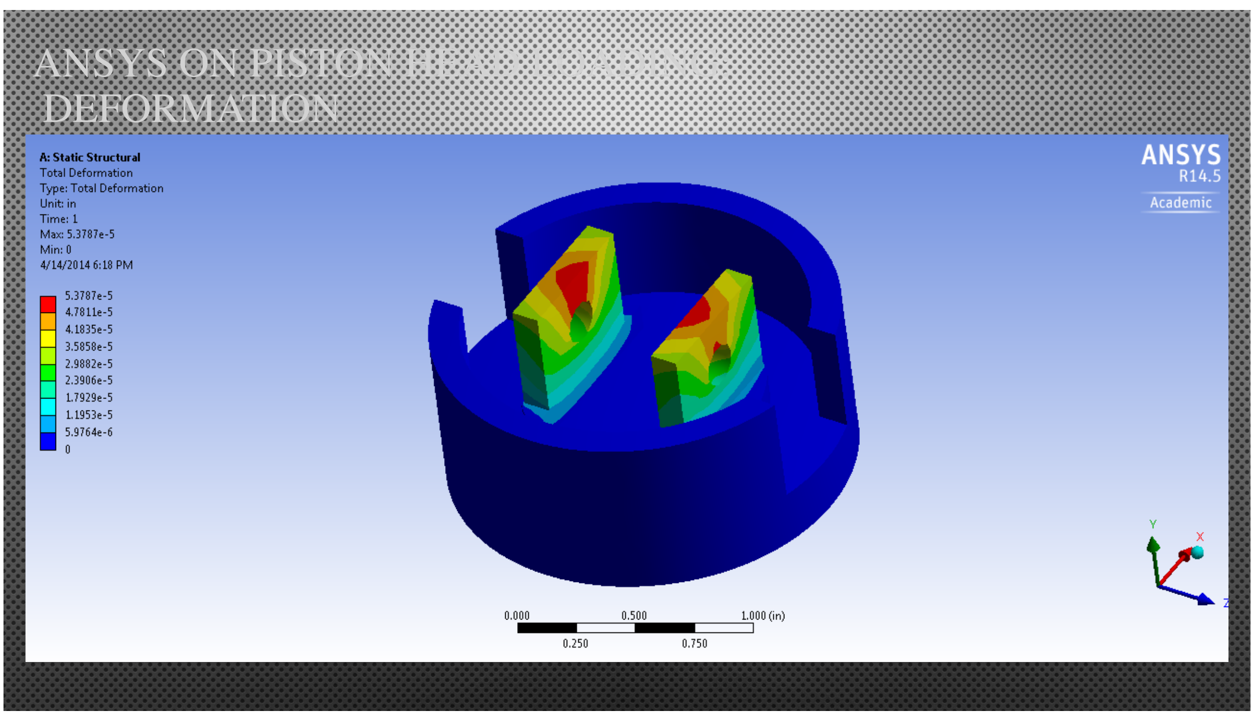

ANSYS ON SCOTCH YOKE LOADING - LOADING CONDITION
A: Static Structural
Static Structural
Time: 1. s
4/14/2014 6:01 PM
A Force: 97.3 lbf
B Fixed Support
C Fixed Support 2
ANSYS
R14.5
Academic
0.000
1.500
3.000 (in)
0.750
2.250

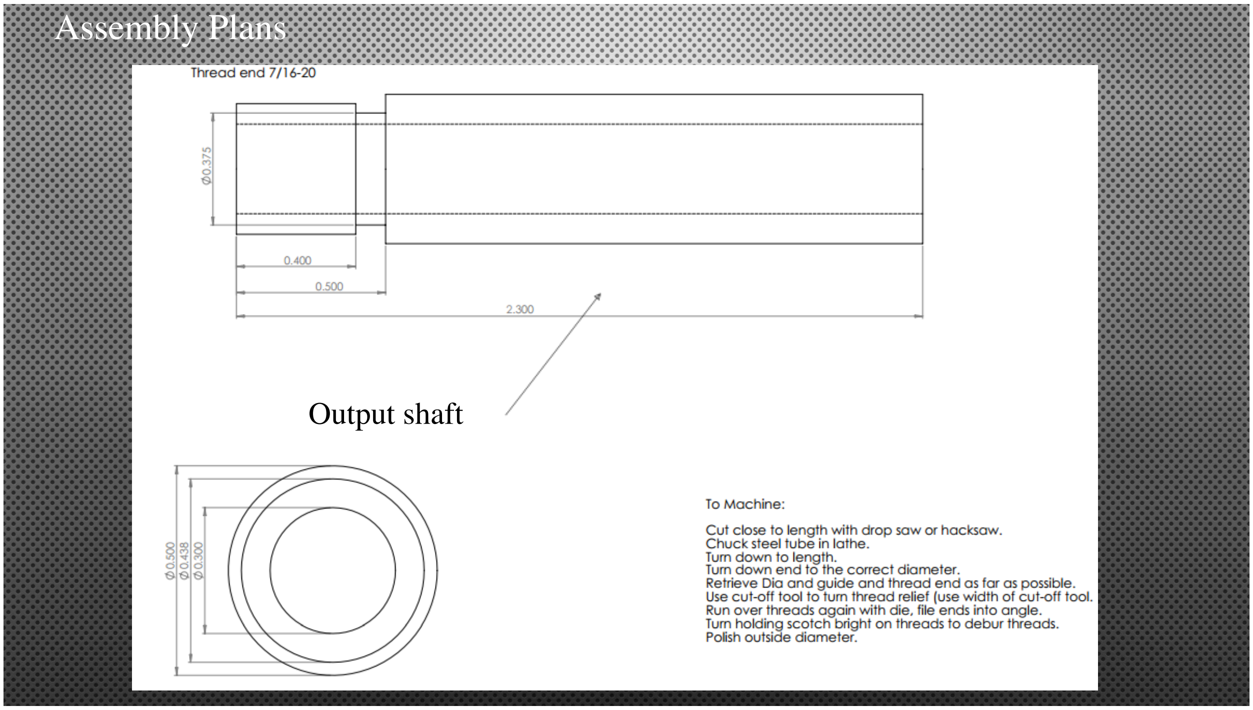

ANSYS ON SCOTCH YOKE LOADING - STRESSES
A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Custom
Max: 99401
Min: 4.0996
4/14/2014 5:57 PM
50000
40000
30000
20000
10000
4.0996
37694
32640
34614
ANSYS
R14.5
Academic
0.000
1.500
3.000 (in)
0.750
2.250

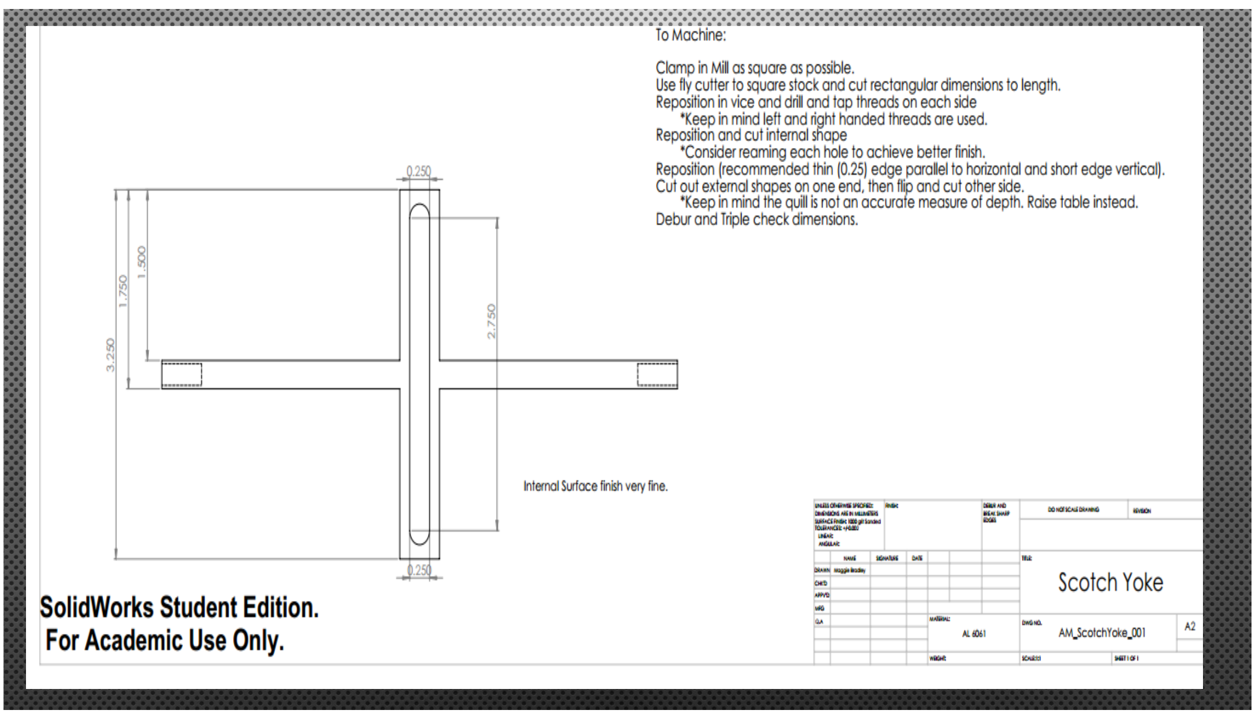

ANSYS ON SCOTCH YOKE LOADING: DEFORMATION
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
Max: 0.056849
Min: 0
4/14/2014 6:03 PM
0.056849
0.050532
0.044216
0.037899
0.031583
0.025266
0.01895
0.012633
0.0063165
0
ANSYS
R14.5
Academic
0.000
1.500
3.000 (in)
0.750
2.250


ANSYS ON PISTON HEAD LOADING: LOADING CONDITION
A: Static Structural
Static Structural
Time: 1. s
4/14/2014 6:18 PM
A Cylindrical Support: 0. in
B Fixed Support
C Force: 48.65 lbf
D Force 2: 48.65 lbf
ANSYS
R14.5
Academic
0.000
0.500
1.000 (in)
0.250
0.750


ANSYS ON PISTON HEAD LOADING: STRESSES
A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
Max: 1508.9
Min: 0.010843
4/14/2014 6:15 PM
1508.9
1341.3
1173.6
1006
838.31
670.65
502.99
335.33
167.67
0.010843
708.85
1427.6
808.13
ANSYS
R14.5
Academic
0.000
0.500
1.000 (in)
0.250
0.750


ANSYS ON PISTON HEAD LOADING:
DEFORMATION
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
Max: 5.3787e-5
Min: 0
4/14/2014 6:18 PM
5.3787e-5
4.7811e-5
4.1835e-5
3.5858e-5
2.9882e-5
2.3906e-5
1.7929e-5
1.1953e-5
5.9764e-6
0
ANSYS
R14.5
Academic
0.000
0.500
1.000 (in)
0.250
0.750

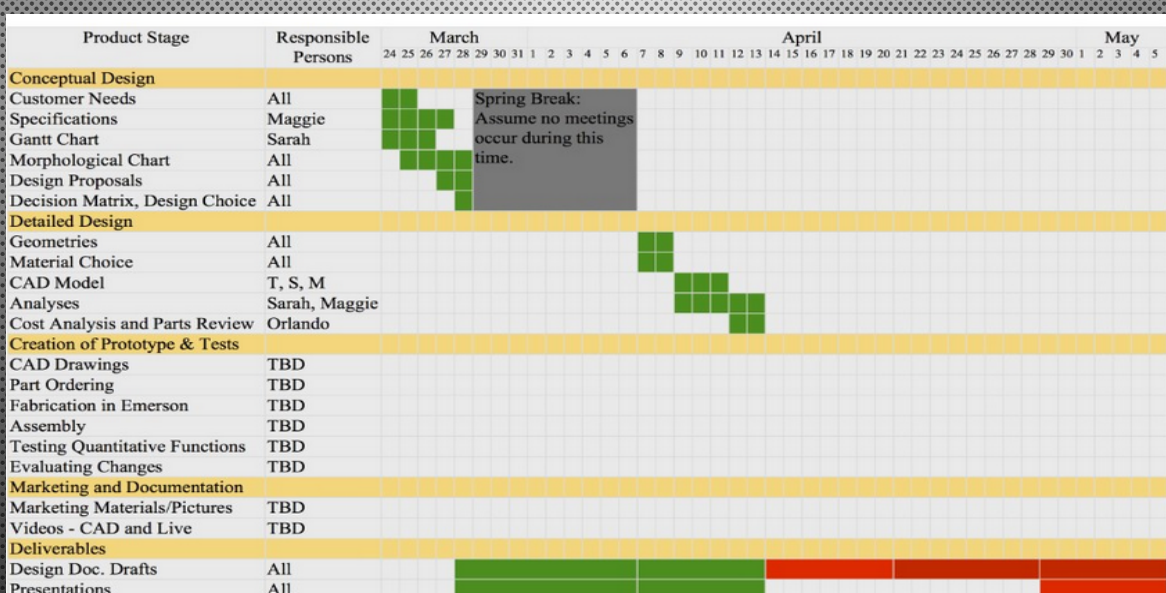

Assembly Plans
Thread end 7/16-20
Ø0.375
0.400
0.500
2.300
Output shaft
Ø0.500
Ø0.438
Ø0.300
To Machine:
Cut close to length with drop saw or hacksaw.
Chuck steel tube in lathe.
Turn down to length.
Turn down end to the correct diameter.
Retrieve Dia and guide and thread end as far as possible.
Use cut-off tool to turn thread relief (use width of cut-off tool.
Run over threads again with die, file ends into angle.
Turn holding scotch bright on threads to debur threads.
Polish outside diameter.


To Machine:
Clamp in Mill as square as possible.
Use fly cutter to square stock and cut rectangular dimensions to length.
Reposition in vice and drill and tap threads on each side
*Keep in mind left and right handed threads are used.
Reposition and cut internal shape
*Consider reaming each hole to achieve better finish.
Reposition (recommended thin (0.25) edge parallel to horizontal and short edge vertical).
Cut out external shapes on one end, then flip and cut other side.
*Keep in mind the quill is not an accurate measure of depth. Raise table instead.
Debur and Triple check dimensions.
0.250
3.250
1.750
1.500
2.750
0.250
Internal Surface finish very fine.
SolidWorks Student Edition.
For Academic Use Only.
Scotch Yoke
AL 6061
AM_ScotchYoke_001
A2

# Cost Analysis

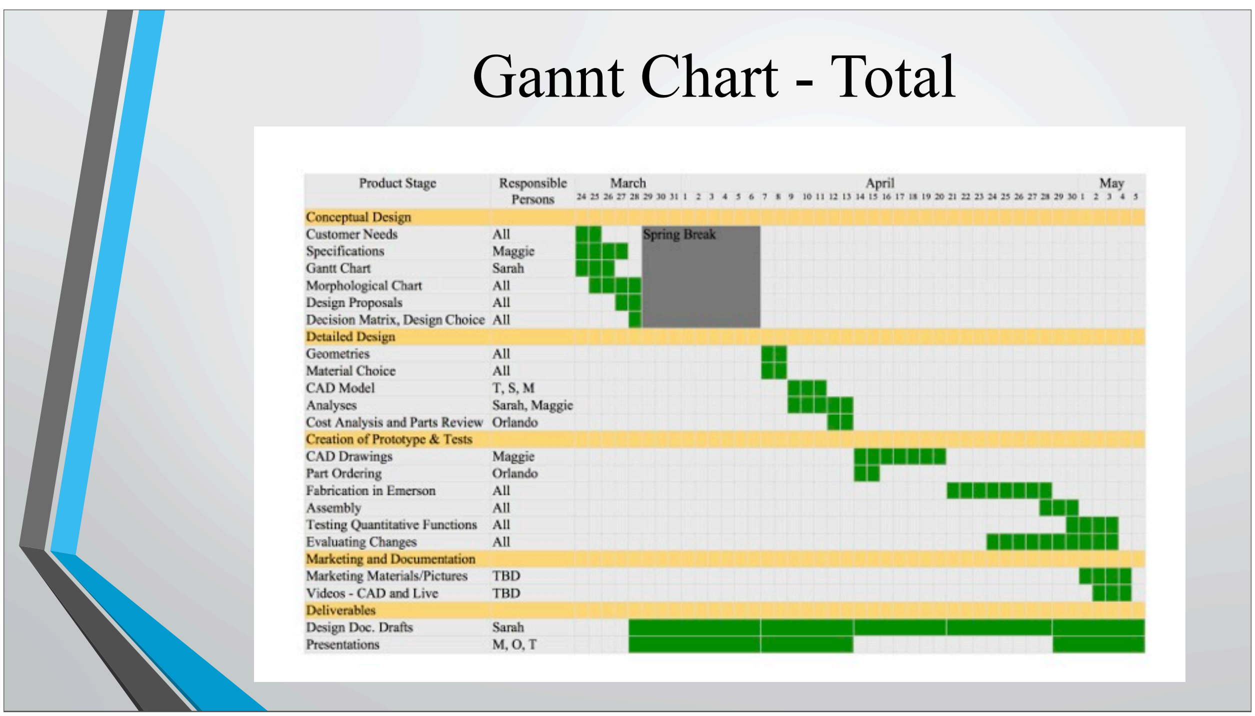
| Item | Purpose | Price per Unit | Purchased from | Quantity | Total ($) |
|---|---|---|---|---|---|
| Cylinders | Piston | $1.00 per Cylinder | Emerson | 2 | $2.00 |
| End Caps | Piston | $1.00 per Cap | Emerson | 2 | $2.00 |
| Rod Ends | Piston heads | $3.52 per rod | McMaster | 2 | $7.06 |
| Tube fittings | Piston | $1.43 per fitting | McMaster | 5 | $7.15 |
| 1/4" diameter steel rod | flywheel pin | $0.10 per inch | Emerson | 2" | $0.20 |
| 1/2" diameter steel rod | output shaft | $0.23 per inch | Emerson | 5" | $1.15 |
| Self-aligning bushing | | $3.00 per bushing | Emerson | 1 | $3.00 |
| Tubing | | $0.31 per foot | Emerson | 4' | $1.24 |
| Threaded rod | Timing mechanism | $1.02 per foot | Emerson | 1' | $1.02 |
| 1/4 - 20 Nuts | Timing mechanism | $0.06 per nut | Emerson | 12 | $0.72 |
| Lock washers | Timing mechanism | $0.02 per washer | Emerson | 10 | $0.20 |
| 1/4" X 2.25" Al 6061 | Timing mechanism | $0.36 per inch | Emerson | 9" | $3.24 |
| 1/2" X 4" Al 6061 | Scotch Yoke | $1.18 per inch | Emerson | 7" | $8.26 |
| 1/4" X 1" Al 6061 | Fly Wheel | $0.14 per inch | Emerson | 4" | $0.56 |
| 1/4" X 2.25" Al 6061 | Base | $0.36 per inch | Emerson | 8" | $2.88 |
| 1/2" X 4" Al 6061 | Back Plate | $1.18 per inch | Emerson | 6" | $7.08 |
| 1/4 - 20 1" Screws | Back Plate | $0.17 per screw | Emerson | 10 | $1.70 |
| | | | | | **$49.46** |

# Gant Chart Bottlenecks



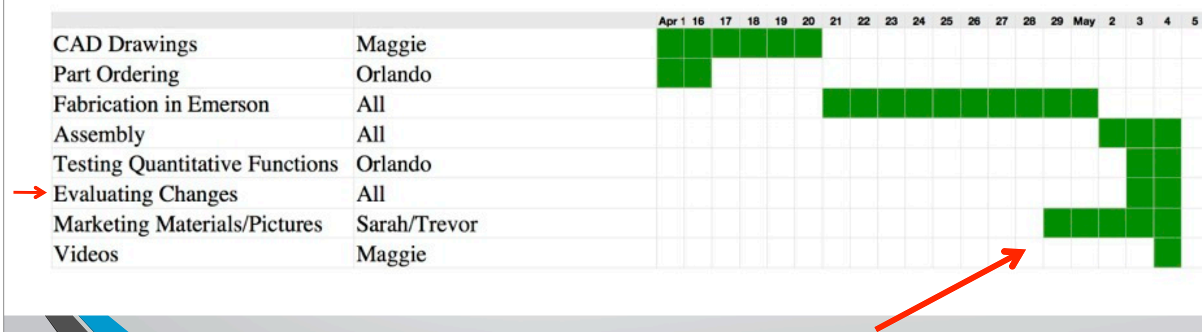
**FDR**


Tuesday, May 6, 14




Tuesday, May 6, 14

# This Week's Progress




Tuesday, May 6, 14

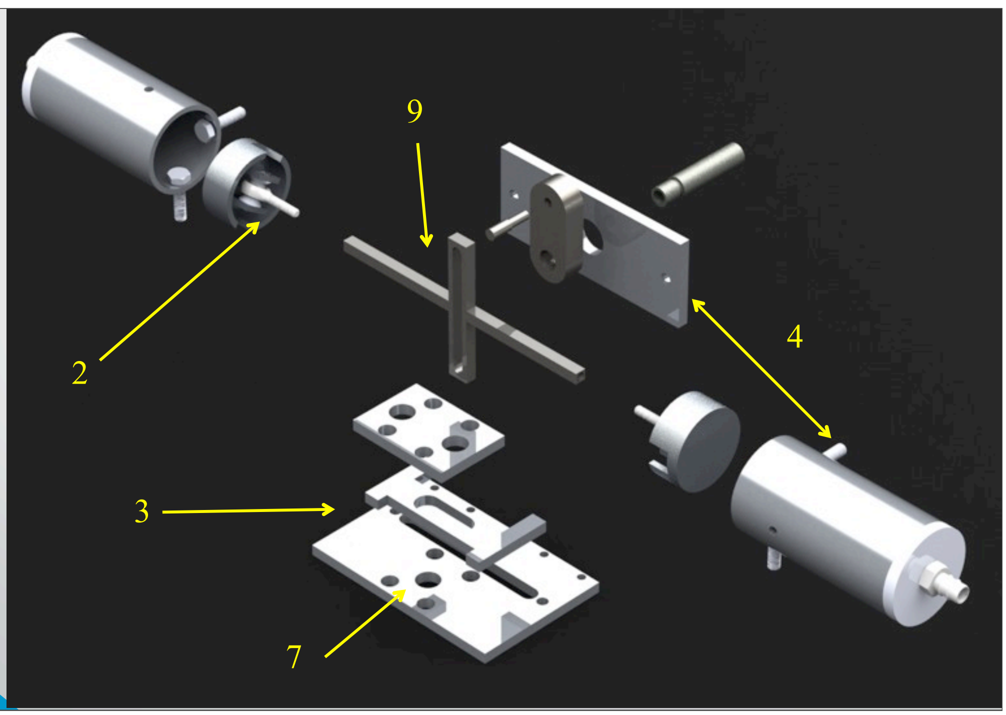
# CAD Model

Tuesday, May 6, 14

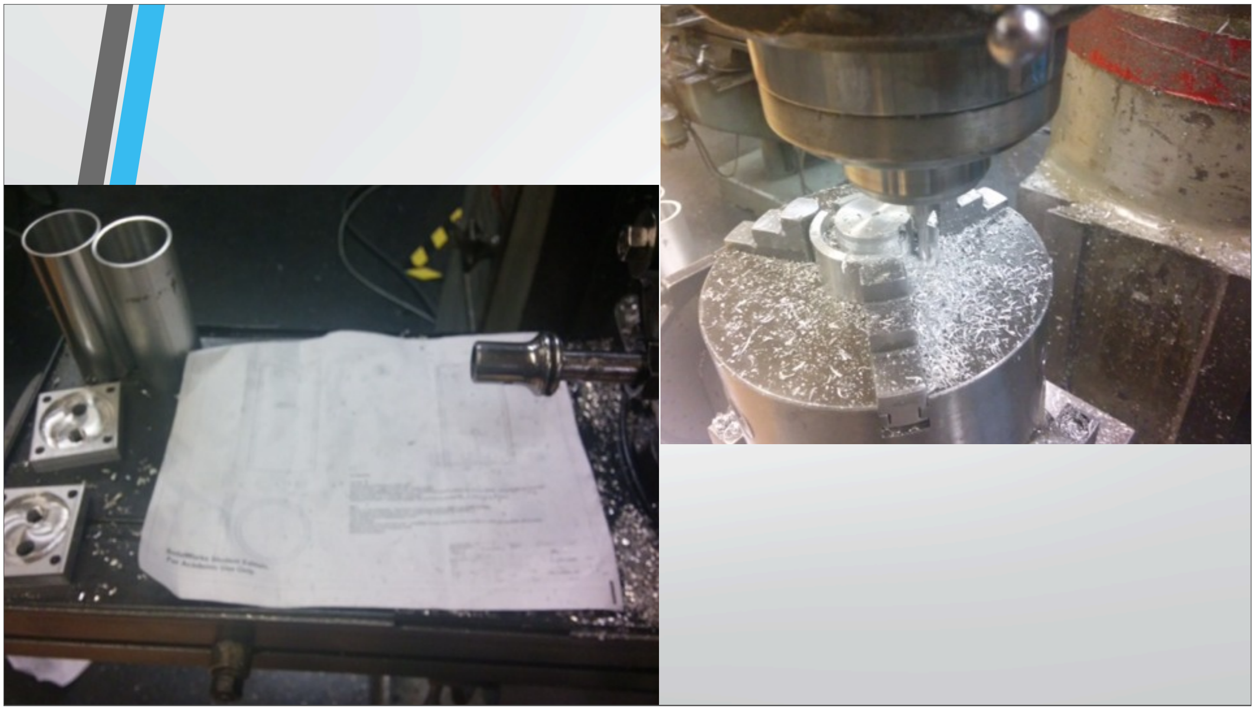
# Motor Features

1. Dual piston
2. Self aligning piston heads
3. Bumper timing
4. Aluminum framing structure
5. Steel output shaft
6. Self aligning output shaft bushing
7. Single input design
8. Externalized, easy to troubleshoot design
9. ‘Spin to adjust’ scotch yoke

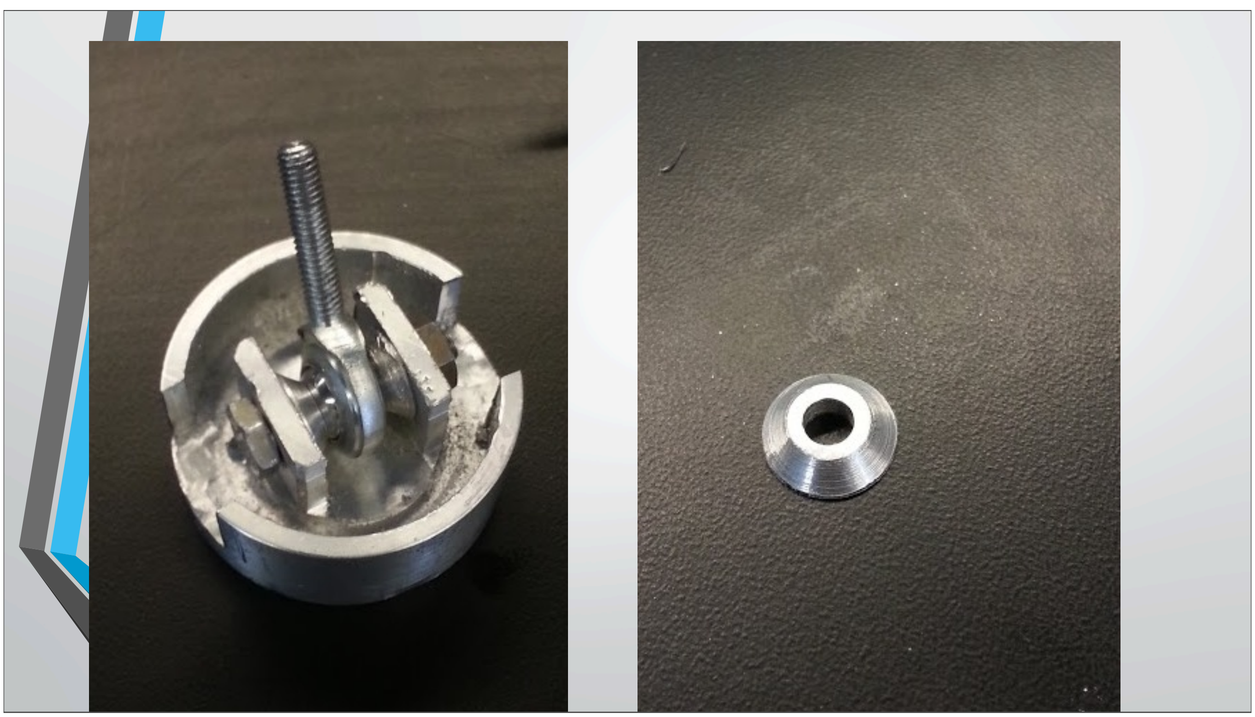





Tuesday, May 6, 14

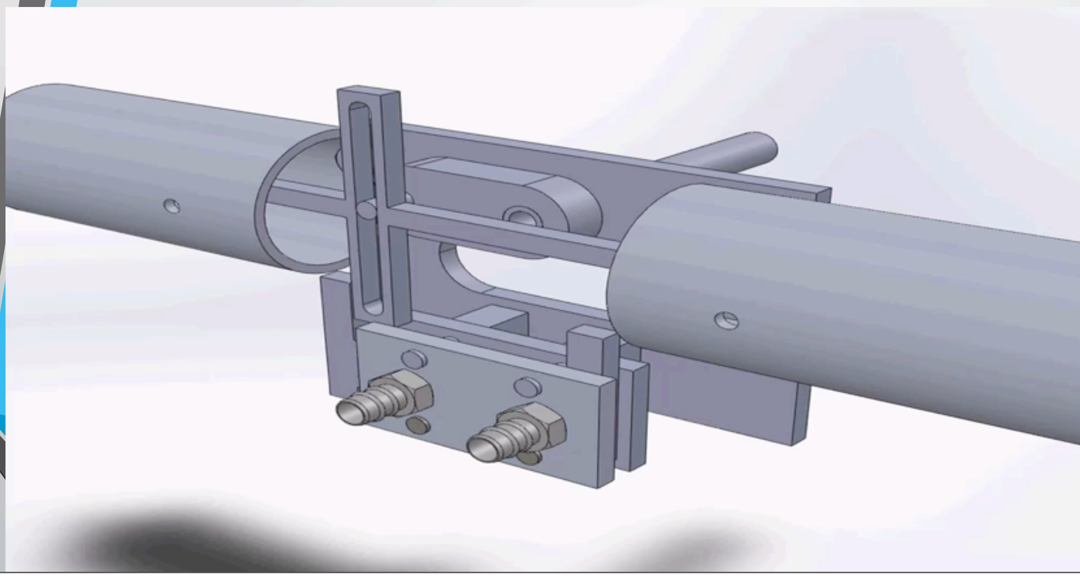


Tuesday, May 6, 14



Tuesday, May 6, 14

# CAD Animation





# Hand Calculations to Find Power

RPM Calculation

MOVING PISTON REQUIRES ACCELARATION & AIR FILLING

↳ filling : $\text{volume}/.012\,m^3/s = (.88\,in)^2 \pi (3\,in)/.012\,m^3/s = .01\ s$

→ acceleration (assume friction negligible) :

$a = 97.3\ lb / 1\,kg = 433\ m/s^2$

$t = \sqrt{2x/a} = \sqrt{\frac{(3\,in) \times 2}{433\ m/s^2}} = .019\ s$

total time = .029 s , or , for whole stroke , .058 s

$.058\ s/rev = 1034\ rpm$

However, we know our motor will not be 100% efficient, so it will run < 1000 rpm

Torque


Force = 97.3 lb

Moment = $(97.3 \text{ lb}) \cos\theta^{\circ} (1.375'')$

Avg. value of $\cos\theta = 2/\pi$

Thus, average torque = 85.2 lb·in

Power

$P = \omega t = (108.3 \text{ rad/s})(85.2 \text{ lb}) = 1.40 \text{ hp} = 1043 \text{ W}$



# Final Cost - Prototyping

Stock..............................................29.12
Rod Ends........................................ 7.06
Tube Fittings.................................. 4.54
Bushing........................................... 3.00
Tubing............................................ 1.24
Nuts & Bolts................................... 3.18
Cylinders & End Caps..................... 4.00

\+ Stock Returned.....- 2.16

= $49.98

# Final Cost - Motor

| | |
|---|---|
| Stock | 26.96 |
| Rod Ends | 7.06 |
| Tube Fittings | 2.27 |
| Bushing | 3.00 |
| Tubing | 0.62 |
| Nuts & Bolts | 1.96 |
| Cylinders & End Caps | 4.00 |
| Lubricant | 0.18 |

= $46.05

# Section 2: Conceptual Design

**Customer Needs:**

We got this list of raw customer needs from the description on the project website, as well from some common sense features pertaining to motors.

1. Runs on 40 psi inlet
2. Runs below 1000 rpm.
3. Has a base of maximum width 4”.
4. Must support 2 kg flywheel and 100 N downward force at output axis.
5. Must have F.O.S. of 2.0 or above.
6. Should not fail catastrophically.
7. Should self start.
8. Must cost less than $50.
9. Should be as light as possible per output power.

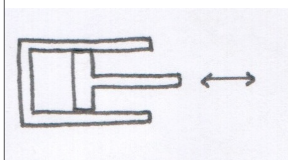
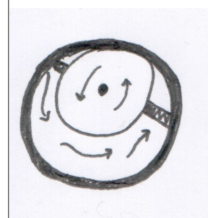
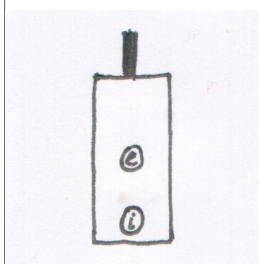
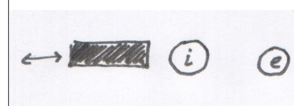
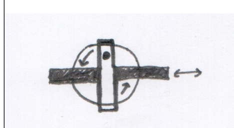
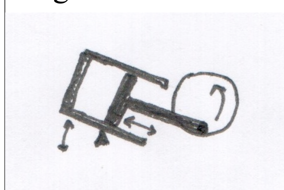
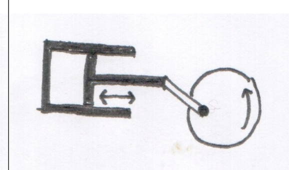
**Specifications:**

The specification matrix below takes he above customer needs and turns them into very specific engineering requirements. This turns vague statements of want into executable goals for our motor.

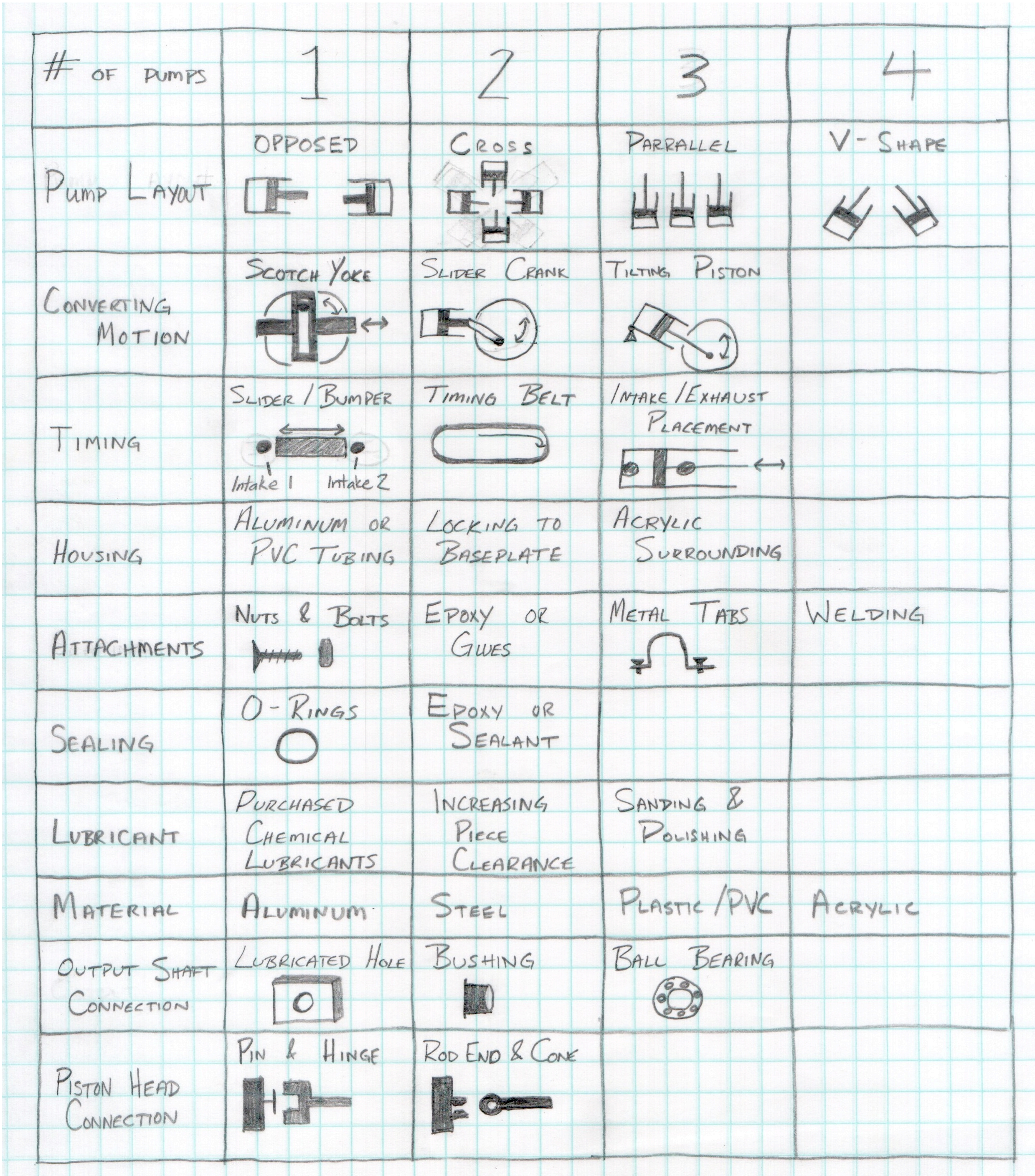
| PROMPT | CONSUMER STATEMENT | INTERPRETED NEED |
|---|---|---|
| **Use of Air Source** | The motor should work within a pressurized air source | The prototype is required to operate on a regulated 40 PSI outlet at 0.012 m^3/s |
| | The motor cannot run too fast given air source | Motor operates below 1000 rpm |
| **Use and Adjustment** | It should be able to be secured as to prevent rattling | Possible to clamp the motor in a vice with a 4” opening |
| | The shaft of the motor should be strong enough to support itself | Must support a 10 Kg downward force at the tip of the axis |
| **Application** | I should be able to use the motor for a flywheel | Must support a 2 Kg flywheel |
| | The price should be reasonable, as should the weight and material use | Cylinder bore diameter is fixed at 1.760”, wall thickness 0.120” |
| | The motor should meet the geometries and sizing required | Motor mount geometry, drive shaft and air intake must conform to consumer specifications |
| **Safety in Operation and Reliability** | No user contact required upon attaching the air inlet | Self-start at any state once connected to air pressure |
| | Needs to be safe | Adequate safety and failure constraints in the event of failure |
| | Chance of failure should be minimal | Designed with a safety factor of 2.0 |

**Concept Generalization:**

General Morph Chart

| | | | | |
|---|---|---|---|---|
| **General Motor Type** | Piston Cylinder<br> | Tesla Turbine<br> | Rotary Vane<br> | |
| **Timing Mechanism** | Timing Belt | In/Ex Placement<br> | Slider/Blocking<br> | |
| **Closure/ Housing** | Aluminum sleeving | PVC tubing | | |
| **Converting Motion** | Scotch Yoke<br> | Hinge<br> | Slider Crank<br> | |
| **Pump Layout** | Opposed (Facing) | Cross (4 Facing Inwards) | V-shaped | |
| **Sealing** | Epoxy/Glue | Nuts & Bolts | O-rings & Other Rubber Pieces | |
| **Materials** | Aluminum | Steel | Acrylic | PVC |
| **Lubrication** | Bearings | Larger Gaps | Oils | |

Updated, Piston-Specific Morphological Chart

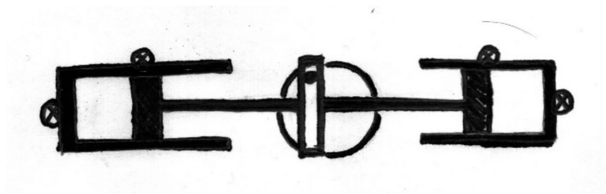


| # of Pumps | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Pump Layout | Opposed | Cross | Parrallel | V-Shape |
| Converting Motion | Scotch Yoke | Slider Crank | Tilting Piston | |
| Timing | Slider / Bumper<br>Intake 1 Intake 2 | Timing Belt | Intake / Exhaust Placement | |
| Housing | Aluminum or PVC Tubing | Locking to Baseplate | Acrylic Surrounding | |
| Attachments | Nuts & Bolts | Epoxy or Glues | Metal Tabs | Welding |
| Sealing | O-Rings | Epoxy or Sealant | | |
| Lubricant | Purchased Chemical Lubricants | Increasing Piece Clearance | Sanding & Polishing | |
| Material | Aluminum | Steel | Plastic / PVC | Acrylic |
| Output Shaft Connection | Lubricated Hole | Bushing | Ball Bearing | |
| Piston Head Connection | Pin & Hinge | Rod End & Cone | | |

**Concept Selection:**

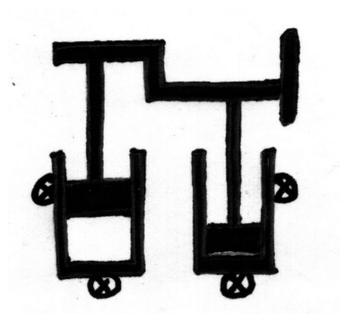
We created these three designs by piecing together components of a motor from our above morphological chart.

Design One:



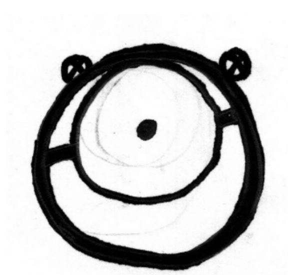
This design features two piston-cylinders, facing each other. The piston heads are connected by a scotch yoke, which spins a center flywheel with attached drive shaft. The timing is regulated by the placement of intake and exhaust. This design will have to be modified a bit so that it fits in a vice, and has a horizontal output shaft. Pros of the design are its simplicity, and relatively few pieces to manufacture. Cons are its limited timing and its weight.

Design Two:



This design features two piston-cylinders, acting next to each other. The pistons turn a bent crankshaft, which is attached to the flywheel with output shaft. Once again, timing is simply devised with intake and exhaust placement. The pros of this design are its small size and easy scaling (to more or less cylinders). The cons, meanwhile, are its limited timing, and need for a very precisely made crank shaft.

Design Three:



This design is a simply rotary motor. A large housing fits a rotating wheel with "arms" that form a vacuum inside the chamber. Intake and exhaust do not need to be timed, and the output shaft comes out of the center of the rotating wheel. The pros of this design are its simplicity and non-need of timing mechanism. The cons are its need for tight tolerancing (creating a vacuum) and pricey housing (would absolutely need to be split with another group.)

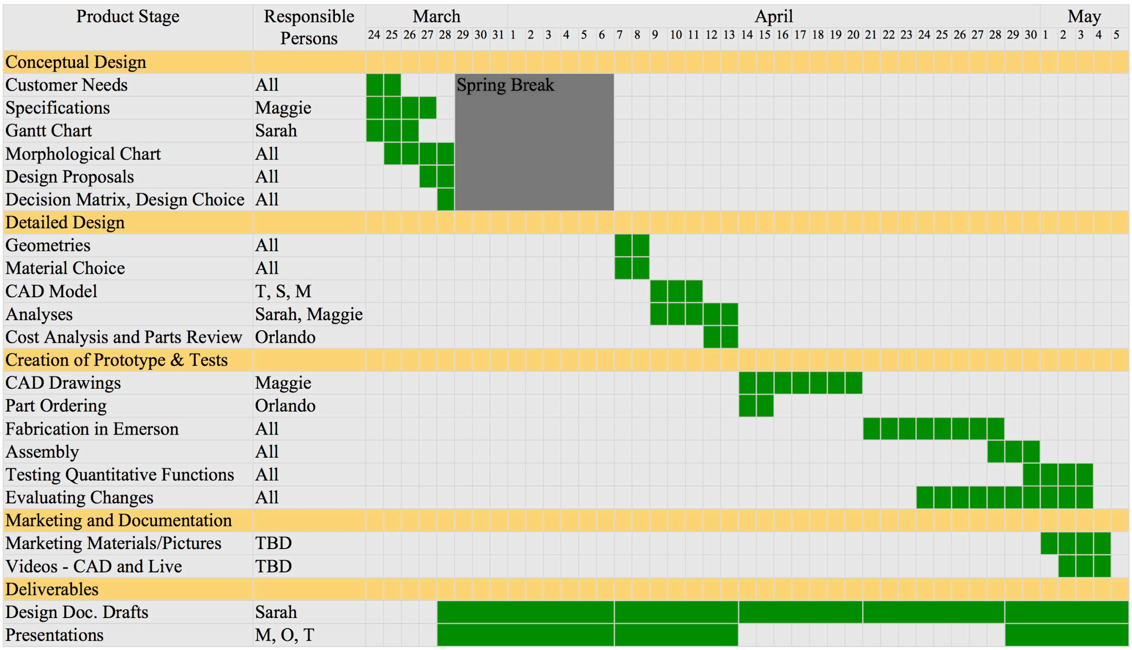
**Decision Matrix:**

This Decision Matrix helped us choose between the above designs, using the listed categories and weights.

| **Issue** | **Importance Factor** | **Design 1** | **Design 2** | **Design 3** |
|---|---|---|---|---|
| Reliability | 15% | 10 | 7 | 5 |
| Ease to Manufacture | 15% | 9 | 2 | 2 |
| Tolerance | 10% | 7 | 9 | 3 |
| Cost | 10% | 9 | 9 | 5 |
| Power | 5% | 6 | 6 | 6 |
| Weight | 5% | 5 | 5 | 8 |
| Torque vs. Weight | 5% | 8 | 8 | 9 |
| Ability to Analyze | 8% | 9 | 9 | 10 |
| Testing Ease | 5% | 8 | 9 | 3 |
| Tuning/Adjustment | 5% | 10 | 5 | 4 |
| Student Understanding | 2% | 8 | 9 | 5 |
| Time | 9% | 8 | 6 | 7 |
| Stresses | 6% | 8 | 4 | 9 |
| Total: | 100% | 8.38 | 6.38 | 5.42 |

Thus, the first design is a clear cut winner. In the next week, we'll have to hone down this idea, that is, assign geometries, and specific pieces, like nuts and bolts.

**Project Plan (Gantt Chart):**




We definitely ran into some bottlenecks during the second week tasks. After coming up with many specific of our design, the only task we could do was CAD modeling. First off, this is a difficult task to split among separate people. Second, we couldn't really do full cost analysis, production drawings, or the like before this was done. However, even with these challenges, our group worked together and got everything done in a timely manner.

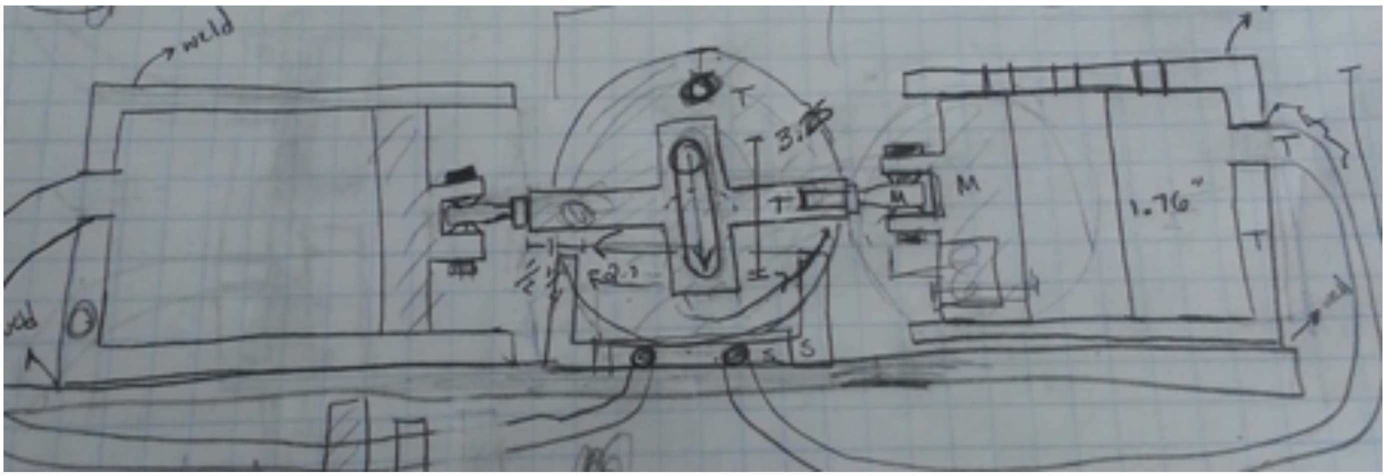
In the third week, the largest issue was that modifying the CAD model was sort of difficult (you have to change lots of parts to match.) This means it really only could be done by one person, and unfortunately, Maggie had to handle the brunt of the load.

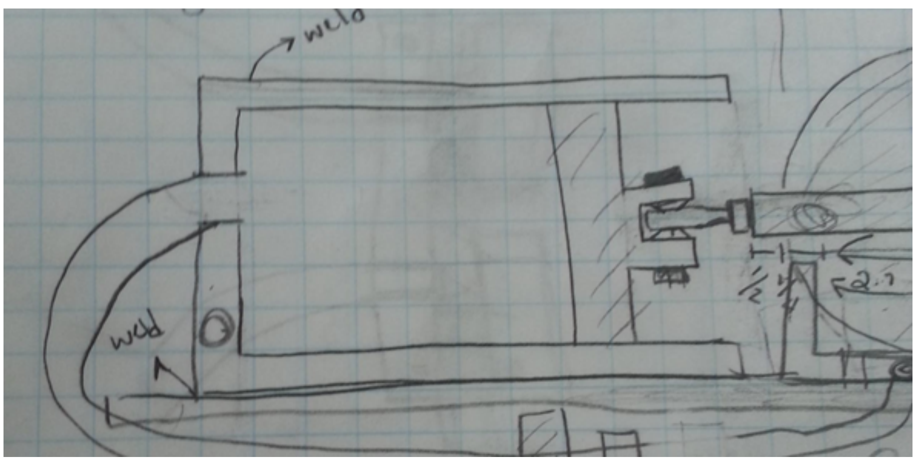
Finally, in the last week or so of our project, we often had to complete tasks in a backwards order. For instance, we began making marketing materials before completing our motor assembly, as we knew we would not have enough time after to do much more than add pictures. We also noticed that the 'evaluating changes' task really was more of a constant in our assembly process, always looking to make sure things fit or if they needed to be modified.

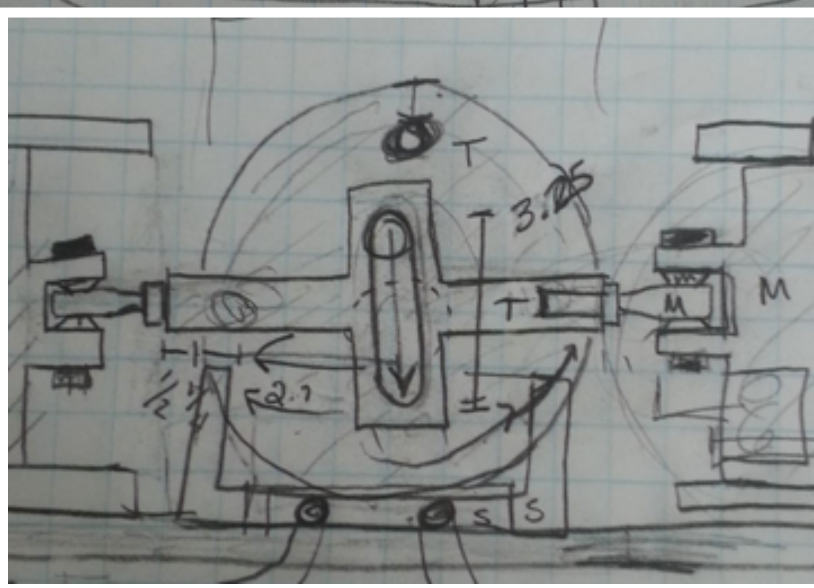
# Section 3: Detailed Design and Analysis

**Initial Design Documentation:**

When we began talking about the specifics of our design, the first step we took was to draw a roughly accurate picture of our motor. Then we began deciding specifics (geometries, etc.) based on this. Here are some of those sketches:



**Key Features of Design:**

1. Our motor features two pistons. Having more than one piston helps the motor continue running even if the timing mechanism does not function perfectly. However, the more pistons you add, the lower the power v. weight ratio (that is, doubling cylinders does not double power.) So, two pistons is the perfect compromise for this.

2. Our pistons are arranged in opposition, with a scotch yoke between them. This is a really simple setup, so that the pistons are always in opposite motion. This should make timing and manufacturing a little easier. The scotch yoke is attached to the piston head using ball bearing rod ends (one left-threaded and one right-threaded) so that they self align and reduce chance of failure.

3. Instead of a flywheel, we are using a crankshaft arm to connect the scotch yoke to the output shaft. We chose this because it saved us huge amounts of weight and money. The arm has a steel pin which the scotch yoke pushes. Then, the output shaft is connected to the other end of the arm. The threads of the output shaft are opposite to the direction of the arm's circular motion - so that the connection tightens as it spins.

4. For timing, we discussed a few options. What we settled on, finally, was a sort of bumper mechanism. A slider is sandwiched between two plates. The top plate accepts air from the outlet, while the bottom plate has two openings - one running to each cylinder. Then, the slider is hit back and forth by the scotch yoke, effectively opening and closing the intake air for each piston at the right time. Meanwhile, exhaust ports are located on the body of the cylinder - we will test different heights to see which is most effective.

5. For framing, we chose to use two plates, a baseplate and a backplate, which the cylinders and timing are screwed into (the plates are screwed together as well.) The cylinders are attached only at the opening, farther up than the piston will travel. Finally, the output shaft runs through a self-aligning bronze bushing in the backplate.

6. To attach pieces, we use a combination of methods. The cylinders and endcaps will be welded together (a small amount of distortion of the cylinder is okay, as the piston will not travel down this far.) Most other pieces are either screwed into each other or attached with screws or bolts. We could also epoxy some of these threads for added security. We will also lubricate our motor using some kind of chemical lubricant.

7. Finally, all the pieces of our motor, except for the crankshaft pin and output shaft, will be aluminum. Those others will be steel.

**Engineering Analyses:**

Hand Calculations

The following test whether we have a factor of safety of at least 2.0 for static loadings, as per the project guidelines, as well as our own safety concerns. The calculations use some general material properties, listed below:

Yield Strength, Aluminum 6061 = 40 ksi    Shear Strength, Aluminum 6061 = 30 ksi
Yield Strength, Steel AISI 4130 = 138 ksi    Shear Strength, Steel AISI 4130 = 60 ksi

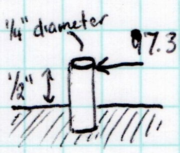
STRESSES IN SCOTCH YOKE

force from air $= (40\ \text{psi})(\pi(.88\ \text{in})^2) = 97.3\ \text{lb}$

axial stress maximum $= (97.3\ \text{lb}) \div (2(1/8\ \text{in})(1/2\ \text{in})) = 778.4\ \text{psi}$

$X = \sigma_u / 778.4\ \text{psi} = 57.8$

STRESSES ON FLYWHEEL PIN




Shear $= 97.3\ \text{lb} / \pi(1/8\ \text{in})^2 = 1982\ \text{psi}$

Moment $= (97.3\ \text{lb})(.5\ \text{in}) = 48.65\ \text{lb}\cdot\text{in}$

Stress $= (48.65\ \text{lb}\cdot\text{in}) \cdot (1/8\ \text{in}) \div (\pi/4 \cdot (1/8\ \text{in})^4) = 31.7\ \text{ksi}$

$X = \sigma_u / 31.7\ \text{ksi} = 4.3$

STRESSES IN CYLINDER

pressure = 40 psi    ID = 1.76"    OD = 2.00"

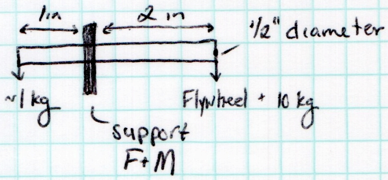
$\sigma_c = Pr/t = (40\ \text{psi})(1'') \div (.12'') = 333.33\ \text{psi}$

$\sigma_l = Pr/2t = 166.67\ \text{psi}$

$\sigma_H = \frac{1}{3}\sqrt{\sigma_c^2 + \sigma_l^2 + (\sigma_c - \sigma_l)^2} = 136\ \text{psi}$

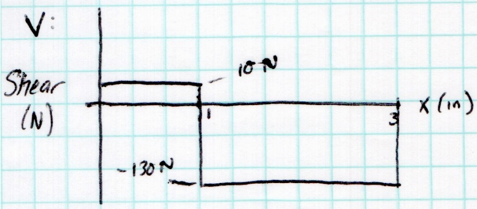
$X = \frac{\sqrt{2}}{3}\sigma_u \div 136\ \text{psi} = 137$

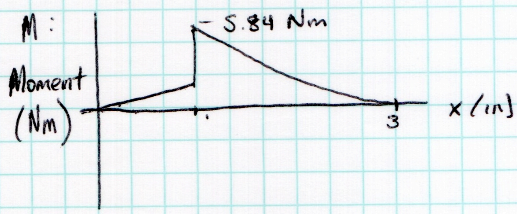
Stress in Output Shaft




$F_{support} = 130$ N

$M_{support} = 5.84$ Nm




Max Shear Stress: $130\text{ N}/\pi(.25\text{ in})^2 = 15.5$ psi

$X_{alum} = 2000$ $\quad X_{steel} = 3870$

Max Axial Stress: $(5.84\text{ Nm})(.25\text{ in}) \div (\frac{\pi}{4}(.25\text{ in})^4) = 4.2$ ksi

$X_{alum} = 10.7$ $\quad X_{steel} = 33$

This next set of calculations begins to predict the output rpm and power of our motor. The motor must operate at or under 1000 rpm, and, obviously, we'd like to produce as much power as possible.

RPM Calculation

MOVING PISTON REQUIRES ACCELARATION & AIR FILLING

↳ filling: $\text{volume}/.012\ \text{m}^3/\text{s} = (.88\text{ in})^2\pi(3\text{ in})/.012\ \text{m}^3/\text{s} = .01$ s

→ accelaration (assume friction negligible):

$a = 97.3\text{ lb}/1\text{ kg} = 433\ \text{m/s}^2$

$t = \sqrt{2x/a} = \sqrt{\frac{(3\text{ in})\times 2}{433\ \text{m/s}^2}} = .019$ s

total time = .029 s, or, for whole stroke, .058 s

.058 s/rev = 1034 rpm

however, we know our motor will not be 100% efficient, so it will run <1000 rpm

Check if frictional force is negligible

Area = $(\frac{1}{2} \text{ in}) \times (\pi)(1.76 \text{ in}) = 2.765 \text{ in}^2$

$\mu$ for plastic-aluminum lubricated = .06

Normal force $\sim$ 7 N

$F_F = \mu N = .094$ lb ← yes, we can discount

Torque


Force = 97.3 lb

Moment = $(97.3 \text{ lb}) \cos\theta° (1.375")$

Avg. VALUE OF $\cos\theta = 2/\pi$

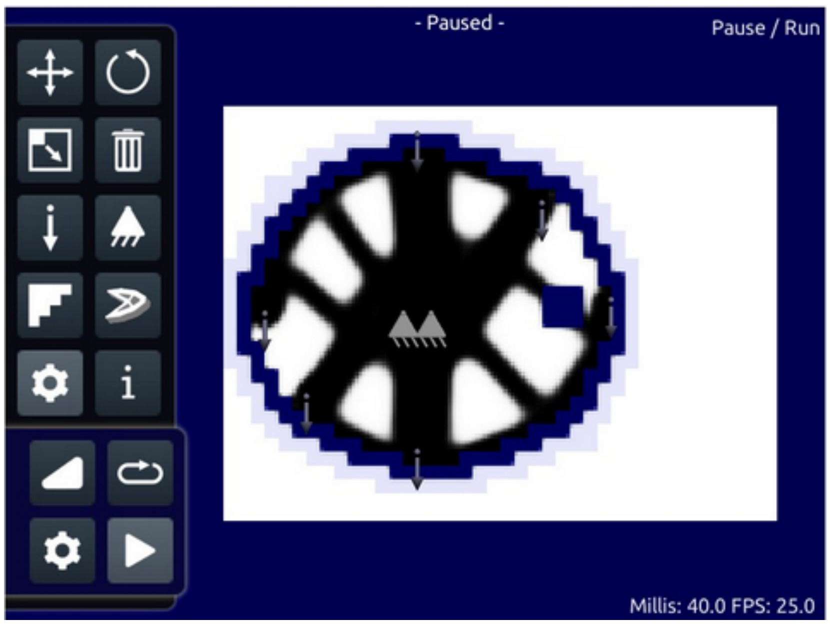
Thus, average torque = 85.2 lb·in

POWER

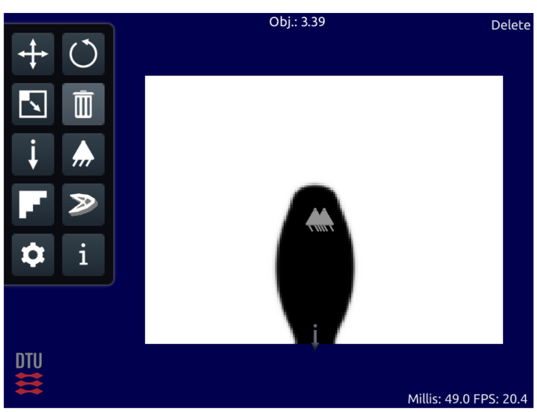
$P = \omega\tau = (108.3 \text{ rad/s})(85.2 \text{ lb}) = 1.40 \text{ hp} = 1043 \text{ W}$

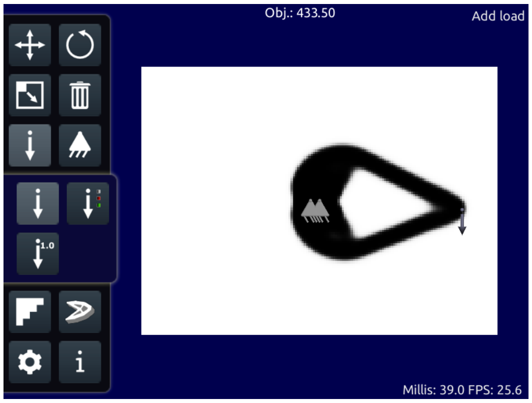
Topological Optimization

One of the tools we used to design our motor was topological optimization. We ran some testing using online topological optimization software (the one Sarah tried to build was way too complicated). This shows the flywheel, which was set to be roughly circular, with central support, and a sort of knob area. Then forces were placed around the perimeter, to receive a computer generated shape. Dark blue and black squares have material in that location.




However, we wanted to see how usable a crankshaft arm would be. Using the smallest possible volume and a central support, these optimizations were generated for forces at angles of 0, 45, and 90 degrees, respectively.

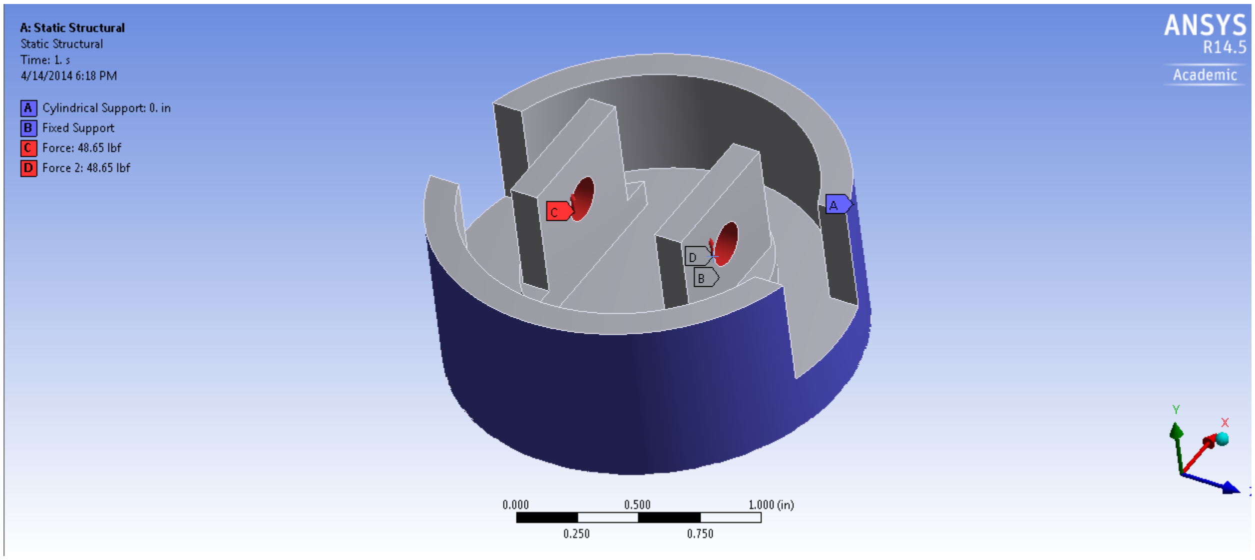


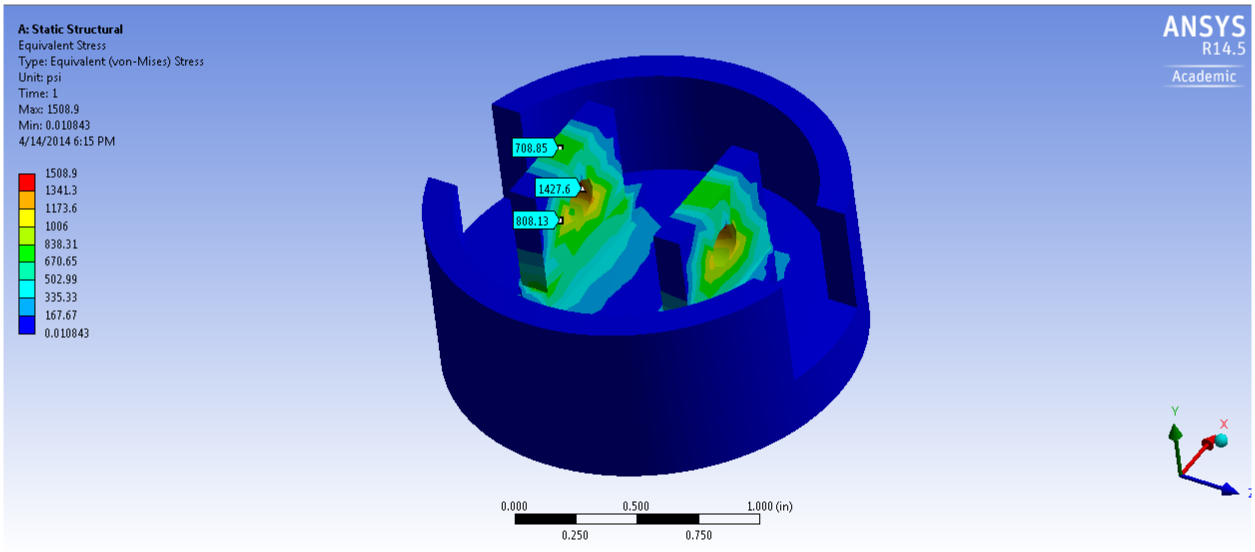

At 0 degree force, an arm is most optimal. At 90 degrees, a sort of triangular arm is generated, and at 45 degrees, the shape is roughly a combination of the two. Therefor, because we are rather limited in what we can manufacture, an arm design seems like a reasonable compromise between these designs.

ANSYS Calculations

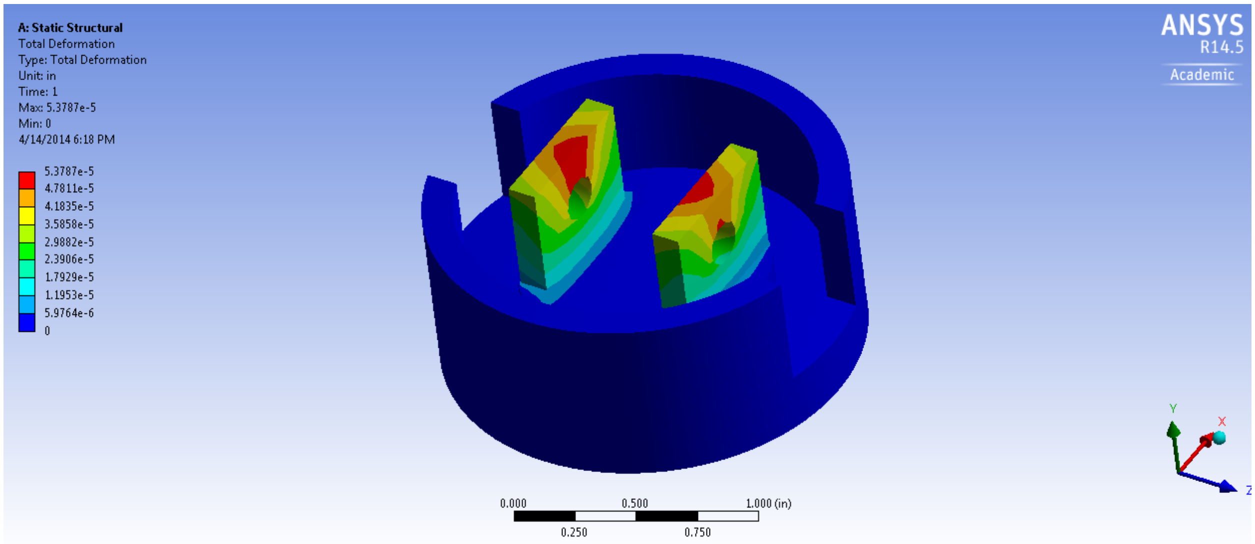
Maggie ran some ANSYS analysis on two of our parts designed in CAD. The first were the piston heads; here we test the clevis design with a static load to look for high stress or deformation.



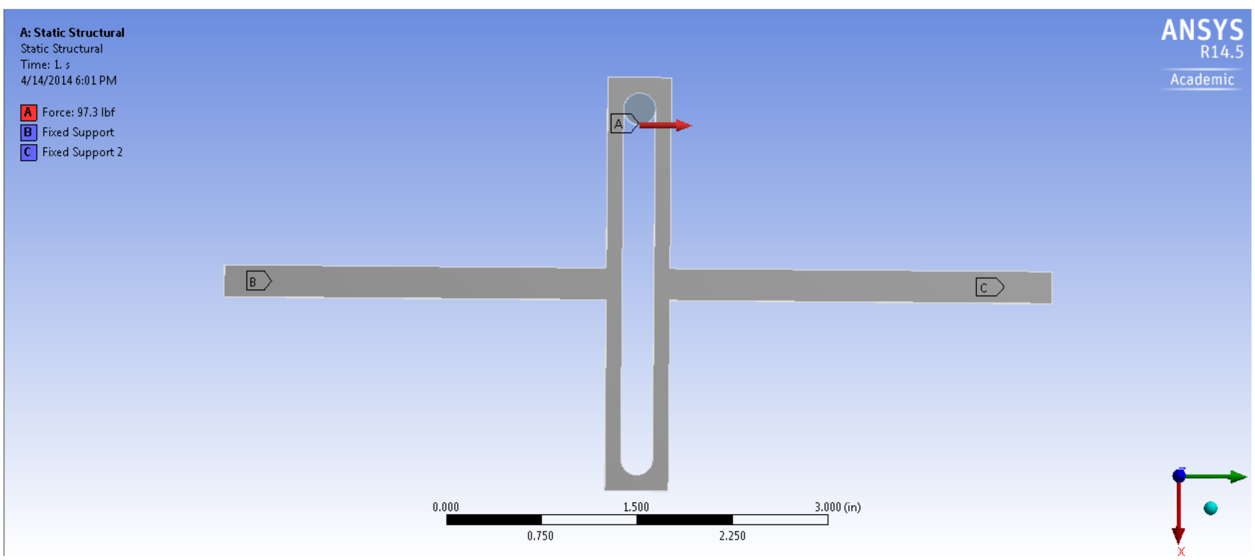

The below shows stresses in the clevis. The regions of high stress are marked in red, however, even these stresses are far far below yield stress of aluminum.



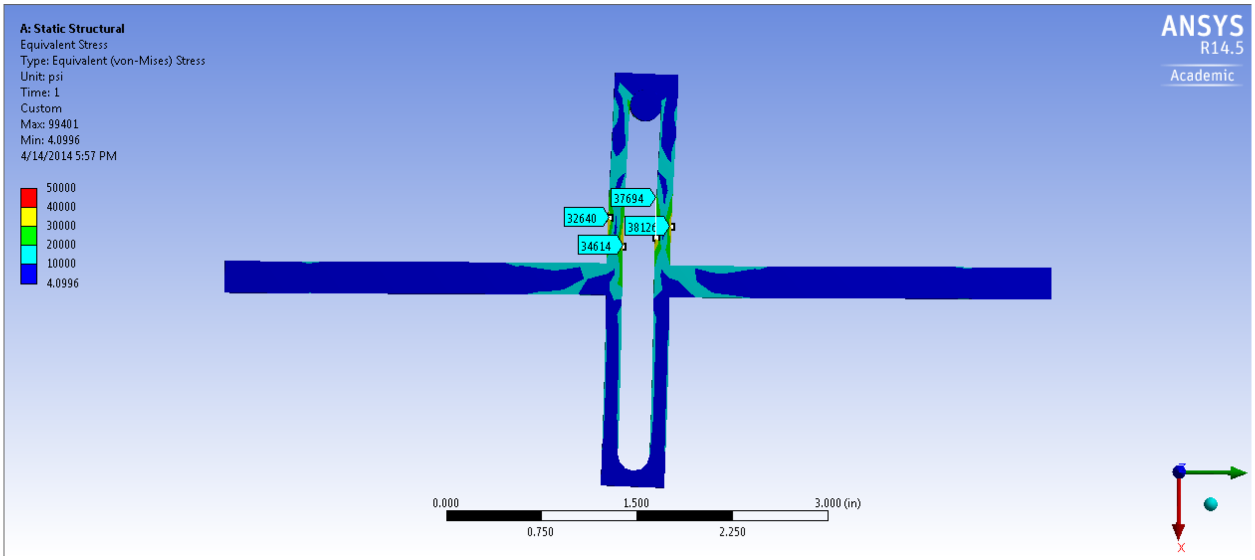
The next picture shows the net deformation in the clevis. The largest deformation is on the order of 10^-5 inches, so it's clear that there will be no appreciable deformation in this part.



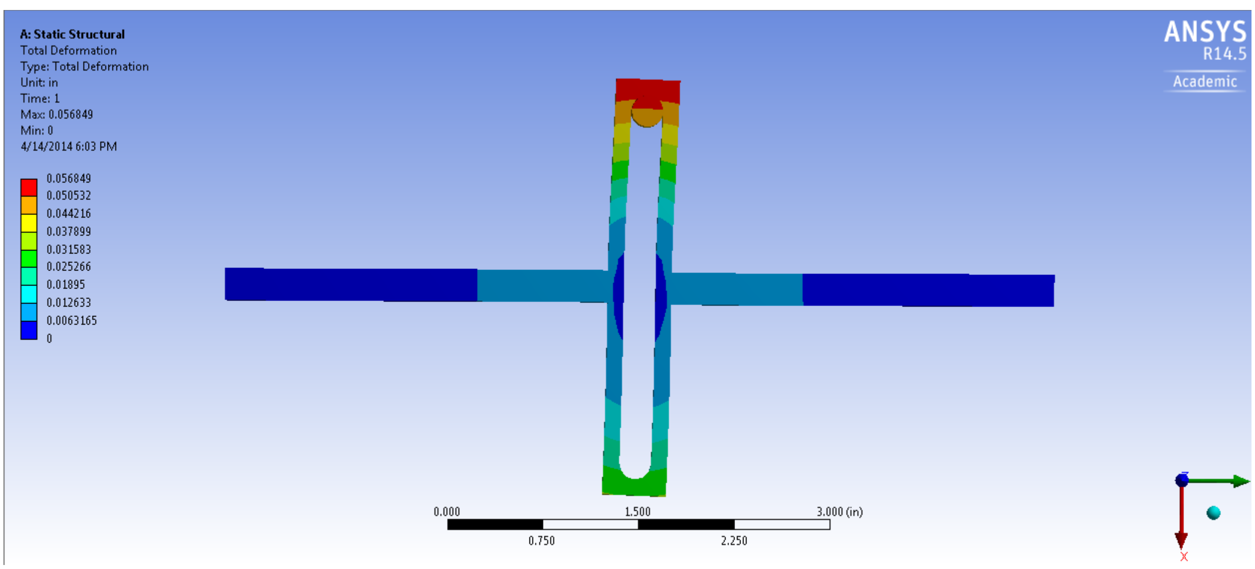

We also used ANSYS to test stresses and deformations in the scotch yoke, both because it's a key feature of our motor, but also because it gave us a perfect opportunity to corroborate our hand calculations. The scotch yoke is given a force (the magnitude of which, 97.3 lb, was found from calculations above) at the location of the pin.



This shows the Von Mises stress in the scotch yoke. It actually perfectly supports the above calculation for stress in the scotch yoke. The stresses here are significant, but still well below yielding. However, for this reason, we plan to thicken some of the 'walls' of the yoke.




Finally, we show the deformation in the scotch yoke. The deformations may be slightly noticeable (the largest is .057 in.) However, because we are well below yield stress, any deformation should be in the elastic region, and should not cause any negative affect in our motor's function.



## Iteration 1

**CAD Model:**

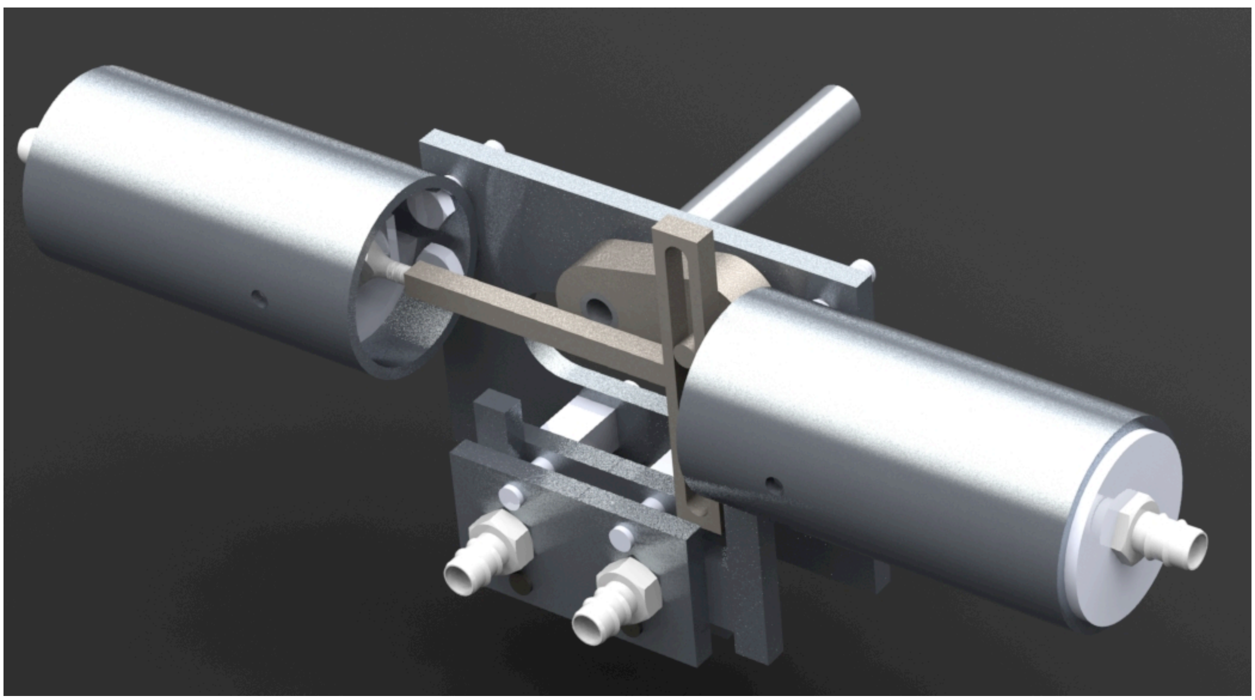
The CAD files that comprise our motor can be found by following the link below. There are Solidworks files for each part, and then the assembly as a whole.

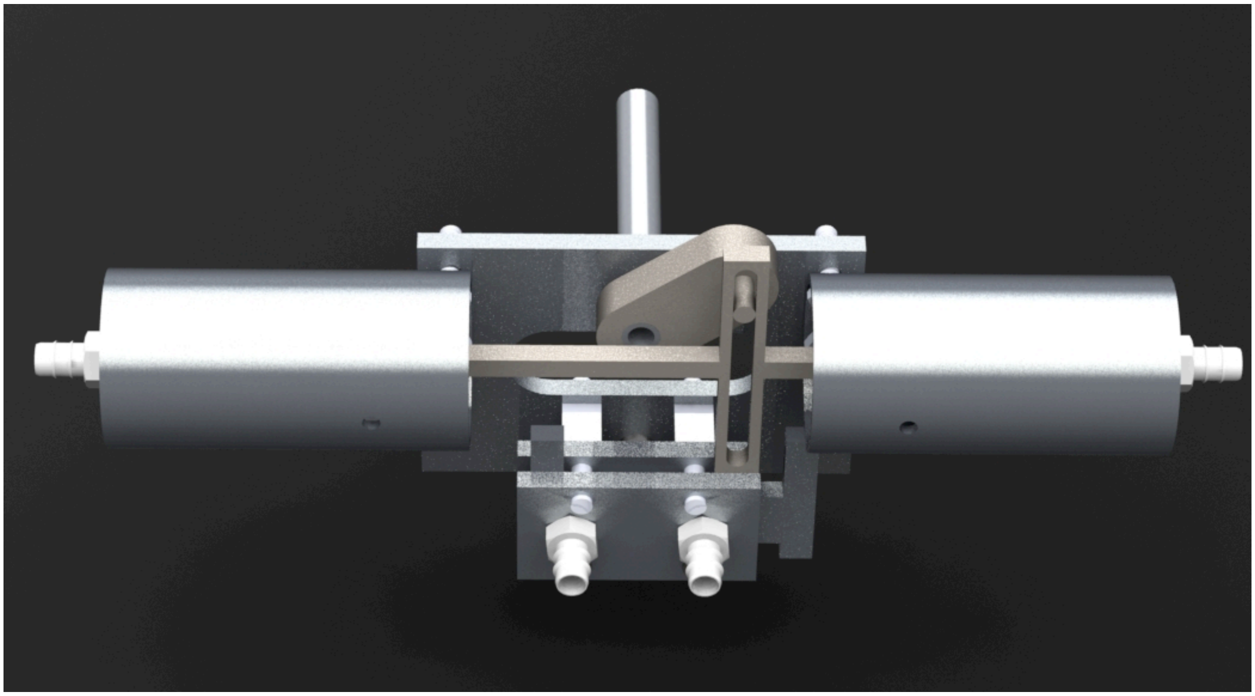
https://cornell.box.com/s/mzkqug4nxbvggmysr16g

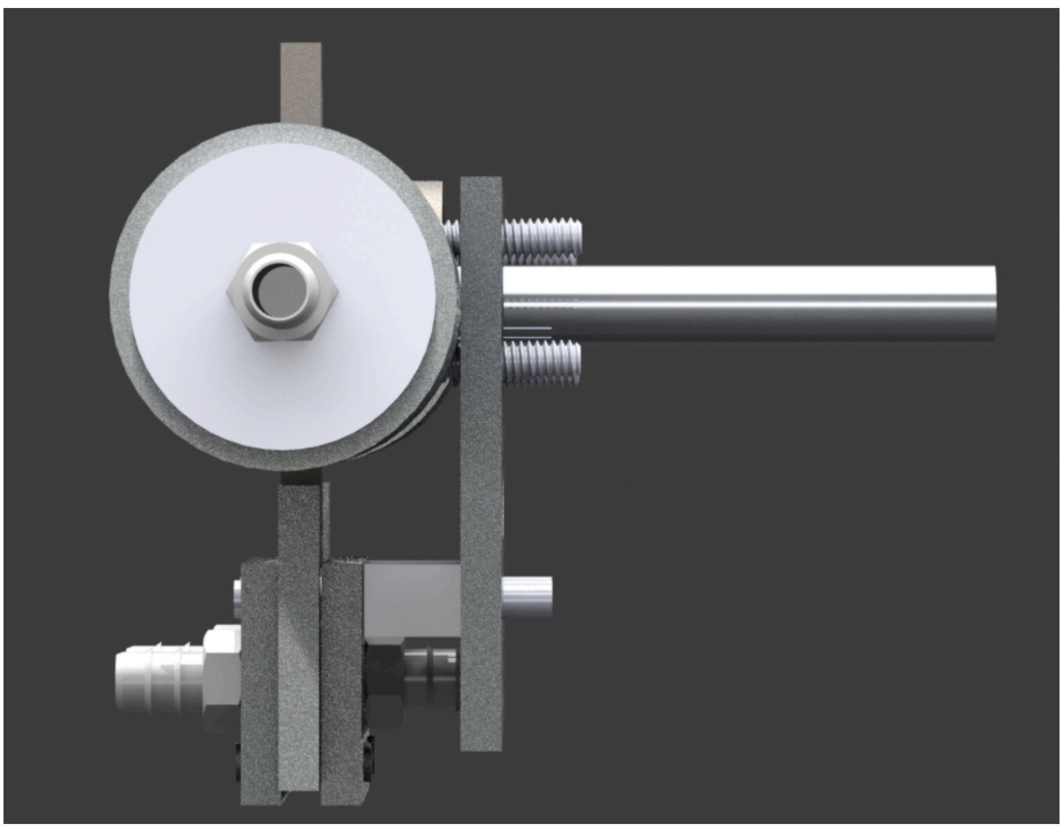
We also created an animation of this assembly, which can be found at the following web address.

http://youtu.be/NDgug_ih5vs

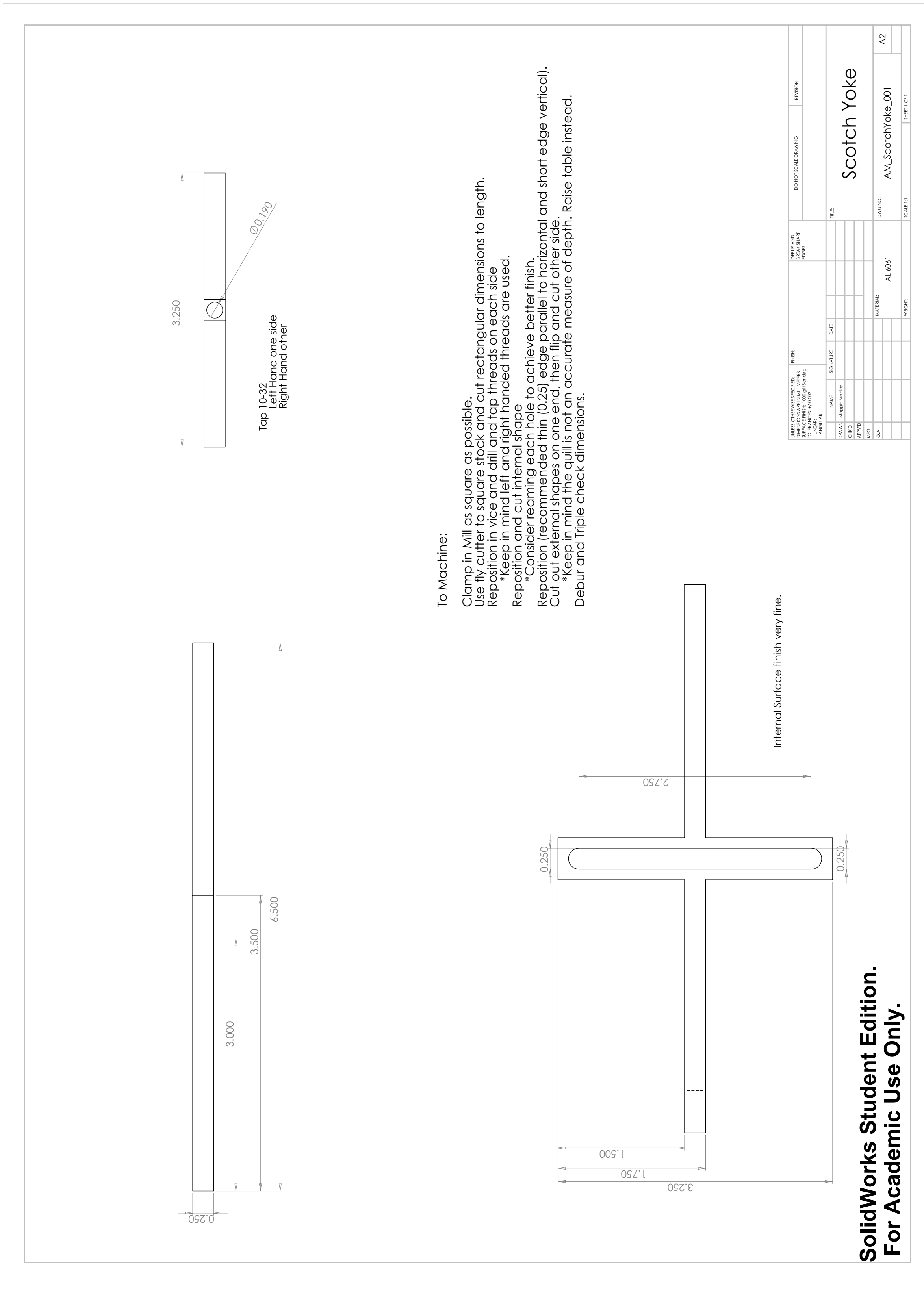
Also, below are some photorealistic renderings of the CAD Model:

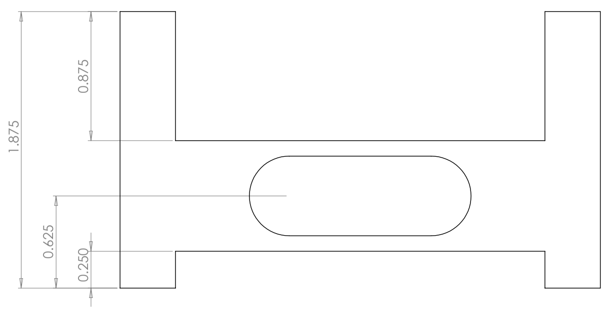






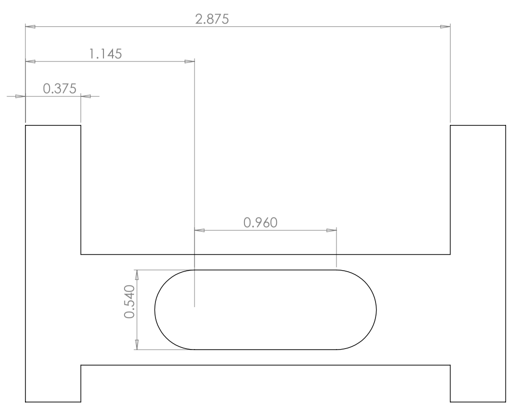
## CAD Drawings and Manufacturing Instructions:

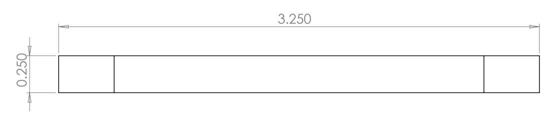





To Machine:

Clamp in Mill as square as possible.
Use fly cutter to square stock and cut rectangular dimensions to length.
*Surface finish important for friction purposes
Reposition and cut internal shape
*Consider reaming each circular section to achieve better finish.
Reposition (recommended thin (0.25) edge parallel to horizontal and short edge vertical).
Cut out external shapes on one end, then flip and cut other side.
*Keep in mind the quill is not an accurate measure of depth. Raise table instead.
Debur and Triple check dimensions.




UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: 1000 grit Sanded
TOLERANCES: +/-0.002
LINEAR:
ANGULAR:

FINISH: Group 6B Monday Section

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | Maggie Bradley | | |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

TITLE: Timing Slider

MATERIAL: AL 6061

DWG NO. AM_Slider_001

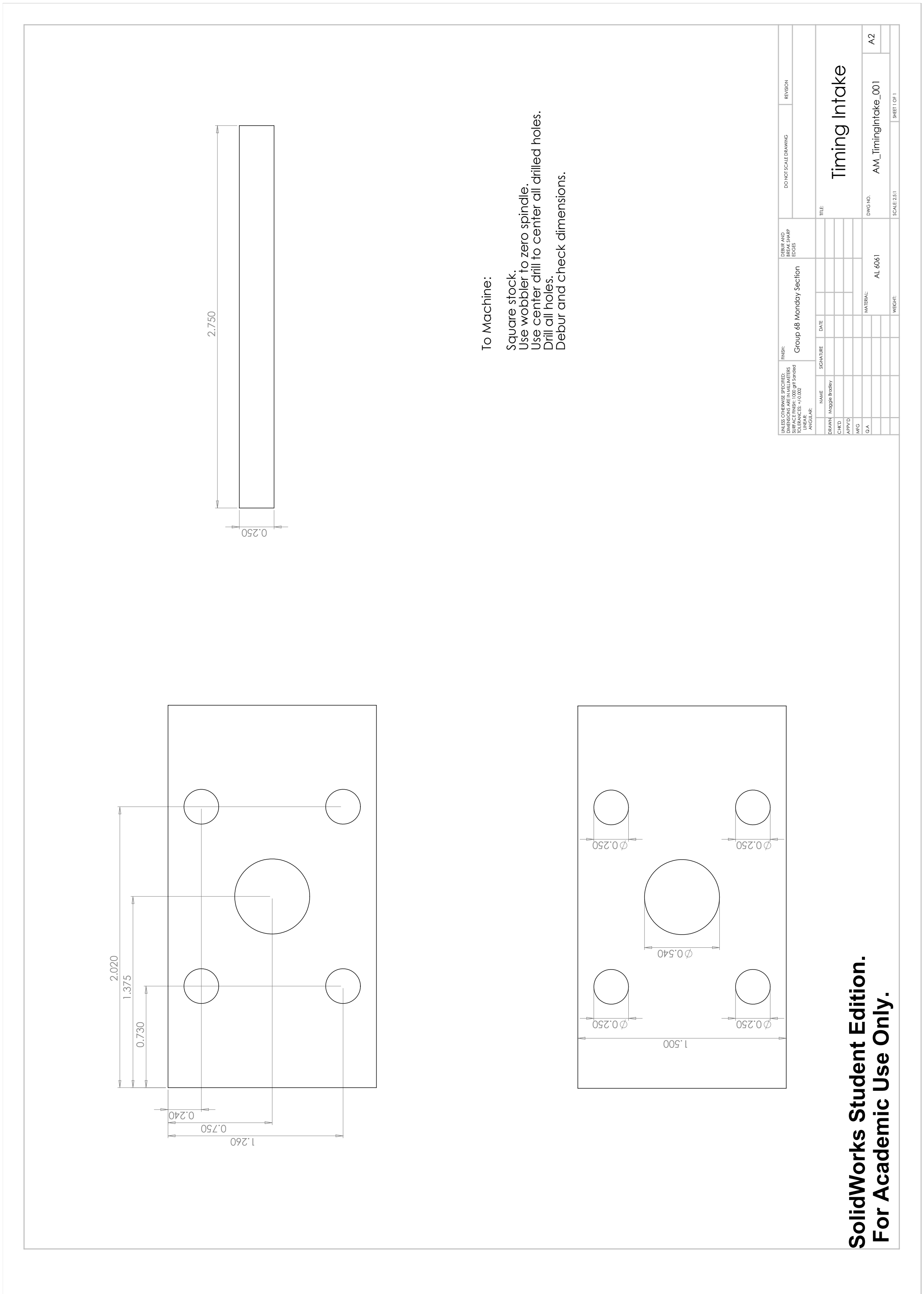
A2

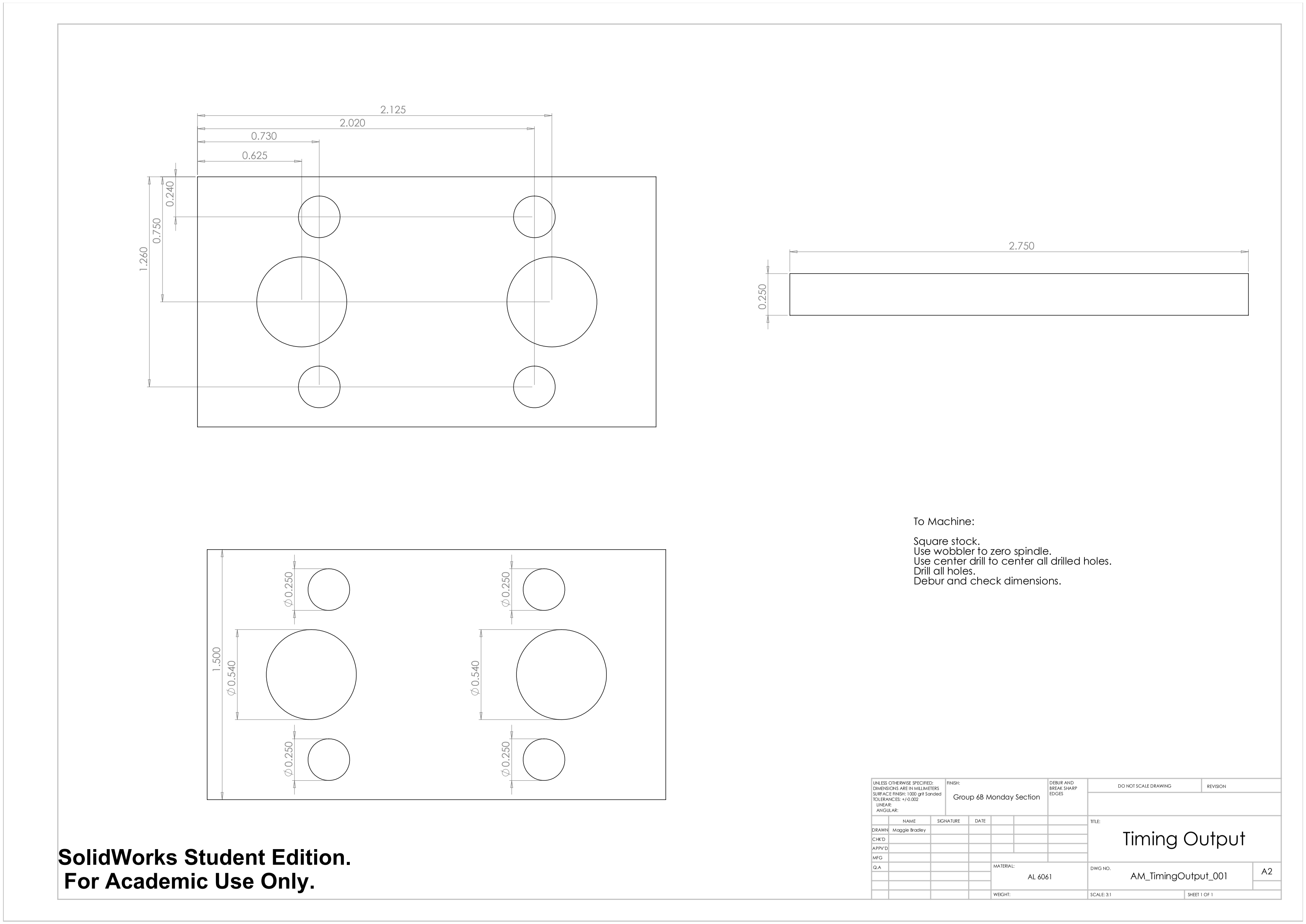
WEIGHT:

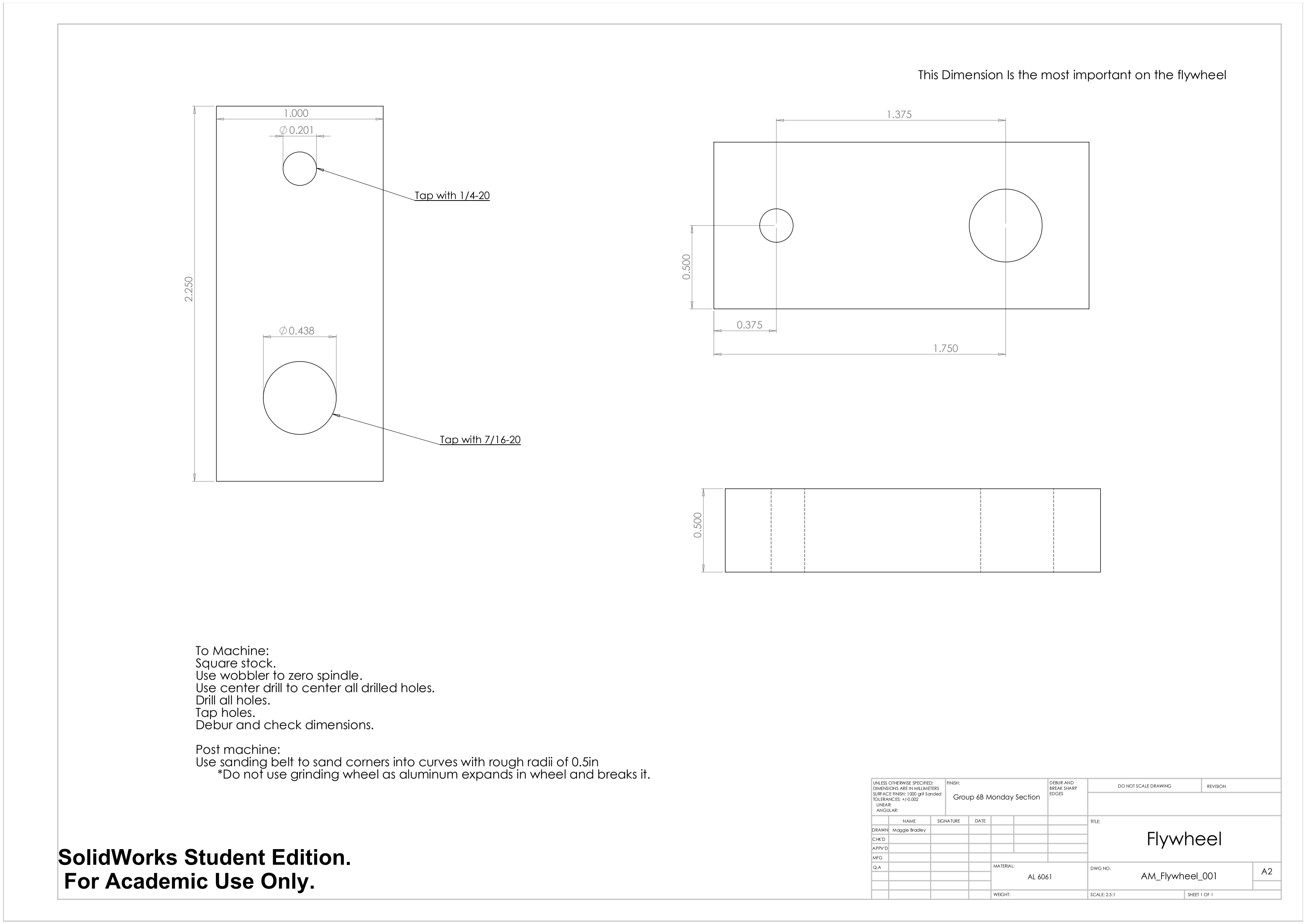
SCALE: 2.5:1

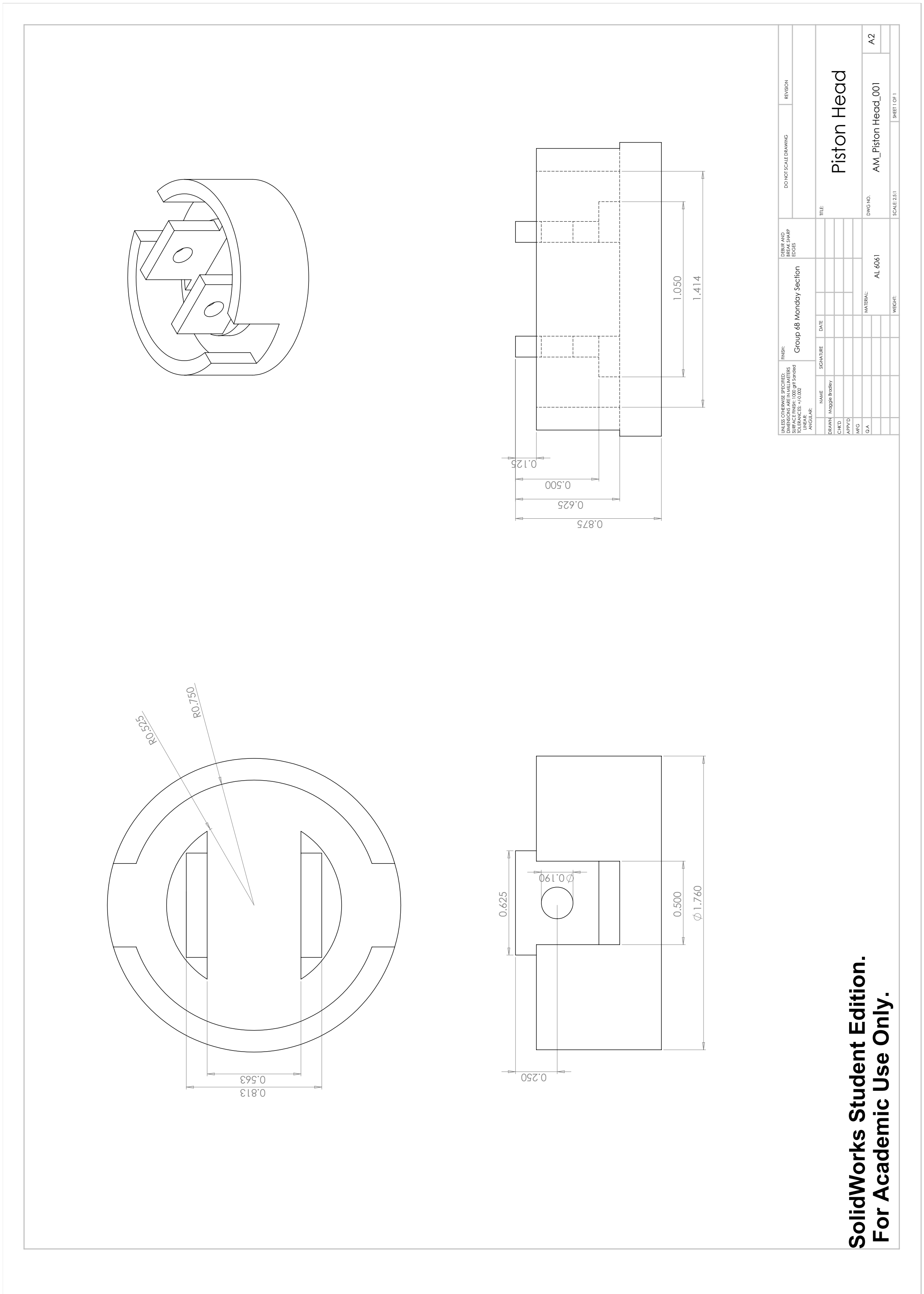
SHEET 1 OF 1

SolidWorks Student Edition.
For Academic Use Only.


Timing Intake
AM_TimingIntake_001
A2
AL 6061
Group 6B Monday Section
Maggie Bradley
To Machine:
Square stock.
Use wobbler to zero spindle.
Use center drill to center all drilled holes.
Drill all holes.
Debur and check dimensions.
2.750
0.250
2.020
1.375
0.730
0.240
0.750
1.260
∅0.250
∅0.540
1.500
SolidWorks Student Edition.
For Academic Use Only.


2.125
2.020
0.730
0.625
0.240
0.750
1.260
2.750
0.250
1.500
∅0.250
∅0.540
∅0.250
∅0.250
∅0.540
∅0.250
To Machine:
Square stock.
Use wobbler to zero spindle.
Use center drill to center all drilled holes.
Drill all holes.
Debur and check dimensions.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: 1000 grit Sanded
TOLERANCES: +/-0.002
LINEAR:
ANGULAR:
FINISH:
Group 6B Monday Section
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
Maggie Bradley
CHK'D
APPV'D
MFG
Q.A
TITLE:
Timing Output
MATERIAL:
AL 6061
DWG NO.
AM_TimingOutput_001
A2
WEIGHT:
SCALE: 3:1
SHEET 1 OF 1
SolidWorks Student Edition.
For Academic Use Only.


This Dimension Is the most important on the flywheel
1.000
∅0.201
Tap with 1/4-20
2.250
∅0.438
Tap with 7/16-20
1.375
0.500
0.375
1.750
0.500
To Machine:
Square stock.
Use wobbler to zero spindle.
Use center drill to center all drilled holes.
Drill all holes.
Tap holes.
Debur and check dimensions.
Post machine:
Use sanding belt to sand corners into curves with rough radii of 0.5in
*Do not use grinding wheel as aluminum expands in wheel and breaks it.
SolidWorks Student Edition.
For Academic Use Only.
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: 1000 grit Sanded TOLERANCES: +/-0.002 LINEAR: ANGULAR:
FINISH: Group 6B Monday Section
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME SIGNATURE DATE
DRAWN Maggie Bradley
CHK'D
APPV'D
MFG
Q.A
MATERIAL: AL 6061
WEIGHT:
TITLE: Flywheel
DWG NO. AM_Flywheel_001
A2
SCALE: 2.5:1
SHEET 1 OF 1


Piston Head
AM_Piston Head_001
A2
Group 6B Monday Section
AL 6061
Maggie Bradley
R0.525
R0.750
0.563
0.813
0.625
0.500
∅0.190
∅1.760
0.250
1.050
1.414
0.125
0.500
0.625
0.875
SolidWorks Student Edition.
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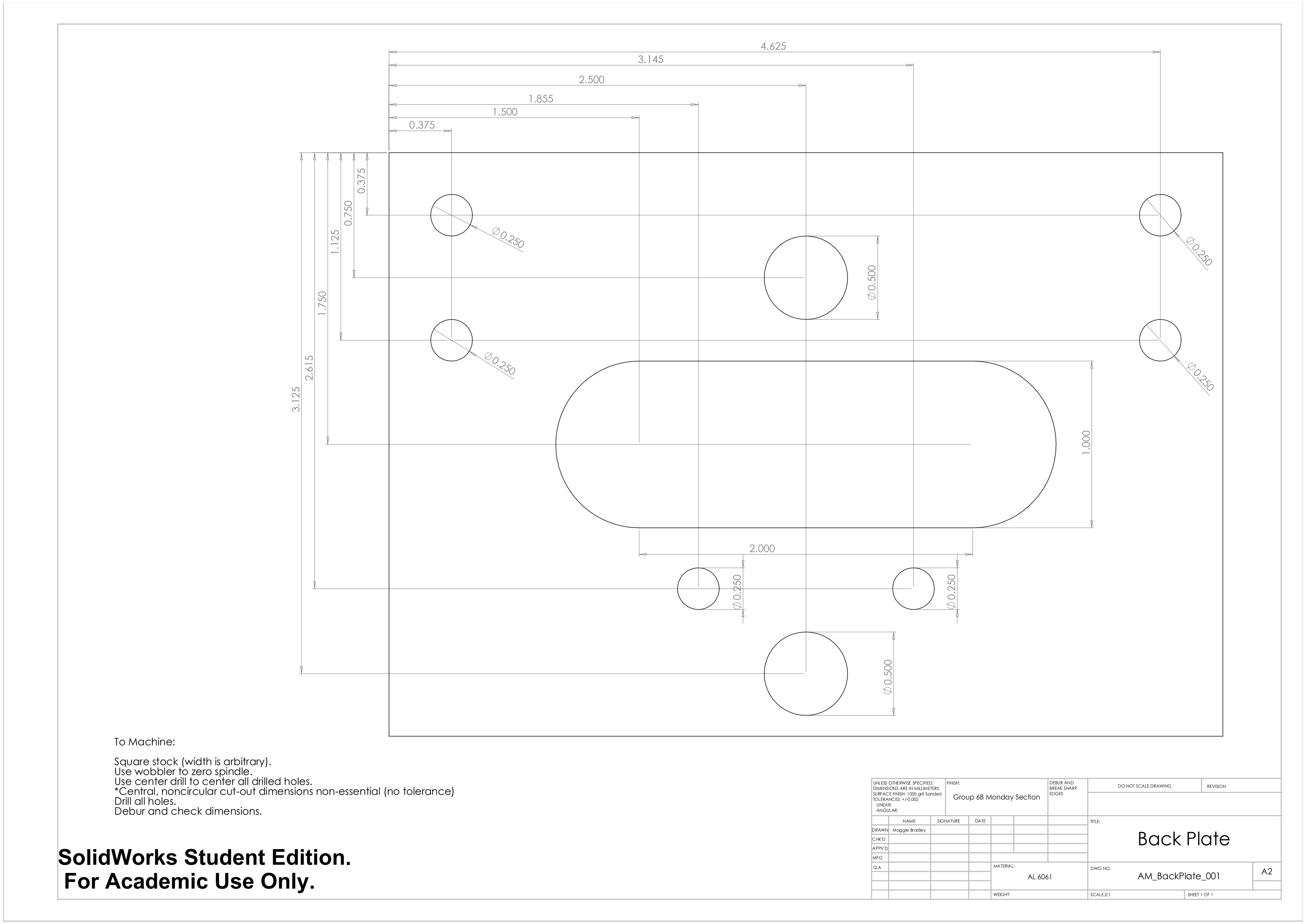
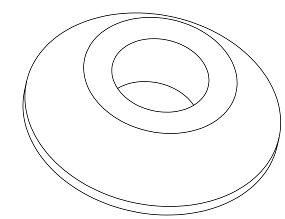
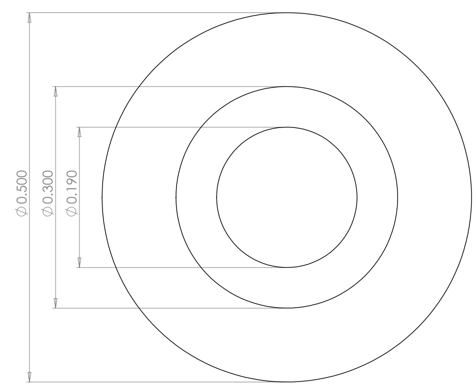
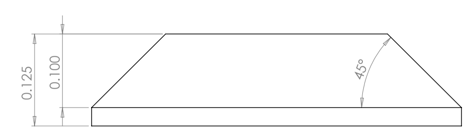

4.625
3.145
2.500
1.855
1.500
0.375
0.375
0.750
1.125
1.750
2.615
3.125
⌀0.250
⌀0.250
⌀0.250
⌀0.250
⌀0.500
⌀0.500
⌀0.250
⌀0.250
1.000
2.000
To Machine:
Square stock (width is arbitrary).
Use wobbler to zero spindle.
Use center drill to center all drilled holes.
*Central, noncircular cut-out dimensions non-essential (no tolerance)
Drill all holes.
Debur and check dimensions.
SolidWorks Student Edition.
For Academic Use Only.
Group 6B Monday Section
DRAWN Maggie Bradley
Back Plate
MATERIAL: AL 6061
DWG NO. AM_BackPlate_001
A2
SCALE:2:1
SHEET 1 OF 1



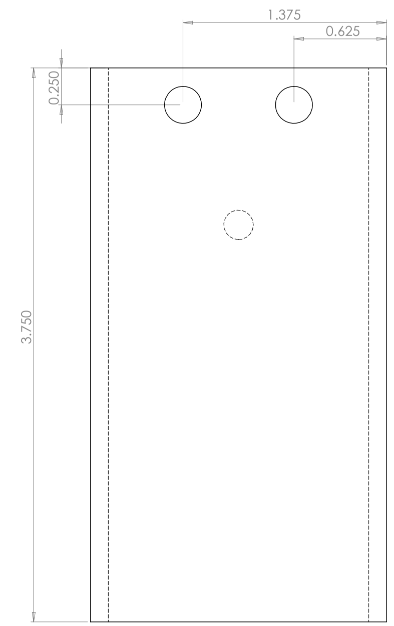
To Machine:
*Best if use collet instead of chuck.
Polish outside diameter with scotch bright (if stock is oversized, turn down)
Center hole with centerdrill
Drill internal diameter.
Unscrew four base holes and turn tool post to 45 degree angle.
*Be aware of orientation of angle, dial should show 135 degrees.
Turn angle, multiple ways to achieve desired length, ask for details. Use trig.
Zero cut-off tool and cut to length+0.001/0.002.
Remove excess material with sandpaper, debur and check dimensions.

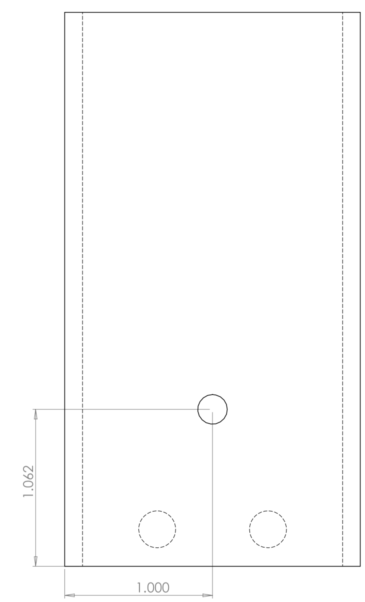



Most important dimensions: 0.125 height and 45 degree angle

| | | | |
|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: 1000 grit Sanded TOLERANCES: +/-0.002 LINEAR: ANGULAR: | FINISH: Group 6B Monday Section | DEBUR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING / REVISION |
| | NAME | SIGNATURE | DATE |
| DRAWN | Maggie Bradley | | |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |
| TITLE: | Piston Head | | |
| MATERIAL: | AL 6061 | | |
| DWG NO. | AM_Piston Head_001 | A2 | |
| WEIGHT: | SCALE: 2.5:1 | SHEET 1 OF 1 | |

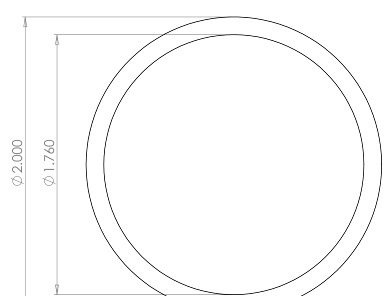



To Machine:

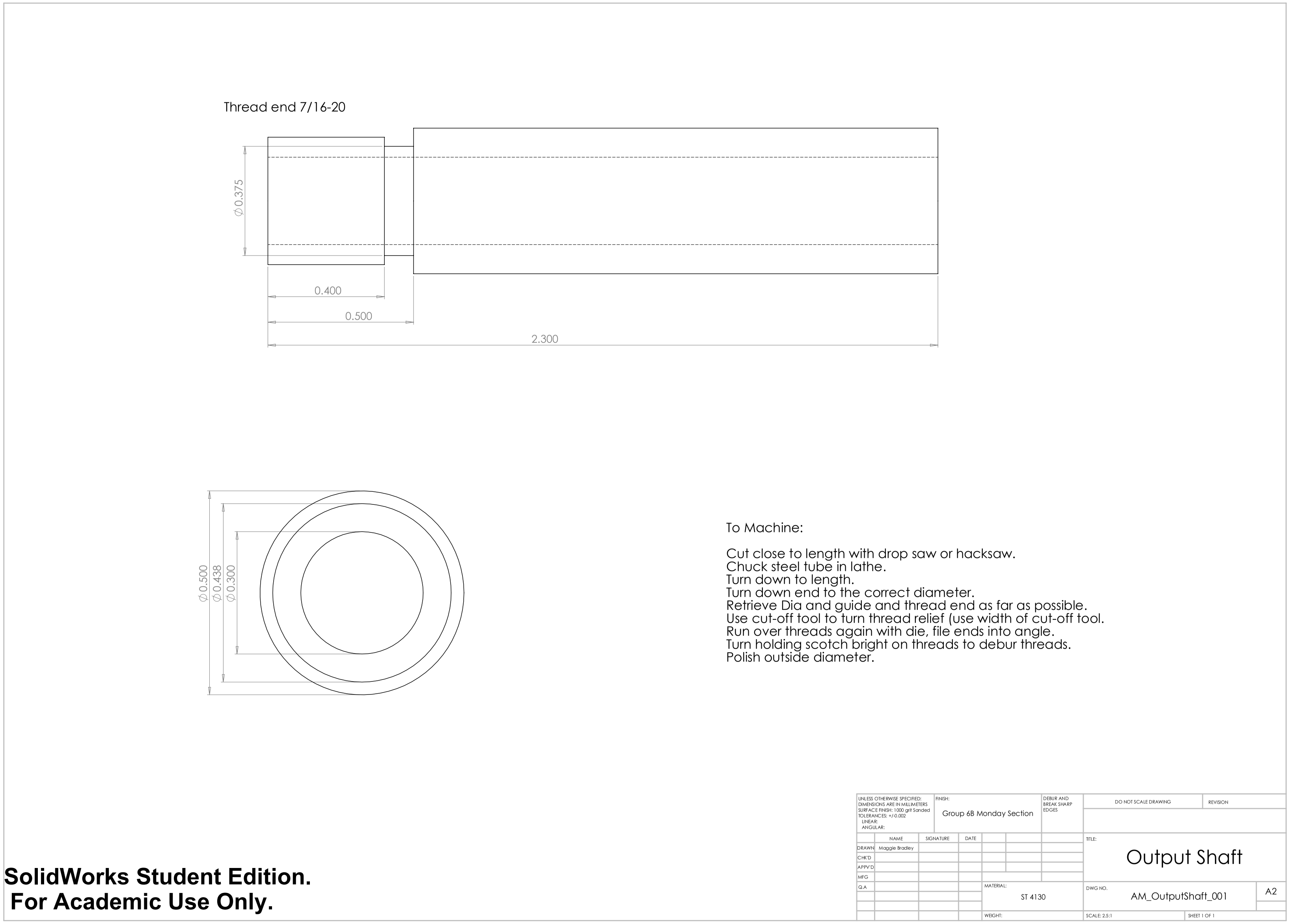
LATHE
Cut Roughly to length on drop saw
Chuck In lathe, polish outside with Scotch bright.
Bore out inside diameter, spinning at 1000rpm and feeding slowly for surface finish. Leave 0.001 on Diameter.
Polish internals up to 2000 grit sandpaper.
Remove from lathe, measure lengths, flip and turn to desired length. Remove and debur.

MILL:
Clamp in mill sideways. Use shims to minimize deformations on outer surface.
Use wobbler to zero side and end, account for diameter of wobbler.
Use center drill to initialize each hole.
Drill out holes.
Remove from vice and flip over, x-position of hole non-essential, but try to make as opposite as possible.
Center and then drill exhaust hole.
Remove and debur.






| | | | | | |
|---|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: 1000 grit Sanded TOLERANCES: +/-0.002 LINEAR: ANGULAR: | FINISH: Bored Inside Surface | | DEBUR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION |
| | NAME | SIGNATURE | DATE | TITLE: Cylinder | |
| DRAWN | Maggie Bradley | | | | |
| CHK'D | | | | | |
| APPV'D | | | | | |
| MFG | | | | | |
| Q.A | | | MATERIAL: AL 6061 | DWG NO. AM_Cylinder_001 | A2 |
| | | | WEIGHT: | SCALE:1:1 | SHEET 1 OF 1 |



Thread end 7/16-20
∅0.375
0.400
0.500
2.300
∅0.500
∅0.438
∅0.300
To Machine:
Cut close to length with drop saw or hacksaw.
Chuck steel tube in lathe.
Turn down to length.
Turn down end to the correct diameter.
Retrieve Dia and guide and thread end as far as possible.
Use cut-off tool to turn thread relief (use width of cut-off tool.
Run over threads again with die, file ends into angle.
Turn holding scotch bright on threads to debur threads.
Polish outside diameter.
SolidWorks Student Edition.
For Academic Use Only.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: 1000 grit Sanded
TOLERANCES: +/-0.002
LINEAR:
ANGULAR:
FINISH:
Group 6B Monday Section
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
Maggie Bradley
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
ST 4130
WEIGHT:
TITLE:
Output Shaft
DWG NO.
AM_OutputShaft_001
A2
SCALE: 2.5:1
SHEET 1 OF 1

**Cost Analysis:**

The below is an itemized list of the parts we plan to order. Nearly all of our budget is spent at Emerson, which provides the large advantage of (supposedly) arriving quicker, allowing us to begin machining as soon as possible. We are very close to our budget of $50, so we must use each part as effectively as possible, and we really don't have room to mess up any parts.

| Item | Purpose | Price | Source | Amt. | Cost |
|---|---|---|---|---|---|
| Cylinders | Piston | $1 each | Emerson | 2 | $2.00 |
| End Caps | Piston | $1 each | Emerson | 2 | $2.00 |
| Rod Ends | Piston Head | $3.52 each | McMaster | 2 | $7.06 |
| Tube Fittings | | $4.54 per 10 | McMaster | 5 | $2.27 |
| 1/4" Steel Rod | Flywheel Pin | $0.10 per inch | Emerson | 2 | $0.20 |
| 1/2" Steel Rod | Output Shaft | $0.23 per inch | Emerson | 5 | $1.15 |
| Self Aligning Bushing | Output Shaft | $3.00 each | Emerson | 1 | $3.00 |
| Tubing | | $0.31 per foot | Emerson | 2 | $0.62 |
| 1/4 - 20 Threaded Rod | Timing | $1.02 per foot | Emerson | 1 | $1.02 |
| 1/4 - 20 Nuts | Timing | $0.06 each | Emerson | 12 | $0.72 |
| Lock Washers | Timing | $0.02 each | Emerson | 10 | $0.20 |
| 1/4" x 2.25" Al 6061 | Timing | $0.36 per inch | Emerson | 9 | $3.24 |
| 1/2" x 4" Al 6061 | Scotch Yoke | $1.18 per inch | Emerson | 7 | $8.26 |
| 1/4" x 1" Al 6061 | Crank Arm | $0.14 per inch | Emerson | 4 | $0.56 |
| 1/4" x 2.25" Al 6061 | Base Plate | $0.36 per inch | Emerson | 8 | $2.88 |
| 1/2" x 4" Al 6061 | Back Plate | $1.18 per inch | Emerson | 6 | $7.08 |
| 1/4 - 20 1" Screws | Back Plate | $0.17 each | Emerson | 10 | $1.70 |
| | | | | | $43.96 |

## Iteration 2

**Changes to Design:**

We didn't change much in our first round of re-design. Our main problem was the clamping of the motor. We need a place for the vice to grip our motor, preferably a metal plate less than four inches wide. The plate also should provide some sort of support for the pistons (i.e. they should screw in.) The first big change we made was to rotate the timing mechanism ninety degrees, so that it is perpendicular to the scotch yoke. This provides two large benefits: the motor is shorter, and it eliminates one of the sandwiching plates needed for the timing, as the base plate can act as one. We then added a base plate, a 1/4" x 2.25" piece of aluminum (later changed to 1/2" x 4") that holds the pistons via screws, and also screws into the back plate. Also, this allows us to affix the timing mechanism using screws rather than threaded rod.

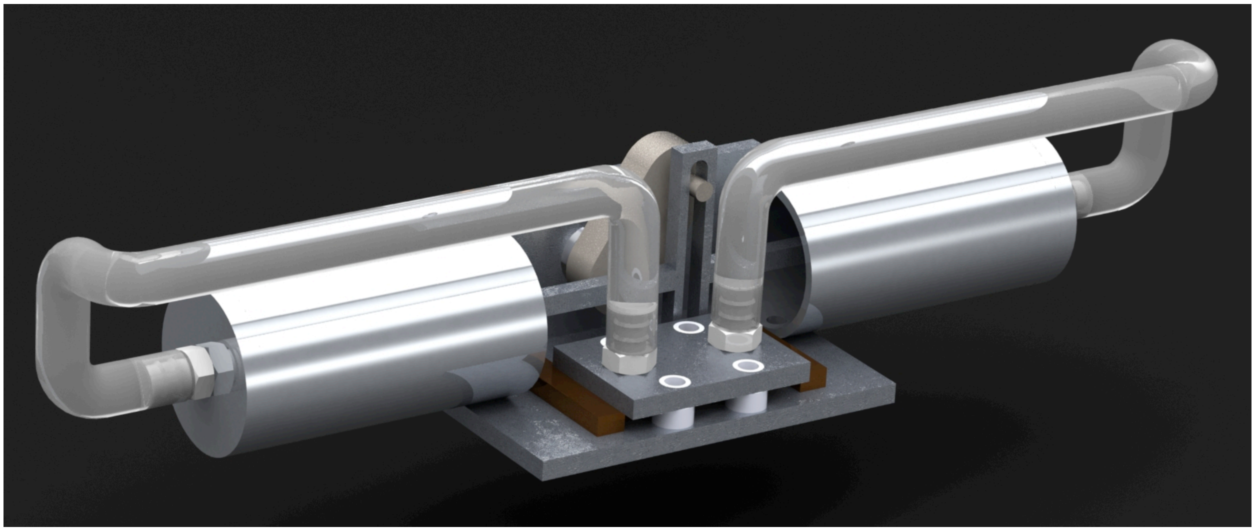
Another change we made was using a 2.25 inch wide back plate. This saved costs (this width is nearly half the cost of the 4 inch width.) We also made the crank arm half an inch thick, rather than a quarter inch. This should allow the output shaft and pin to screw into the arm much more securely, as well as prevent bending or fracture in the arm. Other than this, all the features of the design from Iteration 1 are incorporated into this design as well. The above calculations should also be accurate.

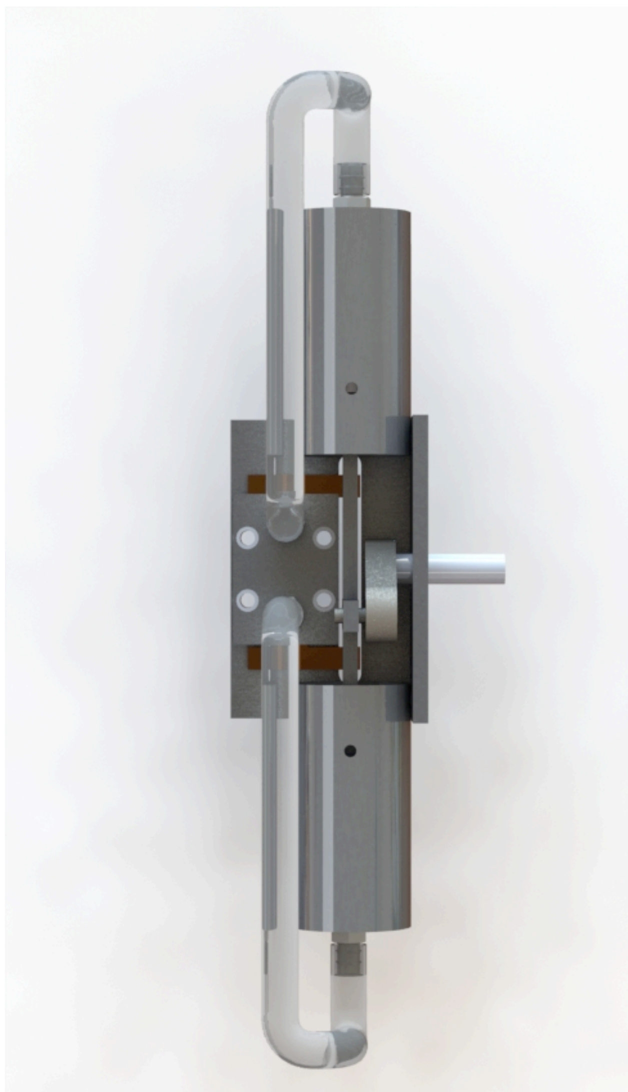
**CAD Model:**

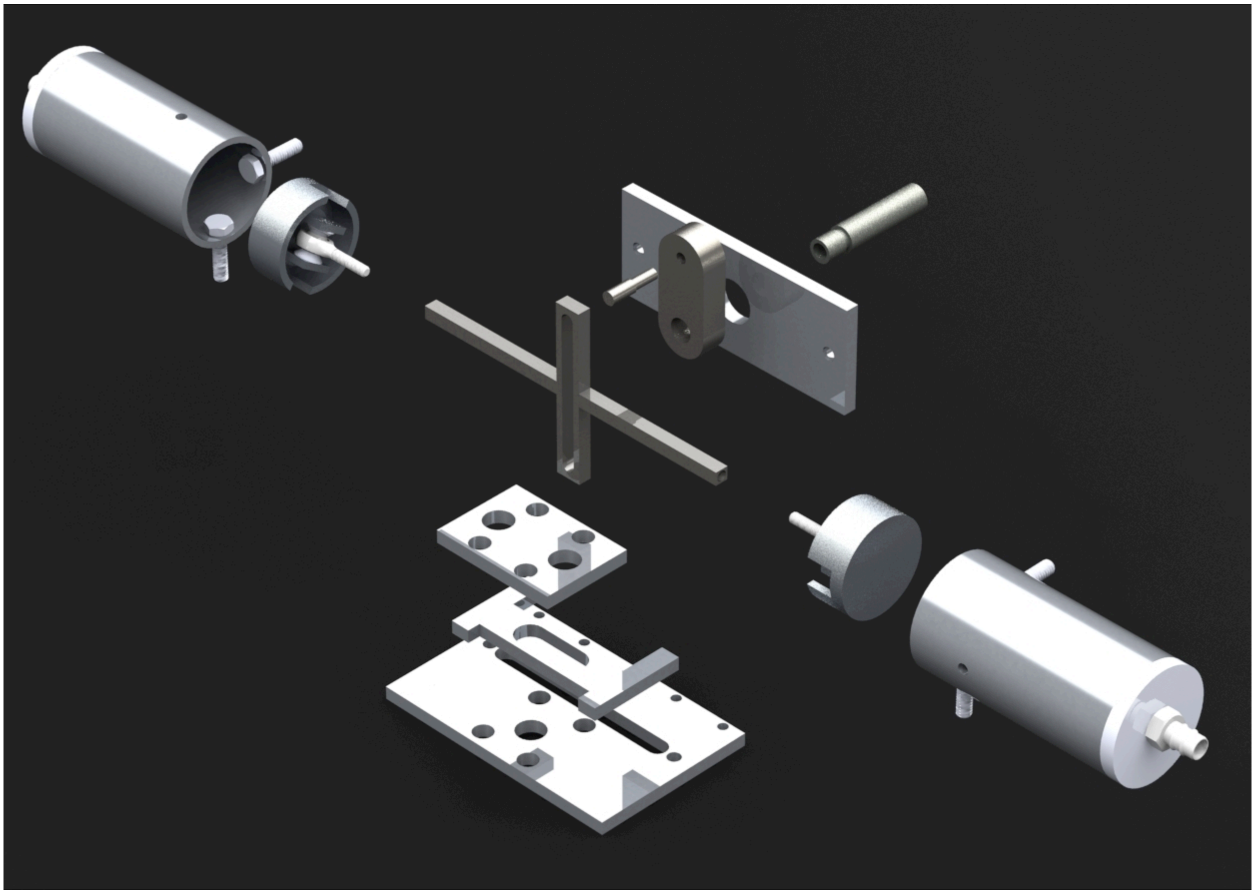
We also updated our CAD Model to reflect the changes to our design, and finalized it. The Solidworks files can be found via the link below:

https://cornell.box.com/s/w9zg027jtj9qv5enirj5

As before, we also created some photorealistic renderings of the new model.







**Drawings and Manufacturing Instructions:**

Drawings for this iteration, as it is the one we chose to manufacture, can be found in the next section, with pictures of the machining process as well.

**Cost Analysis:**

Yet again, we put together a cost analysis for the final motor.  This Iteration is slightly cheaper than the previous.

| Item | Purpose | Price | Source | Amt. | Cost |
|---|---|---|---|---|---|
| Cylinders | Piston | $1 each | Emerson | 2 | $2.00 |
| End Caps | Piston | $1 each | Emerson | 2 | $2.00 |
| Rod Ends | Piston Head | $3.53 each | McMaster | 2 | $7.06 |
| 2” x 3” Al 6061 Rod | Piston Head | $3.00 each | Emerson | 1 | $3.00 |
| Tube Fittings | | $4.54 per 10 | McMaster | 5 | $2.27 |
| 1/4” Steel Rod | Flywheel Pin | $0.10 per inch | Emerson | 2 | $0.20 |
| 1/2” Steel Rod | Output Shaft | $0.23 per inch | Emerson | 5 | $1.15 |
| Self Aligning Bushing | Output Shaft | $3.00 each | Emerson | 1 | $3.00 |
| Tubing | | $0.31 per foot | Emerson | 2 | $0.62 |
| 10-32 Nuts | Scotch Yoke | $1.71 per 100 | McMaster | 2 | $0.04 |
| 1/4 - 20 Nuts | Timing | $0.06 each | Emerson | 4 | $0.24 |
| Lock Washers | Timing | $0.02 each | Emerson | 16 | $0.32 |
| 1/4” x 2.25” Al 6061 | Timing | $0.36 per inch | Emerson | 6 | $2.16 |
| 1/2” x 4” Al 6061 | Scotch Yoke | $1.18 per inch | Emerson | 7 | $8.26 |
| 1/2” x 2.25” Al 6061 | Crank Arm | $0.73 per inch | Emerson | 1 | $0.73 |
| 1/2” x 4” Al 6061 | Base Plate | $1.18 per inch | Emerson | 6 | $7.08 |
| 1/2” x 2.25” Al 6061 | Back Plate | $0.73 per inch | Emerson | 6 | $4.38 |
| 1/4 - 20 1” Screws | Back Plate | $0.17 each | Emerson | 8 | $1.36 |
| Lubricant | Piston | $5.90 per 8 oz | McMaster | 0.25 | $0.18 |
| | | | | | $46.05 |

# Section 4: Production, Testing, and Refinement of Design

**Refinement of Prototype:**

The refinement of our model can be better visualized going through the consecutive Iterations of our design in Section 3. The changes to design feature explains the reasoning behind each change.

**Prototyping Budget Record:**

Our prototyping budget on this project is only fifty dollars. This really isn't much money, especially when we're using it to buy stock. We were able to purchase a lot of the items we needed from Emerson shop, which is very good because it is quicker and cheaper than McMaster Carr. Here is the first order we put in to our TAs from McMaster:

| Item | McMaster Code | Price | Quantity | Cost |
|---|---|---|---|---|
| Steel Ball Joint Rod End, 10-32 RH Male Shank | 60645K111 | $3.53 ea. | 1 | $3.53 |
| Steel Ball Joint Rod End, 10-32 LH Male Shank | 60645K112 | $3.53 ea. | 1 | $3.53 |
| Durable Nylon Extra-Grip Barbed Tube Fitting, Straight for 3/8" Tube ID x 1/4 Male Pipe Size | 5372K117 | $4.54 per pack of 10 | 1 | $4.54 |
| | | | | $11.60 |

Then, here is the first set of things we ordered from Emerson:

| Item | Quantity | Unit | Cost |
|---|---|---|---|
| Bored Cylinders, 4” | 2 | ea. | $2.00 |
| Machined End Caps | 2 | ea. | $2.00 |
| 1/4” Diameter Steel Rod | 2 | inch | $0.20 |
| 1/2” Diameter Steel Rod | 5 | inch | $1.15 |
| Self Aligning Bushing | 1 | ea. | $3.00 |
| Tubing | 4 | ft | $1.24 |
| 1/4 - 20 Nuts | 8 | ea. | $0.48 |
| Lock Washers | 16 | ea. | $0.32 |
| 1/4” x 2.25” Al 6061 | 6 | inch | $2.16 |
| 1/2” x 4” Al 6061 | 7 | inch | $8.26 |
| 1/2” x 2.25” Al 6061 | 1 | inch | $0.73 |
| 1/4 x 2.25” Al 6061 | 6 | inch | $2.16 |
| 1/2” x 2.25” Al 6061 | 6 | inch | $4.38 |
| 1/4 - 20 1” Screws | 14 | ea. | $2.38 |
| | | | 30.46 |

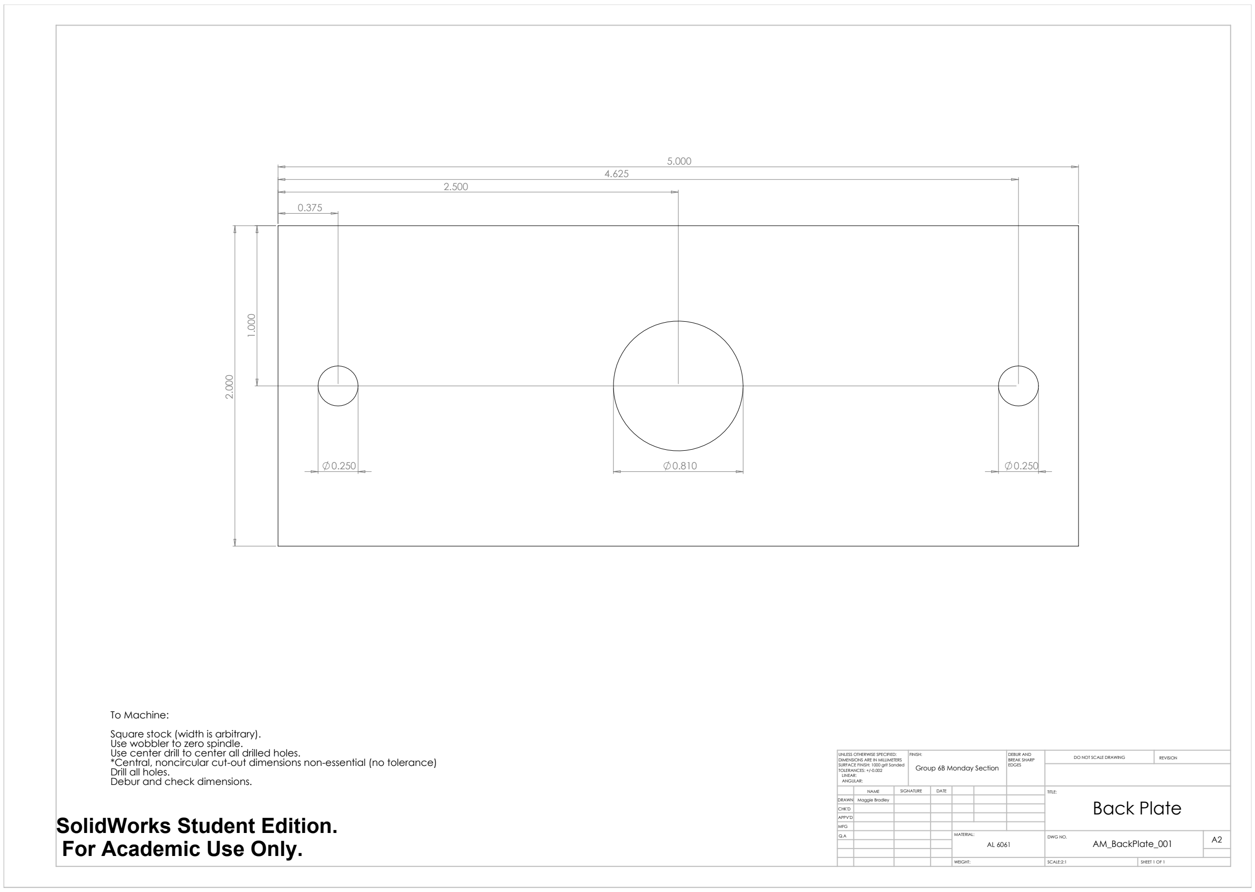
This brings our total budget used so far up to $42.06. This is a pretty good price so far, as it leaves us nearly eight dollars - perfect for buying a bearing, some epoxy, or another piece of stock if we figure we need any of these (or other) parts in the future.

However, when we first got our order, we immediately noticed two things were wrong. First off, we ordered the wrong size stock for our base plate. We needed to order 1/2” x 4” stock, where we ordered 1/4” x 2.25”. Because we could return the wrong plate, this only added $4.92 to our budget. Then, we also noticed that we forgot to order the piston head stock! The round bar of this cost $3.00, bringing our prototyping budget up to $49.98, just a hair under our limit.

**Fabrication:**

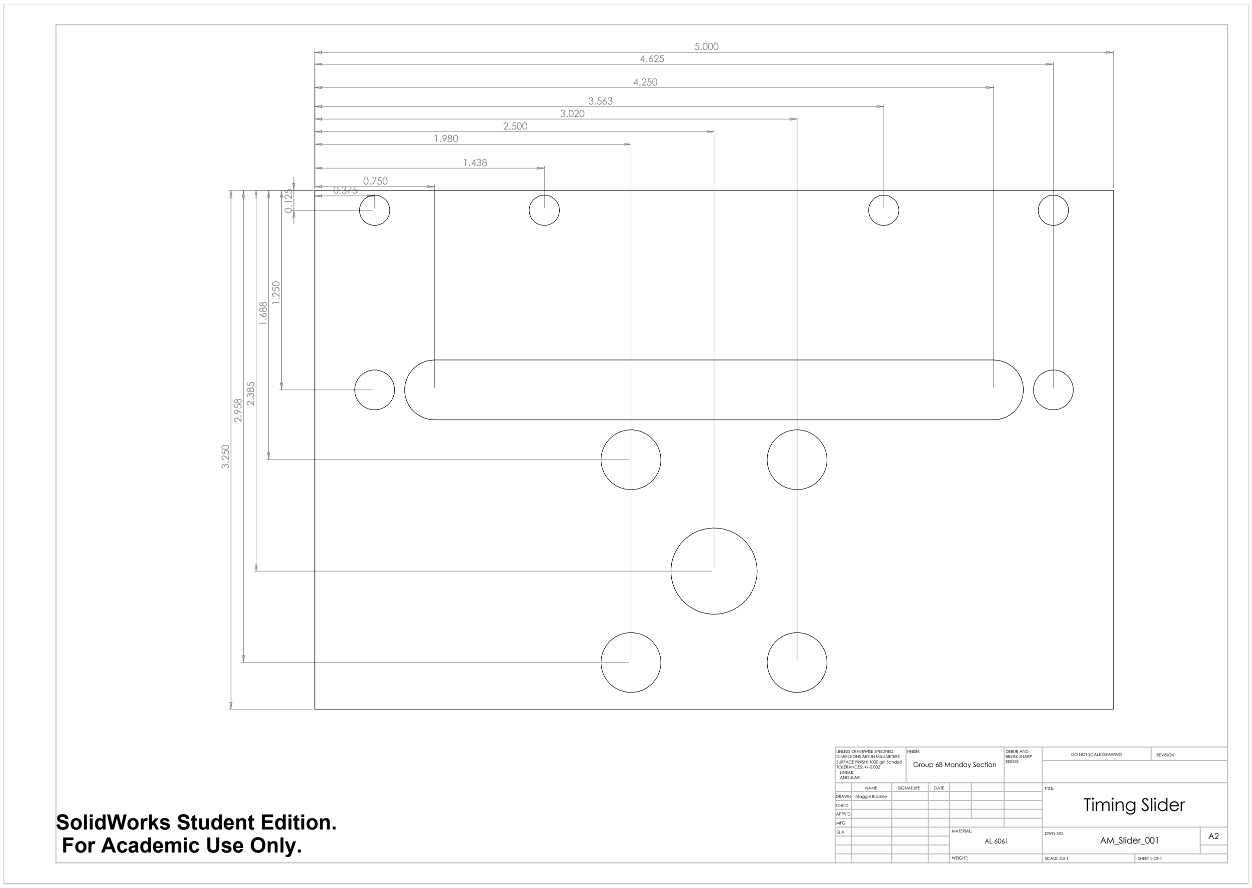
Below are the drawings for each part we plan to make. The part and drawing are listed, along with the stock piece they are made from, the group member responsible, and a cursory list of machining steps. We also include pictures of most of the pieces after manufacture.

1. Backplate. 1/2”x2.25”x6” Aluminum. Orlando and Trevor.

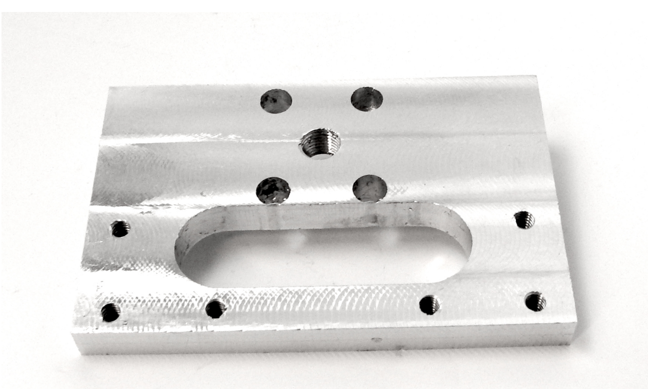


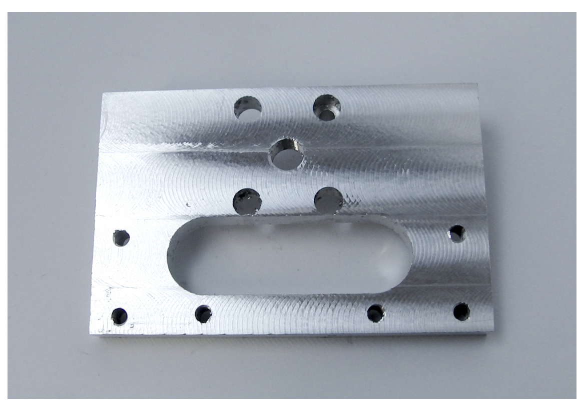

Created April 25th & 28th. ~2 hours machining.

2. Baseplate. 1/4”x2.25”x6” Aluminum. Sarah and Orlando.

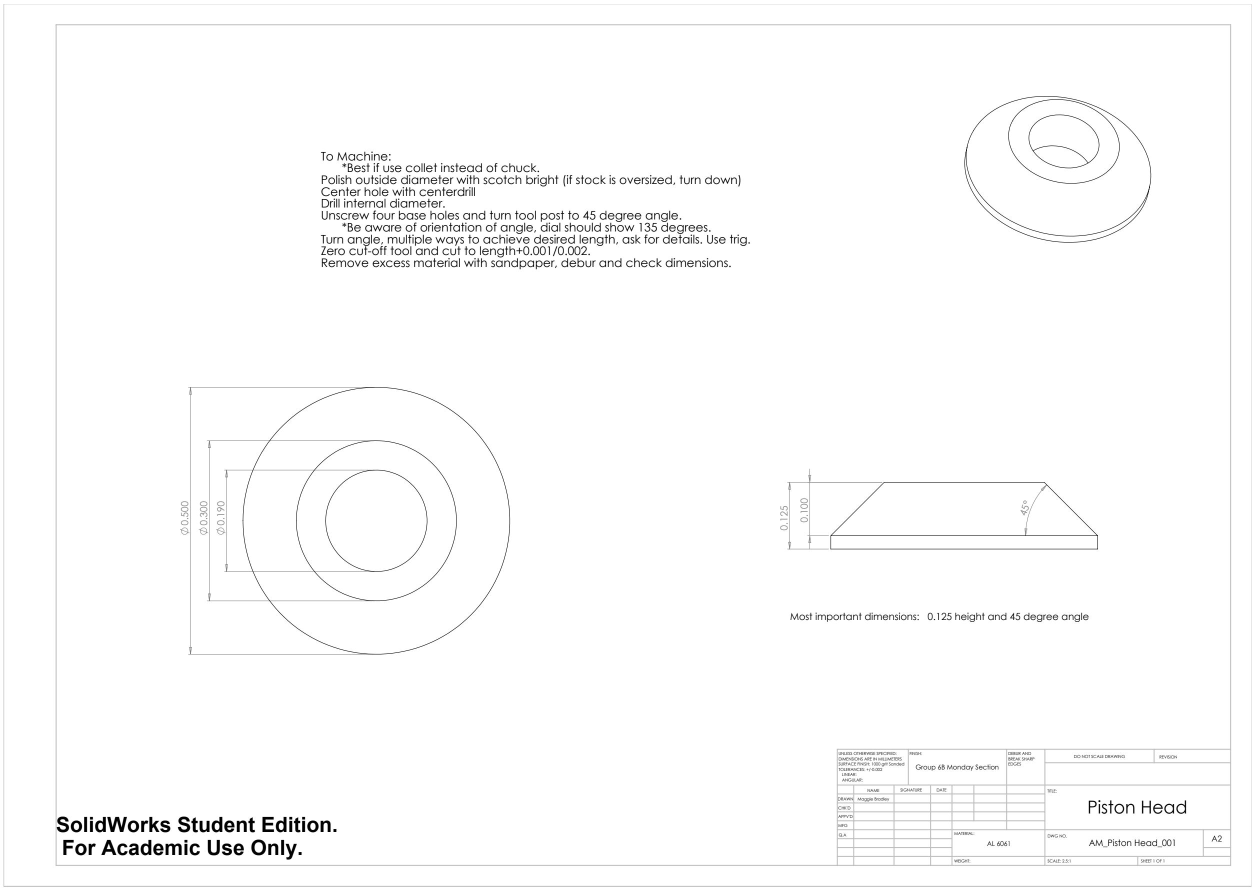



Created April 23rd and 29th. ~ 2 hours machining. Modified to accommodate Crankshaft Arm.



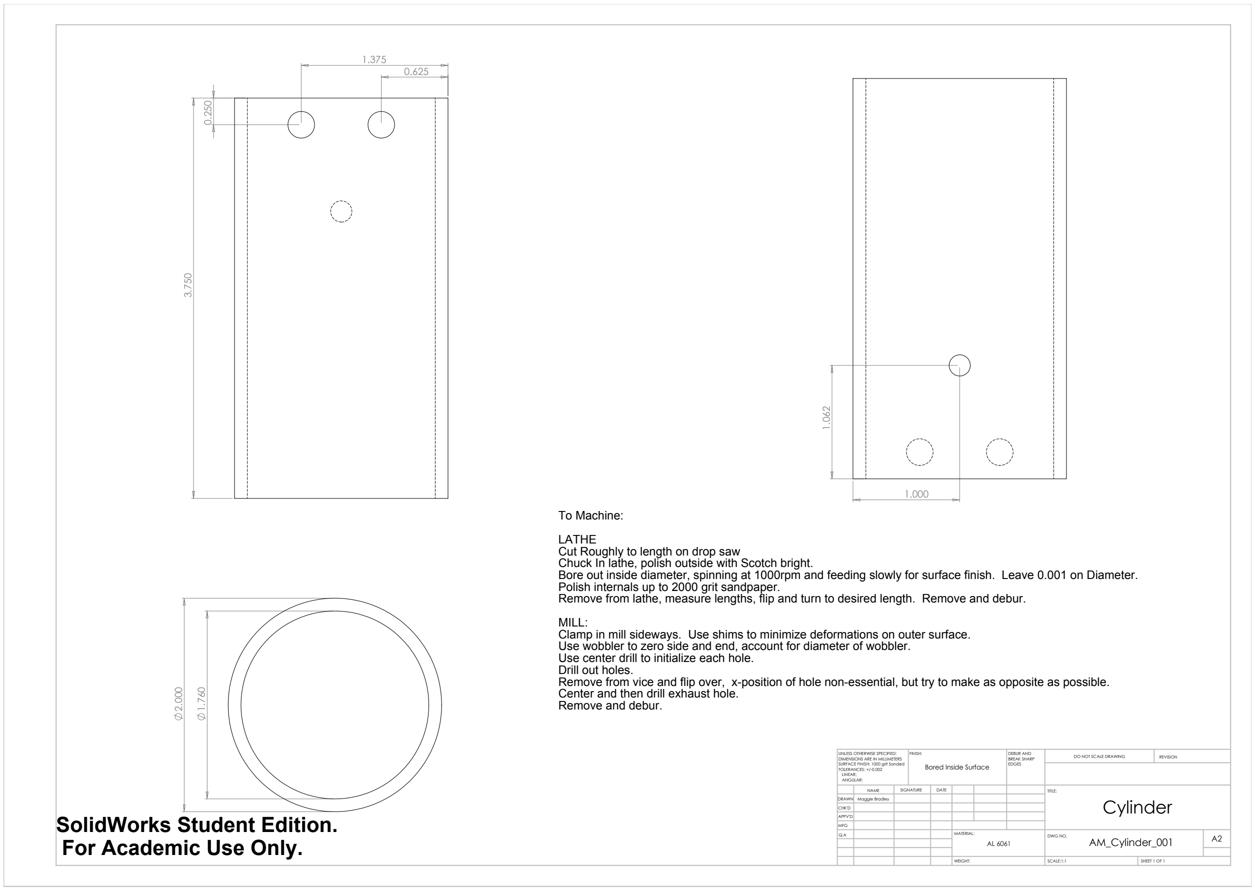


3. Cone x4. Scrap Pieces. Trevor.



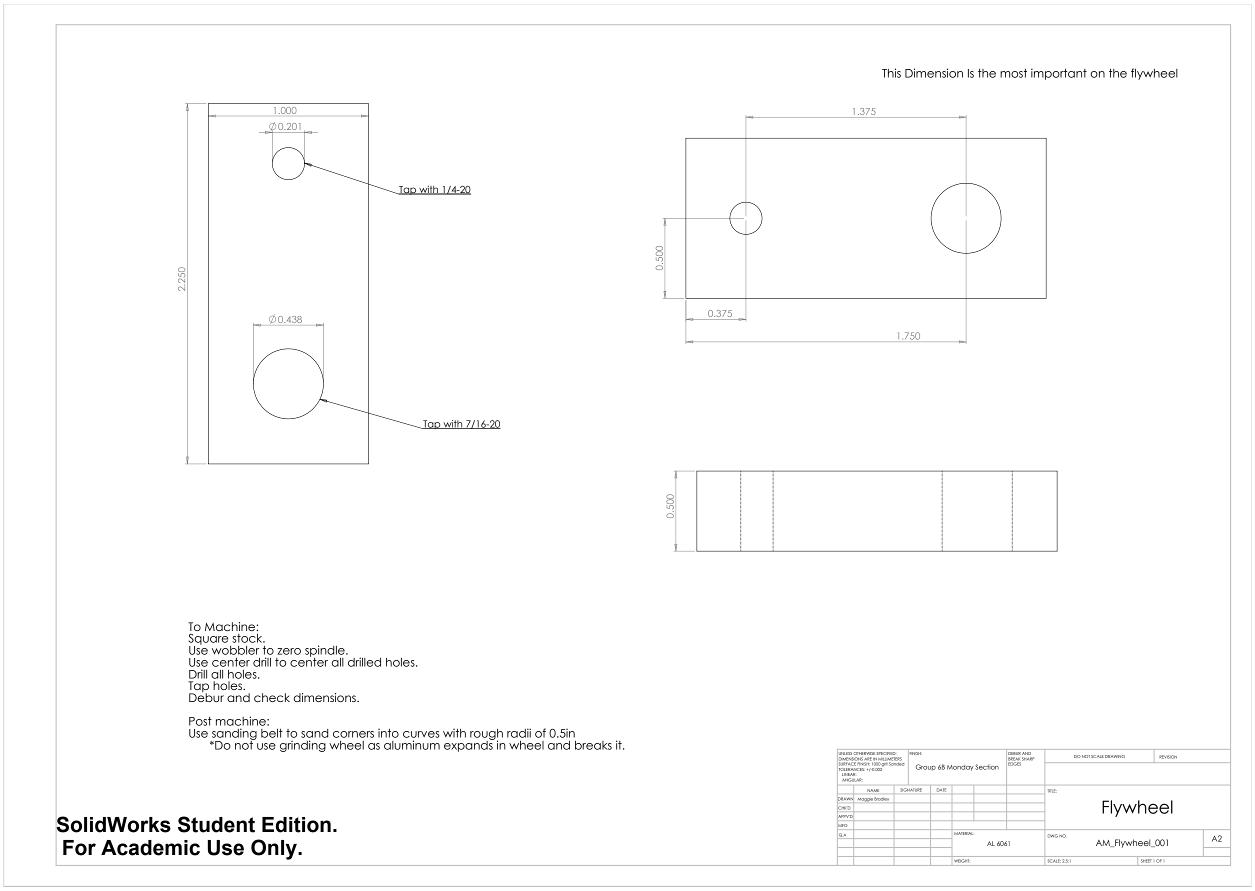

Created April 28th & May 1st. ~ 1.5 hours machining.

4. Cylinders. Bought from Emerson. Modded by Maggie.

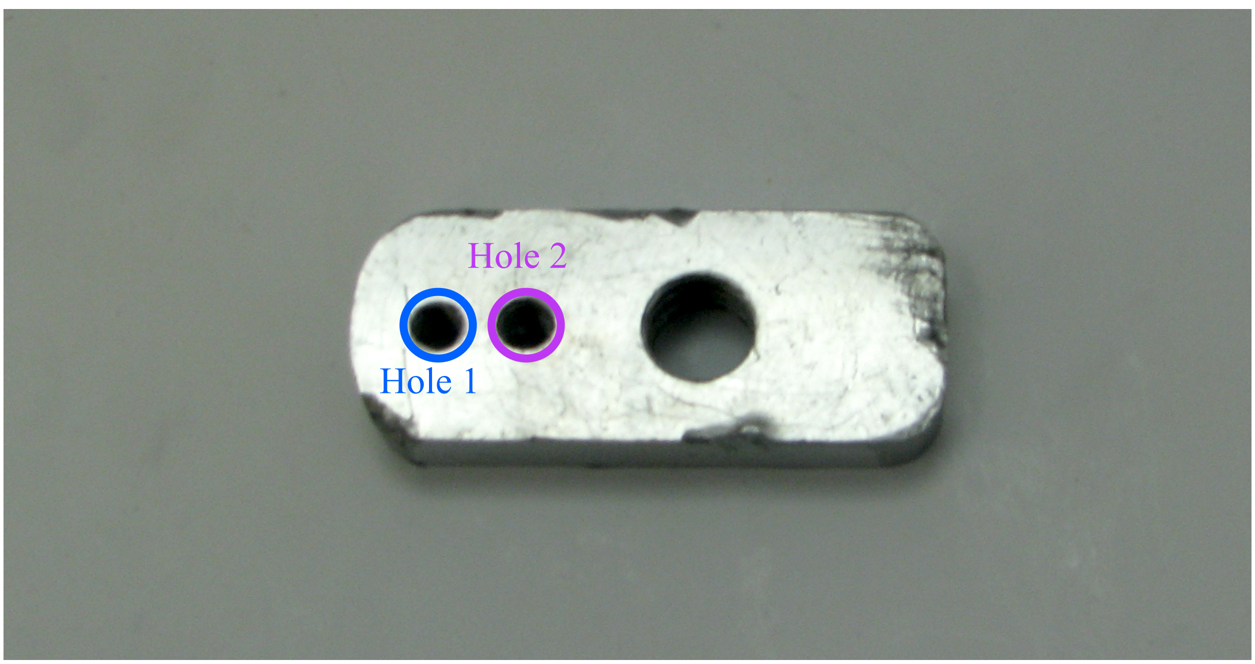



Created May 3rd. ~ 1 hour machining. ~ 3 hour welding.

5. Flywheel/Crankshaft Arm. 1/2”x2.25”x1” Aluminum. Orlando and Trevor.




Created April 25th & 28th. ~1.5 hours machining. Modified later to add another hole.



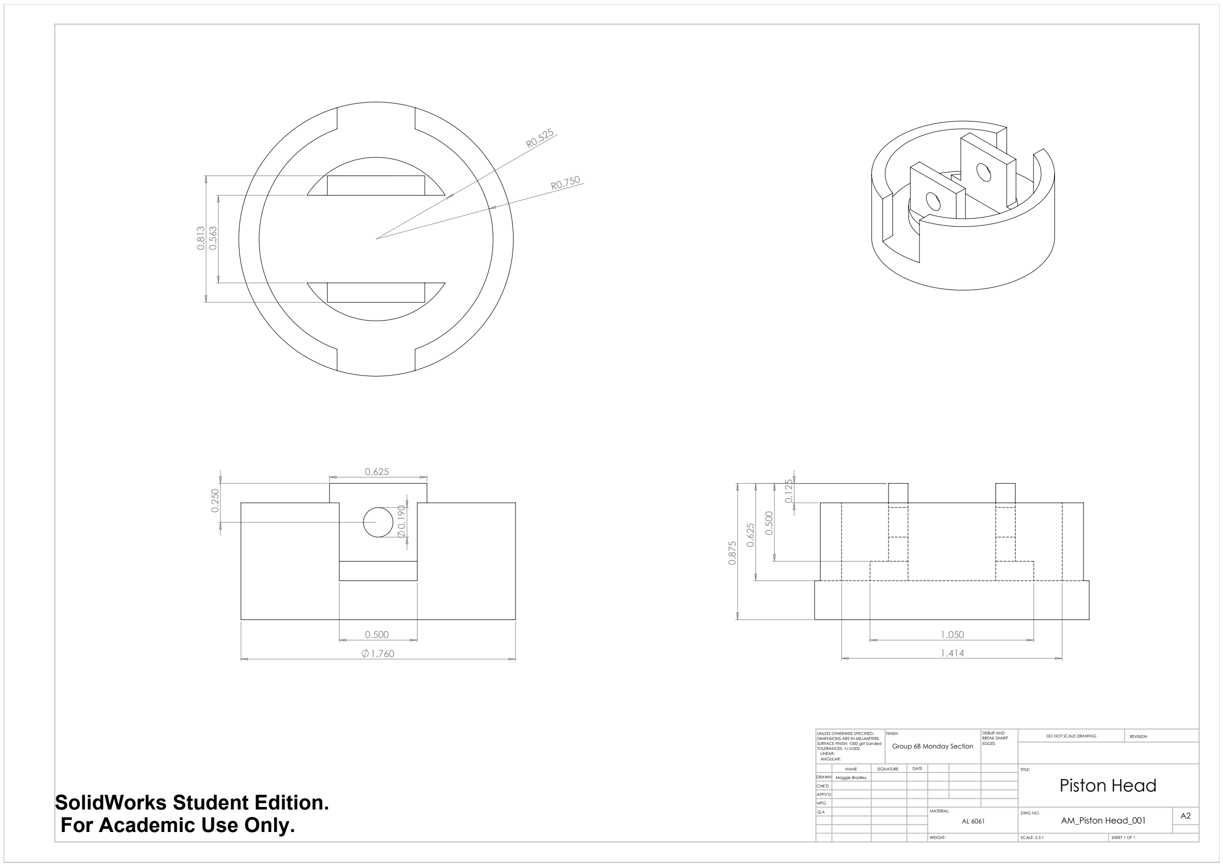
6. Output Shaft. 1/2"x5" Steel Rod. Sarah and Orlando.

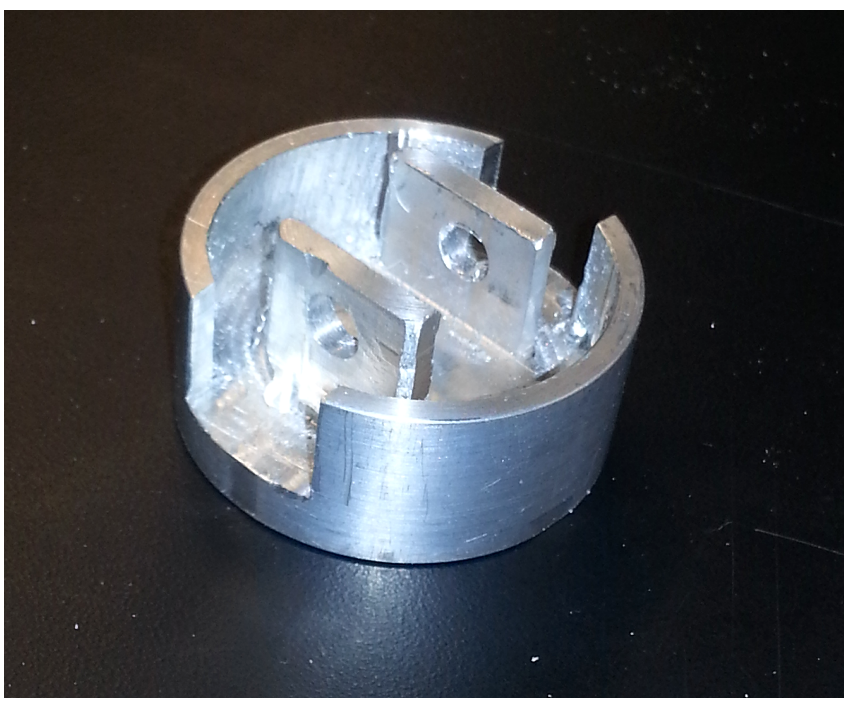
Created April 28th and 30th. ~ 2 hours machining.

7. Steel Pin. 1/4"x2" Steel Rod. Sarah and Orlando.

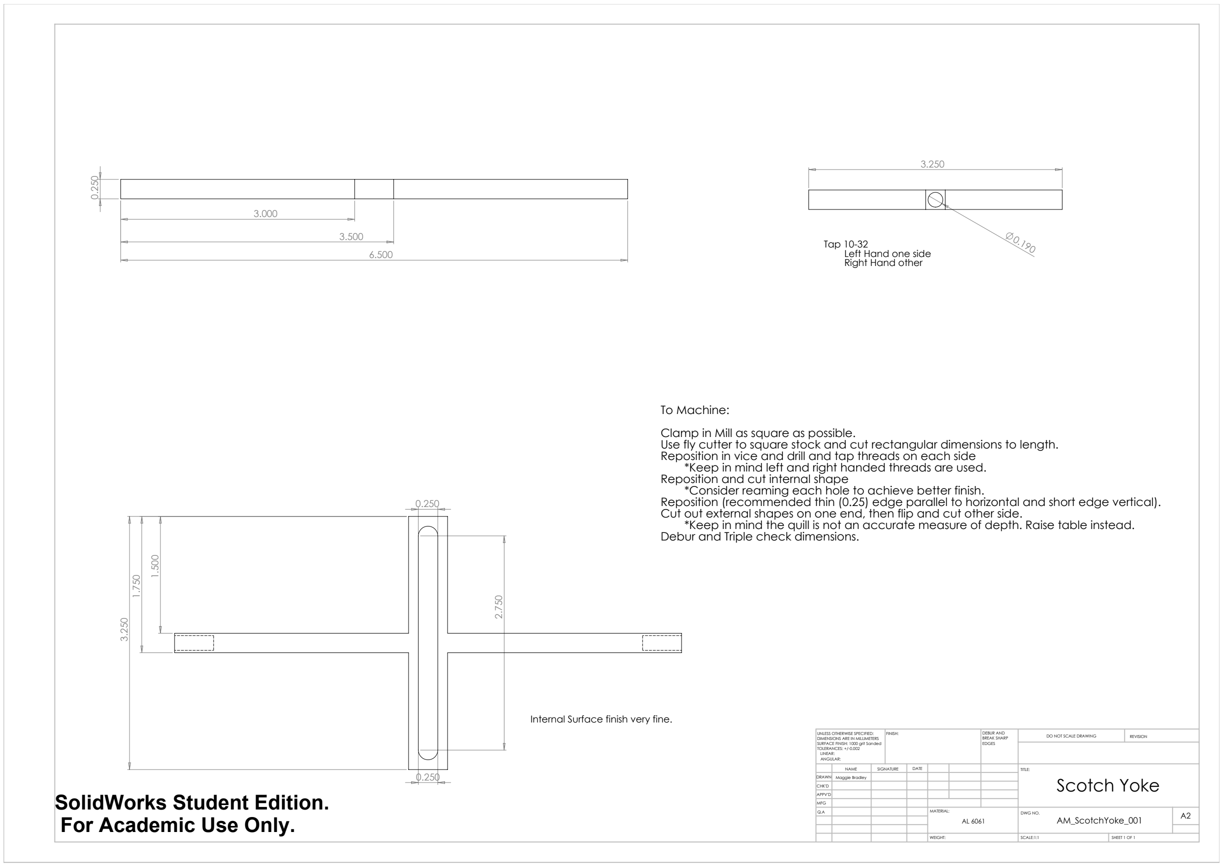
Created April 28th and 30th. ~ 1.5 hours machining.

**8.** Piston Head x2. 2”x3” Aluminum Rod. Maggie



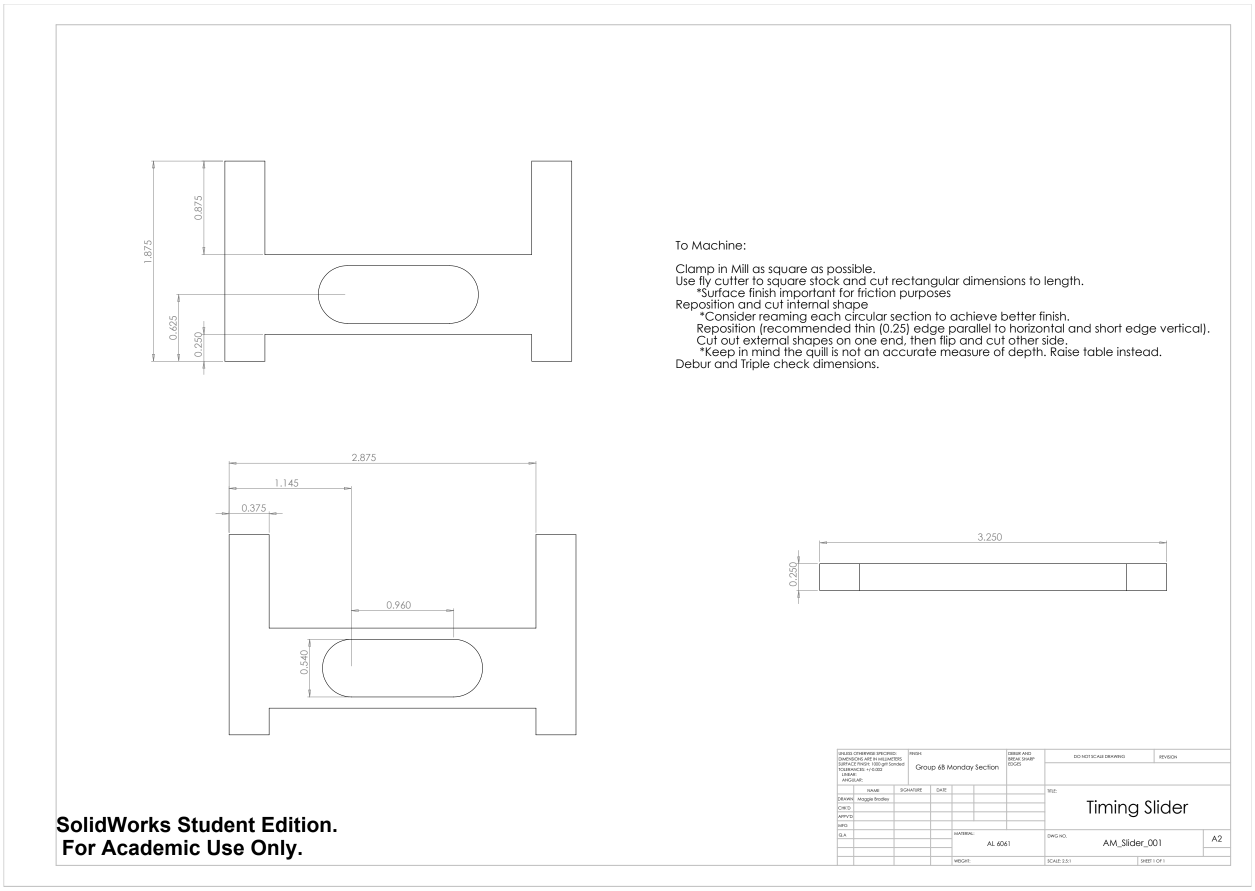



**9.** Scotch Yoke. 1/2”x4”x7” Aluminum. Maggie.

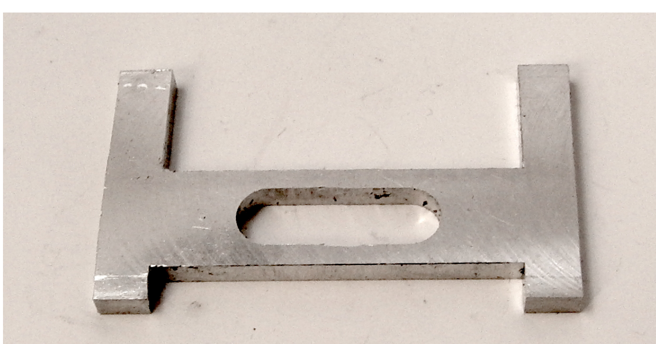


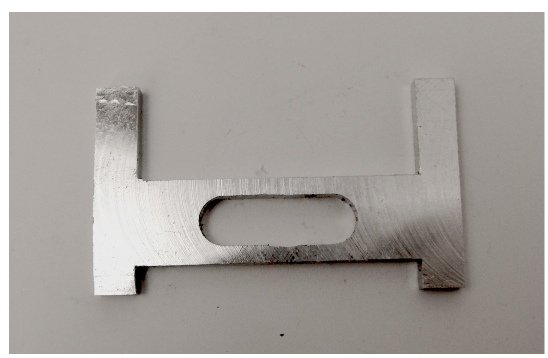

Created May 3rd. ~3 hours machining.

10. Timing Slider. 1/4”x2.25”x4” Aluminum. Sarah

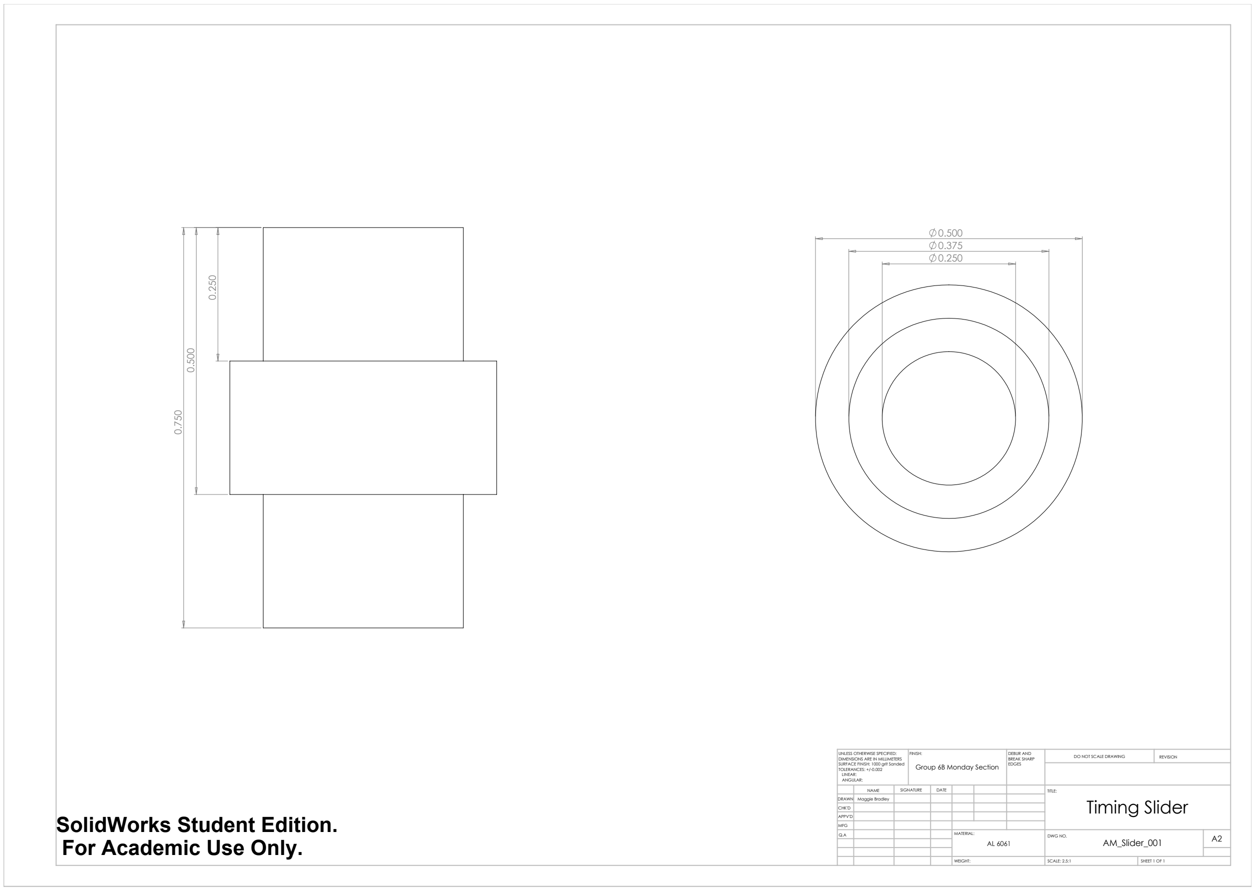



Created April 21st and 23rd. ~ 3 hours machining.



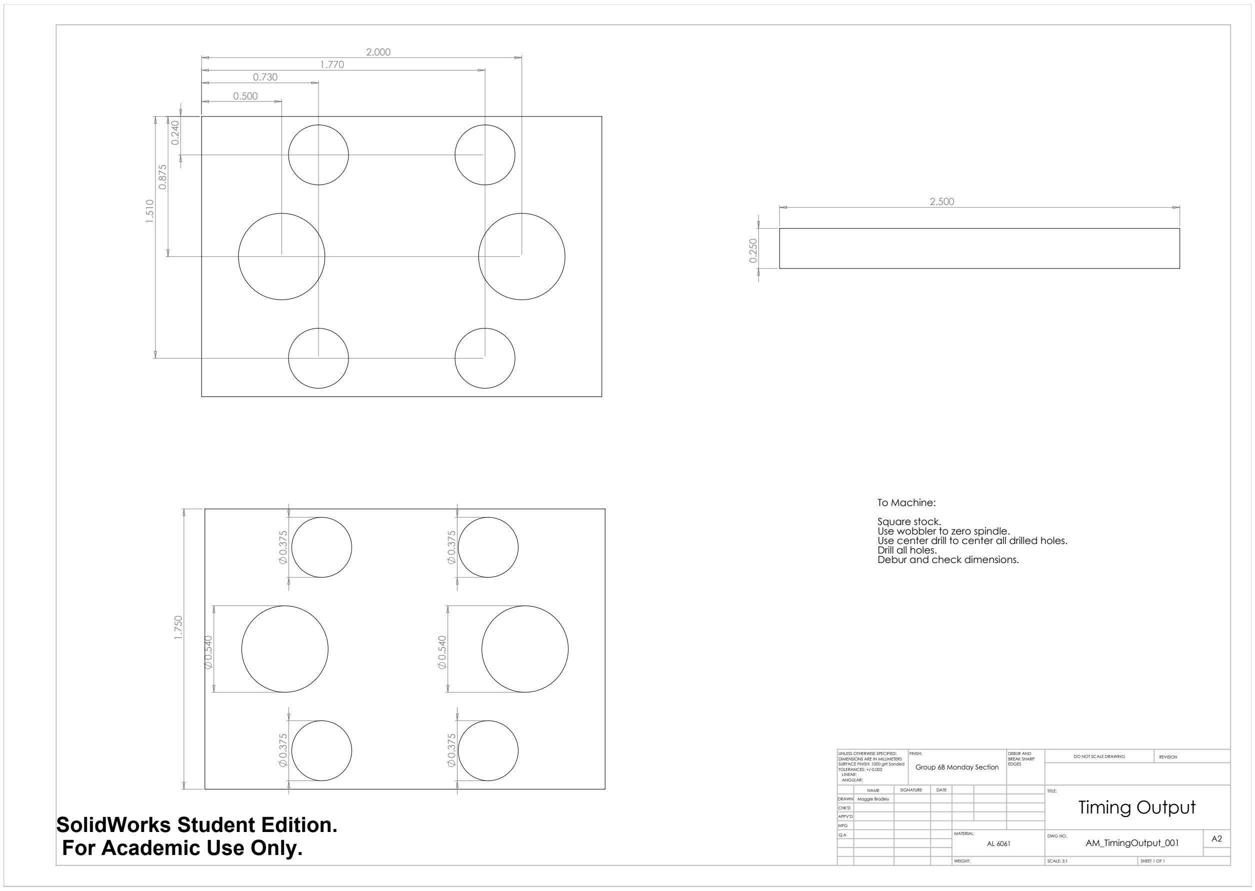


11. Timing Elbow x4. Scrap Pieces. Sarah.




Created April 25th. In progress.

12. Timing Output Plate. 1/4”x2.25”x3” Aluminum. Sarah.




Created April 23rd. ~ 1 hour machining.

**Assembly:**

Now we must take all of the above parts, and connect them. First, the cylinders were welded to the end caps. Then, the piston heads were assembled, affixed to the scotch yoke and inserted into the cylinders. Once they are secure, the cylinders may be screwed into the base plate. To do this, we had to clamp all the plates and cylinders together, then use a hand drill to drill the holes so that they were aligned properly. Then the timing mechanism (with elbows between plates) was press fitted and screwed together.

Next, tube fittings were screwed into the threads in the timing mechanism and end caps. Then we assembled the back plate setup. The bushing was fitted into the back plate hole, and the output shaft put through the bushing. The pin and output shaft was screwed into the crank arm. Finally, we attached these two setups by putting the pin through the scotch yoke, and screwing the cylinders and base plate into the back plate.

However, we hit a snag here. The piston heads were bottoming out, hitting the endcaps. To remedy the issue, we cut a new crank arm quickly, with shorter stroke length, and also shortened the length of the scotch yoke. This still didn't fix it however. Last minute, we drilled another hole in the crank arm, shortening the stroke length even further. After this, we repeated the assembly, and were able to test.

For instance, here's a picture of the piston head assembly before attachment.

**Performance Evaluation:**

Though we don't have our motor completed enough to begin testing, we can begin to layout categories in which we plan to evaluate its performance.

**I.** Max RPM (loaded and unloaded)
Low RPM (<100) and high RPM (~1000) have vastly different potential applications based on need.

**II.** Torque (using 2kg flywheel provided)
Basic measure of performance.

**III.** Cost
Must be below $50, could provide competitive gain or loss.

**IV.** Ability to Self Start
Preferably yes, but not a huge factor for our purposes.

**V.** Reliability (if running between 0 - 100% of the time)
If going to market, reliability is a huge factor in creating a good product.

**Performance Results:**

**I.** Max RPM (loaded and unloaded)
Nearly gets RPM in counter clockwise direction. Overall however, 0 rpm.

**II.** Torque (using 2kg flywheel provided)
N/A

**III.** Cost
$46.05

**IV.** Ability to Self Start
N/A (doesn't start)

**V.** Reliability (if running between 0 - 100% of the time)
0%

A video of our motor testing can be found on youtube at:

https://www.youtube.com/watch?v=VieNboB-4yE&feature=youtu.be

One can see that our motor had some push to counteract flywheel movement, but not enough to gain real rpm.

**Analysis of Issues and Suggested Design Changes:**

Despite our design working in theory, a few oversights in the design process, as well as unanticipated setbacks in the manufacturing process, caused our design to not run when full assembled. Our design was machining intensive, especially when compared to the rotary veins and turbines created by other groups. With 23 individual machined parts, some of which requiring multiple setups between lathes and mills, as well as the welding on the piston cylinders, our design was extremely labor intensive. Our group chose this design because we wanted to emphasize simplicity, functionality, and reliability in accordance with the technical skill each member had. Our main cause of failure was not skill level and execution, but time limitation. This lead to machining bottlenecks, as well as low tolerance zones, which
will be detailed below.

One principle, and unanticipated, delay was the late date at which we received our piston cylinder stock. We did not get this stock until Thursday, and were subsequently unable to machine it until Saturday morning. Not only was this later than our Gantt Chart anticipated, but the stock itself was shorter that we originally ordered. Our scotch yoke design was dependent on a certain stroke length, and after we had machined, welded, and then post machined the cylinders it was already Monday afternoon. It became clear upon our initial assembly attempt that the cylinder lengths necessitated a significant drop in stroke length. To accomplish this, we both shortened the scotch yoke length and changed the hole position of the yoke pin on the crank arm of our design. We were successful in altering our stroke length, but errors in stock acquisition meant this was accomplished 10 minutes before our lab section began. With no time to test or alter our assembly, we simply drilled the exhaust holes we had tentatively placed in the CAD model. In hind sight, finishing our assembly before the weekend (possible if there had been no stock delay) would have allowed us to tune and fix our motor before testing. Our time constraints, not our design, was the main reason for failure.

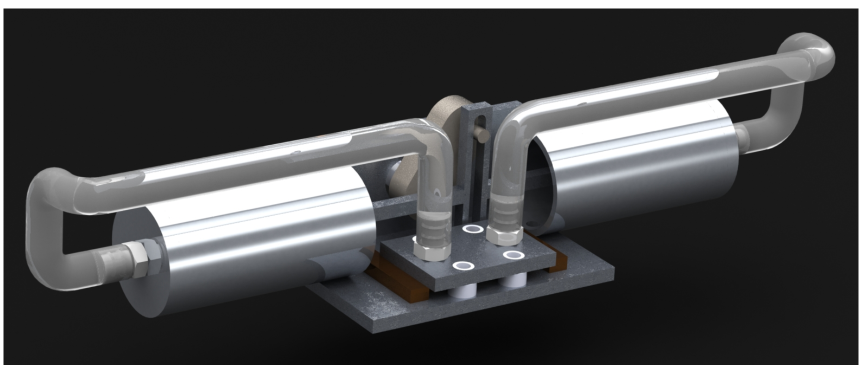
Our exhaust system was another important area of error with this project. Our initial intention was to drill multiple holes and use aluminum tape to conduct testing on ideal exhaust placement and quantity. This hope was thwarted by our late assembly, and as stated previously we reverted to our original exhaust positions. This mistake could feasibly be the principle reason our air motor did not work. With very limited, untested exhaust, our air motor resisted any turning; actually reverting to its original position if any assisted start was attempted. In hind sight, erring on the side of more exhaust may have helped our motor carry its strove through a full 360 degrees.

A final source of error that should be noted is the use of a self-aligning busing with no axial or vertical constraints on the driveshaft. Without these designed constraints, the crank arm would come out of alignment, colliding with the baseplate and rotating the scotch yoke around its horizontal axis. This rotation around the axis connecting the cylinders was assisted by our use of a self-aligning bushing. The lack of structural support vertically made it impossible to maintain the crank-arm and scotch yoke in alignment and lead to the demise of our air motor. Another factor that contributed to this was the fact that the driveshaft was not constrained axially. We attempted to remedy this last minute by installing duct tape to create an increased diameter directly on the outside of the bushing, however a more effective design could have included a snap ring and snap ring grove, or basic machining and geometry changes to constrain the shaft more effectively. In future designs, our team has decided to emphasize degrees of freedom in each moving component, and the effect of material and part choice on the propensity for part misalignment.

# Section 5: User Documentation and Final Materials

**User Manual:**

AIR MOTOR USER MANUAL
Team 6D



**Contents**



## The Motor

This is a 2-stroke piston air motor with a scotch yoke and timing mechanism. This motor is to be hooked up to a 40 PSI outlet for use and should be operated at under 1000rpm. This motor has a rotational output. Please read user manual before use.

## Set Up

**Parts included:**

1. 2 Cylinders
2. 2 Piston Heads
3. 5 Tube Fittings
4. Fly-arm
5. Output Shaft
6. Scotch Yoke
7. Base Plate
8. Back Plate
9. Tubing
10. Fly-arm Pin
11. Timing mechanism
12. 10 Screws

13.12 Nuts

14.10 Lock Washers

**Assembly Steps:**

1. Screw base plate to back plate using screws and lock washers
2. Screw cylinders to back plate and base plate
3. Screw piston heads with rod end to scotch yoke
4. Insert piston heads into cylinders so that scotch yoke is positioned with scotch yoke end implanted in base plate cut out
5. Insert output shaft through self-aligning bushing so that threaded end is closest to scotch yoke
6. Screw threaded end of output shaft into fly-arm
7. Screw fly-arm pin to fly-arm through scotch yoke
8. Screw tube fittings into holes on cylinder ends
9. Place timing mechanism between rows of base plate holes with mechanisms arms oriented so they point towards scotch yoke
10. Place timing mechanism plate so that shoulders are inserted into baseplate holes so that the timing mechanism is sandwiched between baseplate and mechanism plate

11. Screw two tube fittings into timing mechanism plate and one tube fitting into baseplate in indicated holes
12. Attach one end of one tube to tube fitting on one cylinder and attach the other end to a tube fitting on timing mechanism plate
13. Repeat step 12 with other tube and other tube fitting

**Use and Safety Precautions**

1. Clamp motor to solid, sturdy surface
2. Place shield between nearby people and air motor
3. Connect air pressure supply tube to tube fitting on base plate
4. Attach output shaft to utility
5. Slowly increase air pressure to 40 PSI

**Upkeep**

The motor should be checked regularly for holes in tubing and for leaks between cylinder and piston head. If any replacement parts are needed, please contact us.

**Marketing Materials:**

Air Motor Specifications. These should be given to any customer.

| | |
|---|---|
| **Motor Design** | Piston-Cylinder |
| **Size** | 10” x 3” x 4” |
| **Clamping Width** | 4” |
| **Approximate RPM** | none |
| **Power Output** | none |
| **Shaft Diameter** | 1/2” |
| **Shaft Length** | 3.5” |
| **Keyed Shaft** | No |
| **Shaft Alignment** | Self Aligning Bushing |
| **Timing** | Blocking Bumper |
| **Inlet Pressure** | 40 psi |
| **No. of Inlets** | 1 |

Air Motor Features. These could be used on an advertising brochure/posting.

1. Dual piston organization
2. Self aligning piston head attachment
3. First of its kind bumper timing
4. Strong aluminum framing structure
5. Bending resistant steel output shaft
6. Self aligning output shaft bushing
7. Simple, single input design
8. Externalized, easy to troubleshoot design
9. ‘Spin to adjust’ flywheel construction changes stroke span

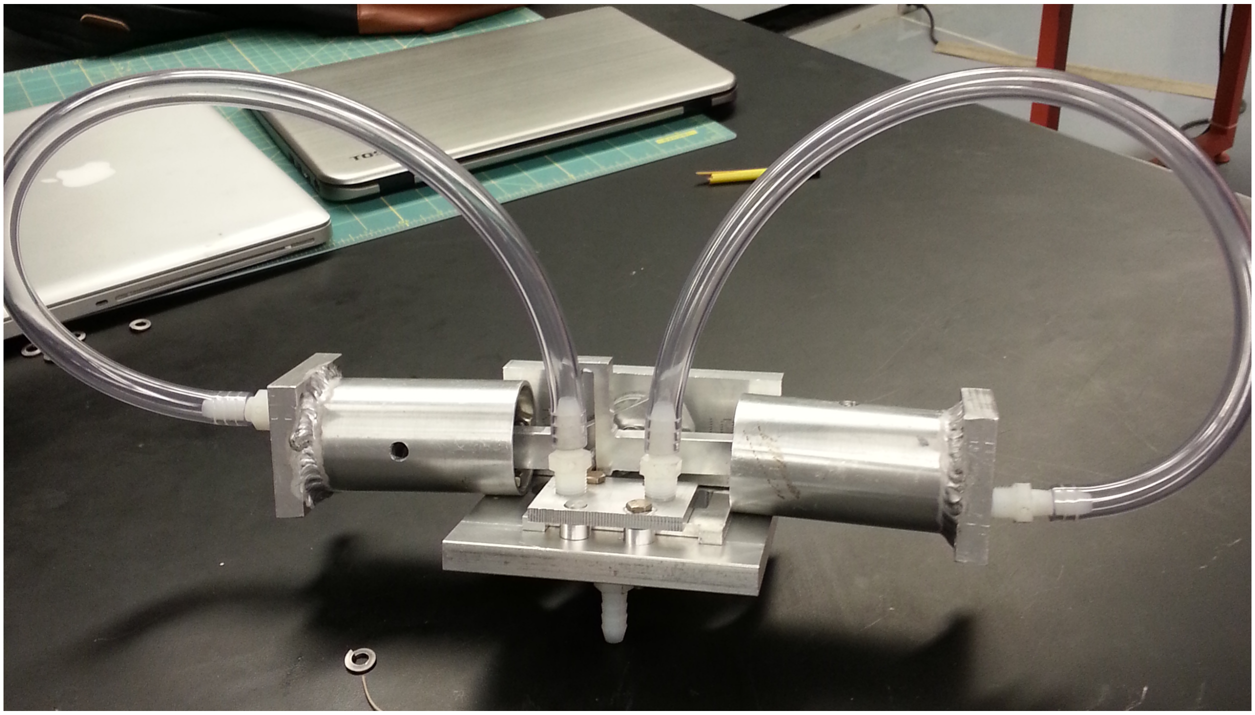
Competitive Analysis.

The main advantage of our motor over others is cost. Even the smallest simplest pneumatic motors on the market cost over $200, while most cost thousands of dollars. Our motor costs only $50, at worst a 75% price cut compared to others. That said, if we were to include real manufacturing costs (that is, labor time,) our motor would likely be far more expensive than comparable models on the market. One other advantage is its weight. Most commercial motors are made with cast iron housing, while ours is primarily aluminum. Thus, our motor should be lighter, and easier to place/transport.

That said, for the most part, our motor does not fare well against those currently for sale. First off, most available models have very good enclosures. This serves to lock in air pressure (while our motor definitely has small leaks) but also to protect the motor from its environment. Assuming the motor is being used in an industrial application, there are many opportunities for dust, oils, or damaging shrapnel to get into our motor's pieces. The one advantage of our externalized design is that it's easy to modify or troubleshoot, as many pieces are visible and accessible.

Our motor also produces much less power than competitors. According to our estimates, our motor produces approximately 1 kW of power - if it's 100% efficient. However, in reality, it does not produce power as is. Most small pneumatic motors we researched produced between 1.5 and 2.5 hp, about 1-2 kW. This definitely is a disadvantage for consumers. Our motor, however, could eventually produce an output rpm (likely a few hundred) comparable to many other motors.

Photos and Videos.



Finally, here's a video of us spinning the output shaft of the assembled motor to show the motion of the integrated pieces:

http://youtu.be/mbTSeSe1koI