AN ABSTRACT OF THE THESIS OF

Matthew Smith for the degree of Honors Baccalaureate of Science in Mechanical Engineering

presented on May 25th, 2010. Title: Design, Construction, and Evaluation of a Miniature Swing Arm Compressor

Abstract approved: ______________________________________
Richard Peterson

A swing arm compressor was designed, built, and tested as an undergraduate senior design project for Dr. Richard Peterson. The system developed, while not functioning entirely as desired, gave some initial data and a good base of knowledge for a second iteration of the project. This thesis describes in detail the design process, implementation, and testing of the device as well as giving suggestions for future improvements on the design.

Keywords: swing arm, compressor, man-portable, power, miniature

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Design, Construction, and Evaluation of a

Miniature Swing Arm Compressor

by

Matthew T. Smith

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Matthew T. Smith, Author

ACKNOWLEDGEMENTS

I would like to thank my mentor, Dr. Richard Peterson, and committee members, Dr. Robert Paasch and Dr. Nancy Squires, for agreeing to be part of this process with me. I would also like to thank my team members, Spencer Heard and Blair Hasler, for their efforts and contributions to this project.

CONTRIBUTION OF CO-AUTHORS

This thesis represents the work of a senior design project group. Some of the material in this thesis was developed in conjunction with other group members, including work done by Spencer Heard and Blair Hasler for the senior project final report.

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INTRODUCTION

The purpose of this project was to design, build and test a small-scale swing arm compression and expansion machine, with a focus on the compression cycle. This project was an undergraduate senior design project completed as part of the mechanical engineering curriculum at Oregon State University. The project was sponsored by Dr. Richard Peterson of the mechanical engineering department at OSU. The team formed to complete this project included two other mechanical engineers, Spencer Heard and Blair Hasler.

BACKGROUND

A swing arm compressor uses rotationally oscillating pistons, as opposed to the linearly oscillating pistons used in most compressors, to compress gases. The swing arm mechanism rotates within a cylindrical housing in order to compress or expand the gas contained inside (Mijit). This design does not use seals to contain the fluid, but instead uses very high precision machining to keep clearances between moving parts below approximately 25 microns in order to decrease both friction and wear in the device.

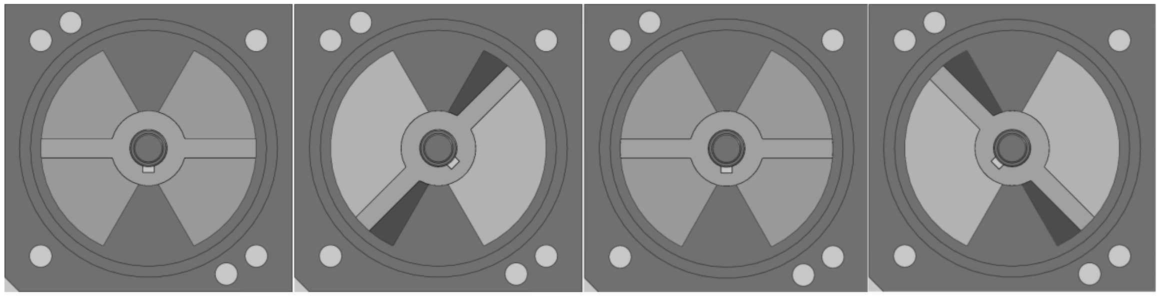


Figure 1: Swing Arm Operation

The swing arm machine developed in this project was modeled after a device previously developed at the University of Michigan (Mijit). Its dimensions are similar in scale to the Michigan device. Additional features were added to this base design including a crank-rocker linkage and ports for measuring pressures. The crank-rocker linkage converts the swing arm device into a kinematically constrained machine as opposed to the free piston design built by the University of Michigan.

A variation of this design lends itself well to making a small Internal Combustion Engine (ICE) to produce electricity more compactly and efficiently than batteries or other current generator designs. This completed project provides a first attempt at a laboratory testing platform for the compression part of such a system.

PROJECT GOALS

The initial project goals as defined in conjunction with Dr. Peterson were as follows:

- The dimensions of the compressor shall be 2.5 +/- 0.5 inches on a side.
- The high precision parts shall be made of stainless steel (Parts SAC01-SAC05, see APPENDIX A: DRAWINGS for drawing details).

- Compressor should achieve a pressure ratio of 3.5 +/- 0.5.
- Compressor should have a leak rate of no more than 10%.
- Total cost for device cannot exceed $2500.
- Device shall have a minimum operating speed of 600 ± 50 RPM.
- Device shall be able to operate at 2500 +/- 500 RPM.
- Device shall have a crank mechanism with an attachment to the motor shaft.
- The device shall be able to operate for no less than 10 hours within the target RPM and leak range as stated above.

DESIGN AND IMPLEMENTATION

The design of this compressor required background research into the current state of the art, high level design decisions, and detailed drawings. Once complete, the design had to be implemented as an actual compressor.

STATE OF THE ART

This project was partially based upon the MICSE produced by Kudijiang Mijit as a part of his doctoral thesis at the University of Michigan (Mijit). The MICSE was developed for use as a portable generator. The compressor designed for this project closely resembles Mijit's MICSE design, and was made as a laboratory test platform for the compressor aspects of the engine in order to continue research on such a micro generator.

The appeal of this design was its simplicity, which helps in miniaturization of the device. There were few moving parts and no seals between the swing piston and housing. This design was inherently balanced due to the symmetrical design of the swing arm. Minimal vibration and noise were possible because of the low mass, low moment of inertia, and small angular motion of the few moving parts. The device ideally relied on clearances of less than 10 microns to control air movement rather than physical seals, which cut down on wear in the device. The dimensions of the device, 2.4” x 2.4” x 1.325”, fit the design requirements nicely.

As an engine, the swing arm design could be operated on both a four-stroke cycle and a two-stroke cycle depending on the valve scheme. The swing arm would sit inside a swing arm housing and divide the two cavities into four chambers that, in four-stroke mode, would allow for any given chamber to be undergoing the compression, exhaust, intake, or combustion stroke simultaneously and would require four ports with valves (Werner). In two-stroke operation there would only be two exhaust ports needed to allow for air flow into and out of the chamber.

Some modifications to Mijit's design were needed in order to adapt to the specific requirements of this project, including the addition of ports for measuring pressures and flow rates, changing dimensions, removing spark plugs, and kinematically constraining the swing arm operation with a crank-rocker linkage.

DESIGN RATIONALE

This section details the rationale behind the different design choices made for this project, specifically for the compressor and the motor linkage.

COMPRESSOR

The basic design of the compressor was taken from Mijit's design. This design had many beneficial characteristics. Since there were few moving parts, the swing arm piston design was much simpler to miniaturize than other compressor types, such as inline piston compressors. The swing arm was inherently balanced, resulting in smooth operation at high RPM. The swing arm piston was designed to operate in an oscillatory motion, allowing for two compression strokes per cycle of the piston. This was a unique characteristic; other piston compression methods rely on an independent stroke for both intake and compression. In order to minimize friction and the associated energy losses, the design did not incorporate any kind of seal between the piston and the chamber.

MOTOR LINKAGE

A crank-rocker linkage was selected as the design for the coupling between motor and compressor. This design was the simplest of those considered. The largest factor in choosing this design was the need for operation at high RPM. All connections in such a design could use bearings, which provided for smooth operation at high RPM while introducing little friction to the system due to the small contact surfaces. Also considered was ease of assembly and the capability to add variable compression ratios, which in this design were easily obtained via holes at different radii in the crank hub. Other design possibilities included two different crank-slider configurations and a purely gear-based solution, but these all had drawbacks that made the crank-rocker linkage the most attractive option.

DESIGN DETAILS

This section discusses the details of the swing arm compressor design. For detailed part and assembly drawings, see APPENDIX A: DRAWINGS.

COMPRESSOR

As mentioned previously, the basis of the compressor design came from Mijit's project at Michigan State University (Mijit). The purpose of the design efforts for this project was to make changes to this existing design in order to make it work as an air compression system.

The main components of the compressor assembly (swing arm, housing, main shaft, dowel pins, and side plates) were machined out of 304 stainless steel. The stainless steel material selection was specified by the project sponsor due to its strength and anti-corrosive properties. These features were important because of the need for durability in a future portable power source based on this design.

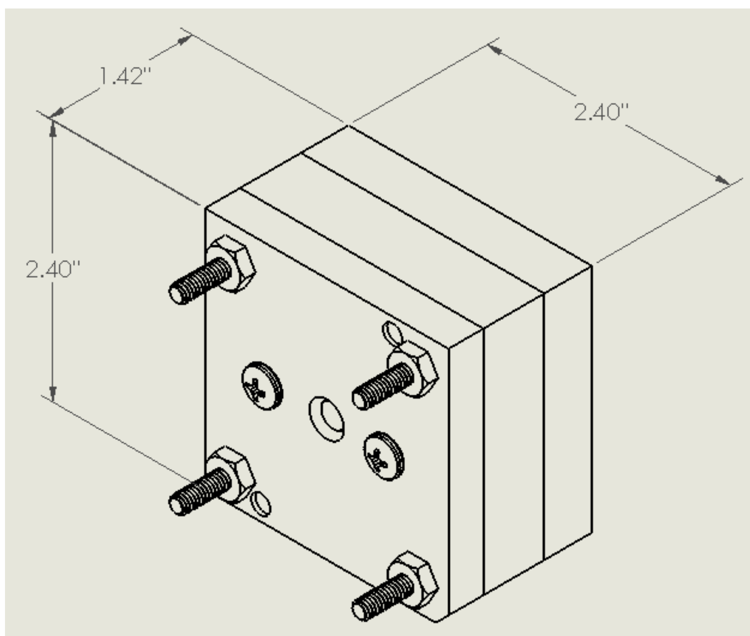


Figure 2: Basic Compressor Dimensions

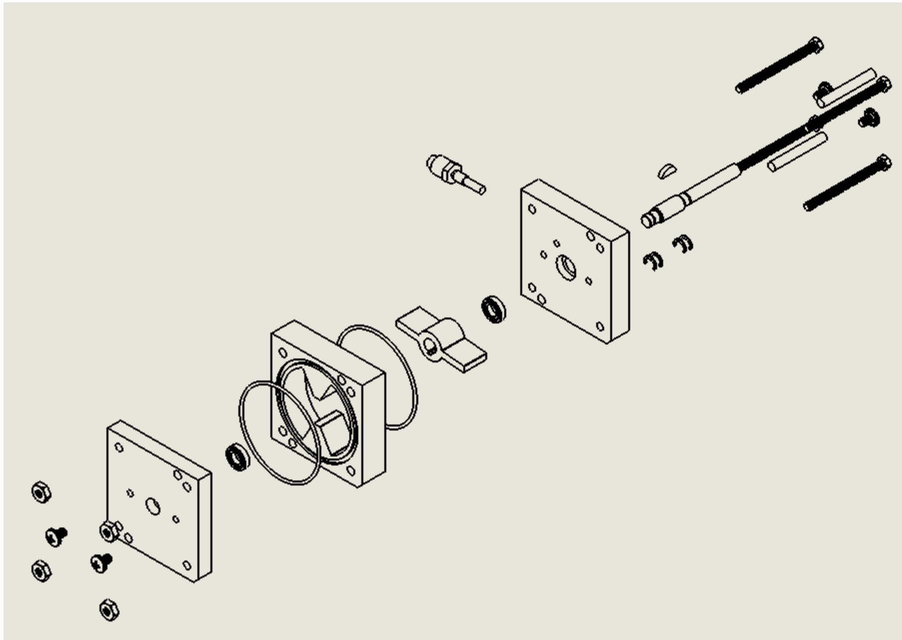


Figure 3: Compressor Exploded View

Adding ports to the device was a simple but necessary change. The existing design used custom, spring-loaded valves in order to let air flow into and out of the housing. This was more than was necessary for the project. The simplest solution was to tap the port holes for airflow into and out of the compressor. Sealing screws could then be inserted into these holes as shown below (see Figure 4). Air flow could be controlled by simply inserting or removing the screws.

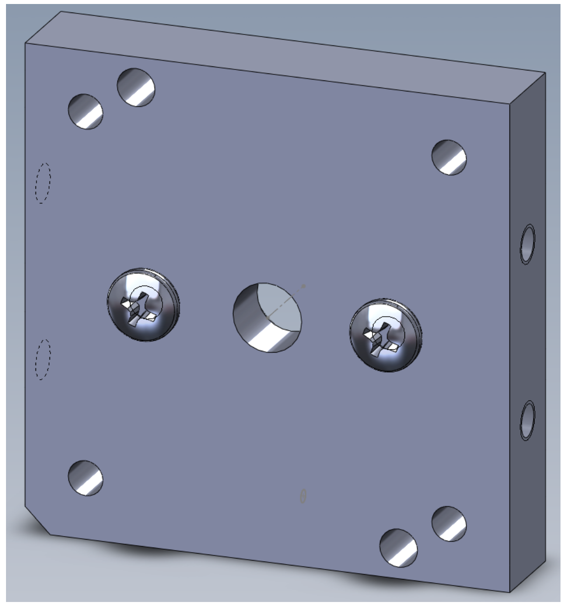


Figure 4: Side Plate with Port Screws Inserted

An o-ring was added to the design in order to keep air from leaking out of the side plates of the compressor despite the tight tolerances. The o-rings are set in grooves on the main housing as seen below in Figure 5. Silicone was chosen for the o-ring material due to its affordability and generally good performance in the required range of pressures.

The tight tolerances in the compressor assembly required adding locating features to ensure that the parts all lined up correctly. To address this, locating pins were used in holes in the top left and bottom right corners of the main housing and the side plates, as can be seen in Figure 5. In order to ensure that the compressor was assembled in the correct orientation each time, chamfers were added to the housing and end plates (see Figure 4 and Figure 5).

Consulting with machinists at Wright Prototype yielded the suggestion that very small radius fillets be added to both the housing and swing arm. The purpose of the fillets was to reduce the risk of cracking, since cracks tend to propagate from discontinuities in the material surface that cause stress concentrations (scratches, notches, sharp corners, etc).

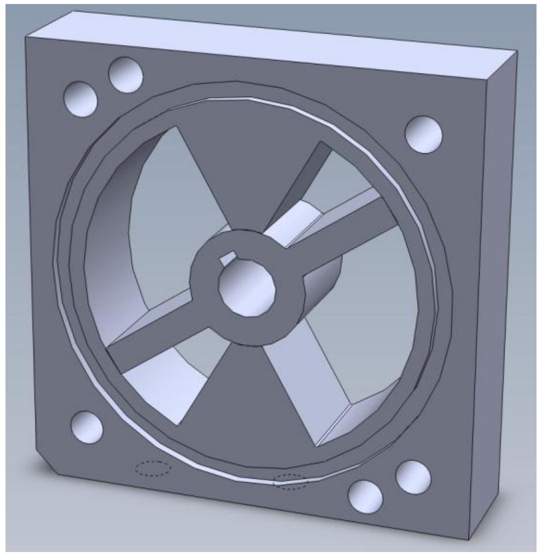


Figure 5: Housing and Swing Arm with O-Ring Groove

Tolerance stack-up was an issue with this design. Since there are no seals present between the housing and the swing arm, it was vital that the side plates, crank shaft, housing, and swing arm were all machined to strict tolerances. The level of precision necessary, however, was somewhat challenging in practice, as will be seen later in the Implementation and Testing sections.

MOTOR LINKAGE

The crank-rocker linkage provided the means to convert rotational motion from the electric motor into oscillatory motion to drive the compressor. The input shaft on the left side of Figure 6 was connected to the DC motor. The output shaft, shown on the right side of Figure 6, was driven to an oscillatory motion by means of the two linkage bars which complete the crank-rocker linkage. To ensure smooth operation and low friction in the linkage motion, bearings were added at each linkage attachment point. Aluminum was used to machine the crank-rocker parts because it was light, easy to machine, and relatively inexpensive.

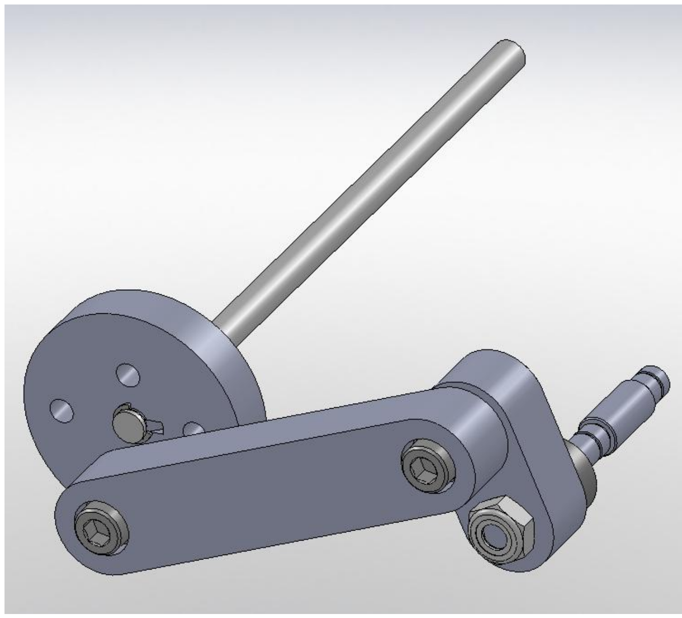


Figure 6: Crank-Rocker Mechanism

The crank hub had four holes at various radii (Figure 7) to allow for different pressure ratio settings. The holes were designed to accommodate compression settings of 2:1, 3:1, 4:1, and 5:1. This ensured that the device would be able to meet the pressure ratio requirement, since there was some uncertainty of how much leakage the device would have.

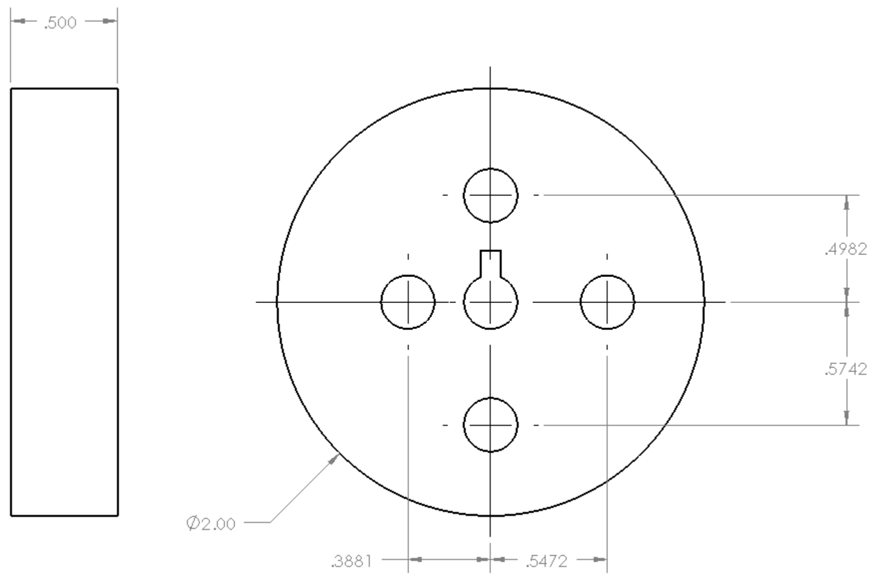


Figure 7: Crank Hub

The main shaft was used to drive the motion of the swing arm. A keyway with a woodruff key was used to mate the swing arm with the shaft as shown below in Figure 8. Snap rings in the grooves on the main shaft kept the swing arm from moving axially, as well as holding in place the bearings that constrained the shaft.

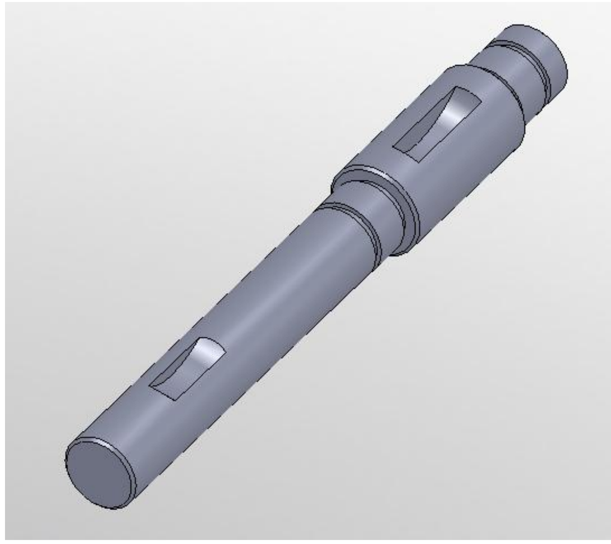


Figure 8: Main Shaft

PERIPHERAL COMPONENTS

An Endevco Model 8540 pressure transducer was used in order to monitor the pressure within the housing. The length of the transducer provided a challenge in the design process, since it was longer than the wall thicknesses of both the side plates and the housing. It proved to be necessary to drill holes in the side plate in order for the transducer to be exposed to the gas inside the housing while keeping it from interfering with the motion of the swing arm.

All bearings in this design were held in place by snap rings. Press fits were initially considered but they were ruled out due to the concern that it would affect the tolerances of the end plates. The dimensions of the end plate holes, where the bearings and end plates mate together, were equal to the outside dimensions of the bearings themselves, eliminating any motion in the direction normal to the main shaft. The main shaft diameter matched the inside diameter of the inner bearing race for a sliding fit.

A variable-speed DC motor was used to drive the system. The motor was coupled to the device using a torque-limiting shaft coupler. The variable speed allowed monitoring the leakage in the compressor system at various speeds. In addition to these parts, many “off the shelf” parts were used including screws, snaps rings, o-rings, nuts, etc.

LEAKAGE MODEL

In order to help predict how this system would react at different speeds, a mathematical leakage model was developed using Mathematica. The program models the air pressure in one chamber over the course of one revolution of the motor shaft. Due to the unknown coefficient of discharge, this model was not able to be fully developed until testing of the compressor gave some numbers against which to calibrate.

The model program is divided into two sections. The first section steps through the rotation of the drive shaft in increments of 0.25°, calculating the position of each link in the crank-rocker linkage using basic geometry. From this the program is able to determine the position of the swing arm at each angular step. Since the drive shaft is modeled to be rotating at a constant velocity, these angular steps can be converted into time steps for any motor speed.

The second part of the model program takes the swing arm locations calculated in the first part and simulates one of the chambers using this data. For simplicity, whenever the swing arm is beyond the hole that opens out to the atmosphere, the pressure in the simulated chamber is assumed to be atmospheric pressure.

When the swing arm moves beyond this hole, at every time step the estimated mass lost since the previous step is calculated. In order to calculate this, it is first necessary to calculate the angular velocity at this time step, a simple matter of dividing the angular difference by the time step. It is also necessary to calculate the volume of the trapped air in the chamber, again a simple calculation since the relationship between volume and angle is a linear one, with full volume at 0° and zero volume at 60°. This is then supplemented with the volume added by the pressure transducer hole.

The mass loss is split into two different terms. The first of these terms is the mass lost past the tip of the swing arm. This term has two components. First, there is the air lost due to the swing arm's velocity. This is calculated using Equation (1), where v is the tip velocity, A is the cross sectional area of the gap between the tip and the housing, and ρ is the current air density in the chamber. The second component comes from the pressure difference across the end gap. If Equation (2) is true, the flow is not choked and Equation (3) is used to calculate the mass flow rate out of the chamber. If Equation (2) is false, the flow is choked and Equation (4) is used instead.

$$Q = v * A * \rho \tag{1}$$

$$\frac{P}{P_A} < \left(\frac{k+1}{2}\right)^{k/(k-1)} \tag{2}$$

$$Q = C\,A\,P\sqrt{\left(\frac{g_c\,k\,M}{Z\,R\,T}\right)\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \tag{3}$$

$$Q = C\,A\,P\sqrt{\left(\frac{2\,g_c\,M}{Z\,R\,T}\right)\left(\frac{k}{k-1}\right)\left[\left(\frac{P_A}{P}\right)^{2/k} - \left(\frac{P_A}{P}\right)^{(k+1)/k}\right]} \tag{4}$$

Q =	Mass flow rate (lb/s)	P =	Chamber Pressure (psia)
C =	Discharge Coefficient	P_A =	Atmospheric Pressure (psia)
A =	Discharge Area (ft^2)	M =	Molecular Weight (28.97 for air)
g_c =	32.17 ft/s^2	R =	Universal Gas Law Constant (1545.3 ft-lb/(lbmol-°R))
k =	c_p/c_v (1.40 for air)	T =	Temperature (529.67 °R)
ρ =	Density (lb/ft^3)	Z =	Gas Compressibility Factor (1 for air at applicable temperatures and pressures)

A similar process is used for the other mass loss term, that of the loss along the sides of the swing arm. The difference is that the mass loss due to the velocity of the swing arm is integrated along the radius to account for the different speeds at different radial distances along the swing arm. These two mass loss rate terms are then multiplied by the time step to get the mass lost during the previous time step. This is subtracted from the previous mass in the chamber to get the new mass.

Once the total mass in the system is determined, Equation (5) (a variant of the ideal gas law) is used to determine the pressure in the chamber. This process is repeated for each angular step of the drive shaft. This entire process is repeated for a range of input motor speeds and the maximum pressure from each is then plotted against speed in RPM to get Figure 14, seen later in the Final Results section. The discharge coefficient was determined by varying C and fitting the pressure curve as closely as possible to the experimental pressure curve.

$$P = P_A * \left(\frac{V_o}{V_i}\right) * \left(\frac{m_i}{m_o}\right) \quad \textbf{(5)}$$

Model calibration to exact values was difficult due to inconsistencies in the gaps of the final compressor and the limited test data. Even without a high level of calibration, the model at least gives a general idea of how frequency and leakage are related and could potentially be calibrated more precisely with future data.

IMPLEMENTATION

Wright Prototype produced the high precision parts using a combination of conventional CAM techniques and wire EDM. The high precision surfaces, especially on the swing arm and housing, were produced using wire EDM. The holes, counter bores, and other features were produced using the more conventional methods, including using computer controlled milling machines and lathes.

All other lower precision parts were made by hand using conventional machining methods. The follower, link, drive shaft block, base plate, base legs, and motor offsets were made using a milling machine. End mills were used to face each external edge to the correct dimension. Holes were cut using drill bits of the appropriate sizes and hand tapped. Keyways were made using a press and a broaching tool. The drive shaft and crank hub were cut to size on a lathe. The grooves in the drive shaft were also cut on the lathe, while the axially oriented slot was cut using an end mill on a milling machine.

The initial assembly went well overall, with only minor problems encountered. Initially the locating pins were too large for the locating holes by less than 0.001". In order to correct this and allow assembly, first slightly smaller nylon dowel pins, nominally the same size as the locating holes, were tried, but when these did not hold alignment well enough, the steel pins were once again used, this time sanded down to a diameter less than 0.001" smaller than the locating holes to allow a tight sliding fit.

There was also an issue with the woodruff keys being slightly larger than they nominally should have been. This was an easy fix; we sanded them down until they fit where they needed to.

Once the compressor was assembled correctly, testing began.

TESTING AND RESULTS

In this section the testing equipment setup, testing procedures, and testing process will be discussed. The testing process brought to light many difficulties that had not been apparent in merely assembling the device.

TEST EQUIPMENT SETUP

The primary test variable for this project was the pressure in one of the chambers. In order to accurately record pressure data, the pressure transducer was connected to a computer through a National Instruments data acquisition device, as seen in Figure 9. The hardware details are listed in Table 1. A program was created using LabVIEW software to then log the data from the pressure transducer. A tachometer was used to measure the speed output of the motor.

The pressure transducer was inserted into the tapped hole on the right side of the compressor endplate. An o-ring integral to the pressure transducer sealed the transducer off from the atmosphere so that it was exposed only to the pressure conditions in the inside of the device. The pressure transducer was wired into a 10-pin Ethernet plug, which in turn connected into the DAQ interface.

The LabVIEW program read the state of the pressure transducer at a frequency of approximately 1600 Hz, high enough to very easily see the changes in a signal that should not exceed 50 Hz (3000 RPM). These pressures were then both displayed on a chart and stored in a spreadsheet for later analysis. The layout of the LabVIEW program can be seen in Figure 10 and Figure 11.

Table 1: Equipment Used

Part	**Manufacturer**	**Model**	**Notes**
Interface	National Instruments	NI 9237	
Data Acquisition Device	National Instruments	Ni cDAQ-9172	
Pressure Transducer	Endevco	8540-200	Full Piezoresistive Wheatstone Bridge, 0-200 psi range

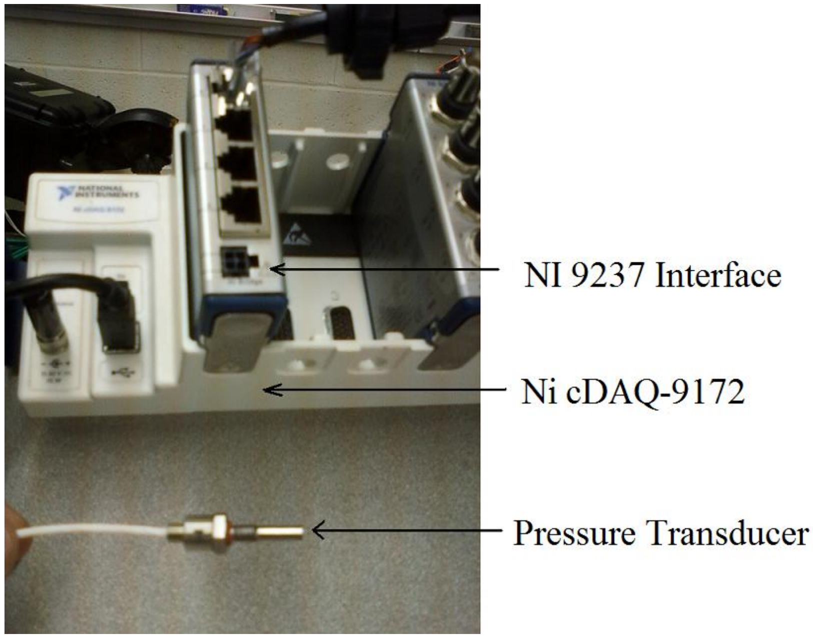


Figure 9: Data Acquisition Hardware

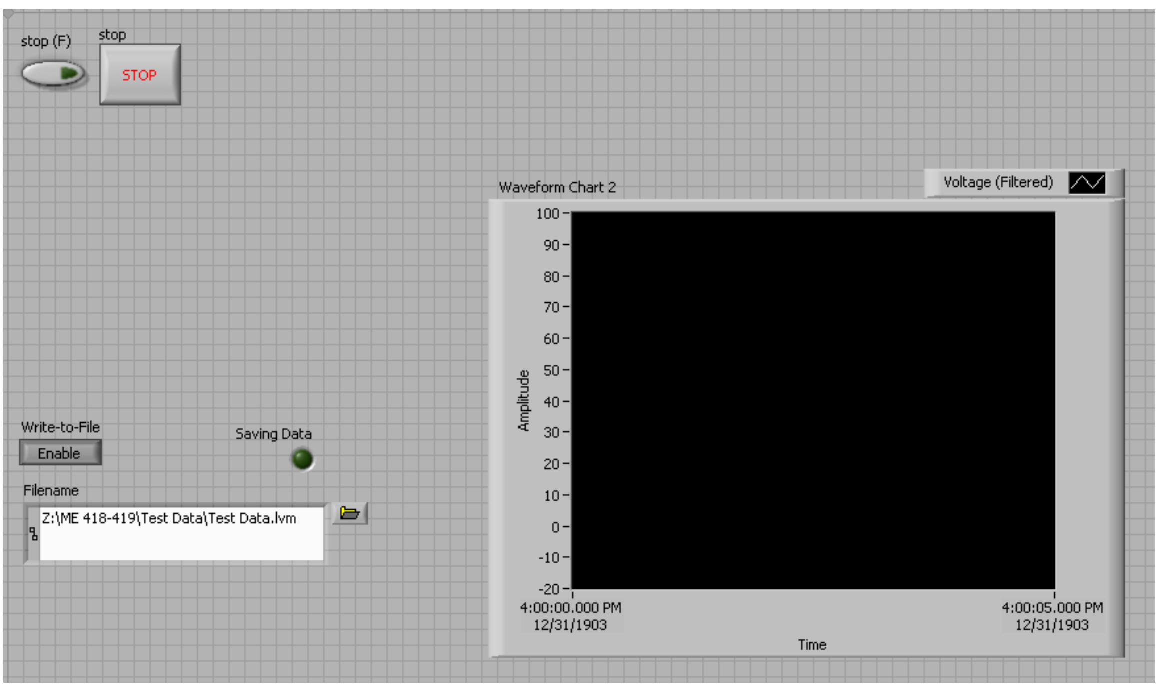


Figure 10: LabVIEW Program Front Panel

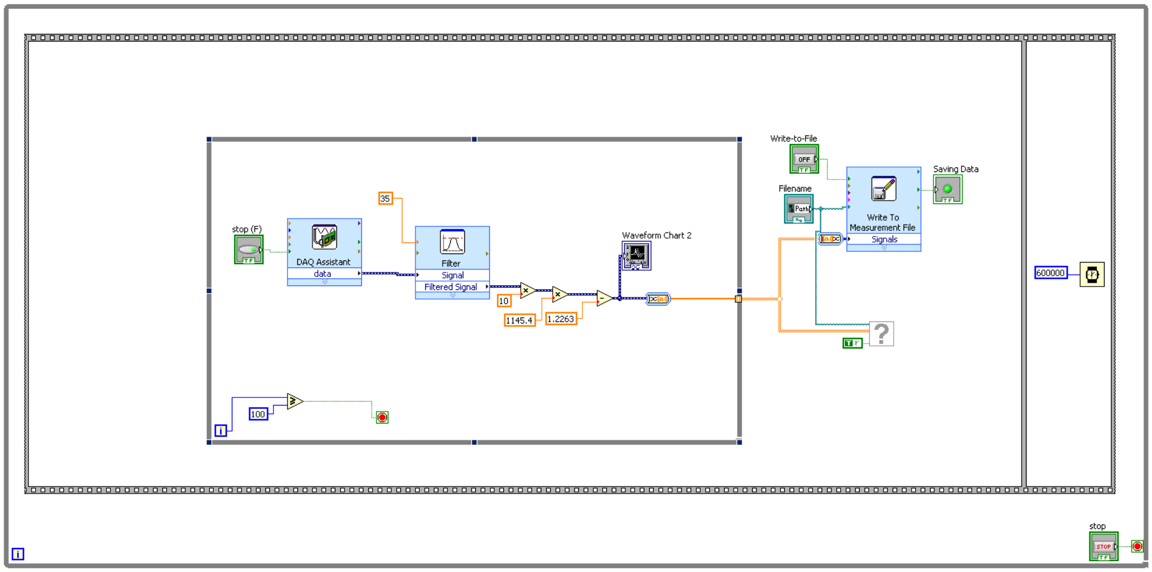


Figure 11: LabVIEW Program Block Diagram

TESTING PROCEDURES

In order to test the compressor, procedures were developed for each major test. Below are listed the specific testing procedures for each major test of the compressor:

PRESSURE RATIO TEST

1) Assemble device
    a) Assemble compressor as shown in drawing SAC-A1
    b) Assemble base plate and crank linkage as shown in drawing SAC-A2, using the "4:1" pressure ratio hole (0.5472" from center) on the crank hub
2) Set up testing equipment as described in the previous section
3) Begin LabVIEW program

4) Turn on motor and gradually increase speed to 2000 RPM, tracking it with the tachometer
5) Determine peak pressure values at 2000 RPM from collected data
6) Divide peak pressure by atmospheric pressure (14.7 psia) to determine pressure ratio

LEAK RATE TEST

1) Assemble device
    a) Assemble compressor as shown in drawing SAC-A1
    b) Assemble base plate and crank linkage as shown in drawing SAC-A2, using the "4:1" pressure ratio hole (0.5472" from center) on the crank hub
2) Set up testing equipment as described in previous section
3) Begin LabVIEW program
4) Turn on motor and gradually increase speed to 600 RPM, tracking it with the tachometer
5) Determine peak pressure values at 600 RPM from collected data
6) Calculate theoretical pressure with no leakage using Equation (6)
7) Divide the measured peak pressure value by the theoretical pressure, then subtract this from 1.0 to get the leak rate

$$P_2 = P_1\left(\frac{V_1}{V_2}\right) \quad \textbf{(6)}$$

ENDURANCE TEST

1) Assemble device

   a) Assemble compressor as shown in drawing SAC-A1
   b) Assemble base plate and crank linkage as shown in drawing SAC-A2, using the "4:1" pressure ratio hole (0.5472" from center) on the crank hub
2) Set up testing equipment as described in previous section
3) Set up LabVIEW program for long-term measurement, taking data every 5 minutes
4) Begin LabVIEW program
5) Turn on motor and gradually increase speed to 2000 RPM, tracking it with the tachometer
6) Leave running for 10 hours, verifying by collected data that device ran correctly the entire time

TESTING PROCESS

Due to the strict tolerances of the compressor assembly, it was difficult to assemble the device so that the swing arm did not encounter any rubbing from the housing or end plates during its swing. When the initial assembly was performed, we were unable to tighten the four end plate bolts more than hand tight without the occurrence of rubbing. Part of the problem was due to the fact that nylon dowel pins were first used for alignment, which later were replaced with the initially design stainless steel dowel pins, providing a more rigid alignment.

This did not entirely fix the problems, however. Every time the device was assembled, it would seize up after very little time running at even very low speeds (less than 200 RPM). Each time this happened, the surfaces that had been in contact would need to be cleaned up with very fine grit sandpaper to bring the scratches back down to the level of the surrounding material. Every time the compressor went through this process, some of the sealing ability was lost due to increased clearances between the various surfaces.

The surface that was scratched varied depending on the trial. The two most common surfaces were the end plates and the cylindrical surface surrounding the middle of the swing arm. The scratches on the end plates were arcs, following the motion of the swing arm. It did not scratch in the same place every time, but varied along the swing arm length. The scratches would usually have one spot that was more deeply gouged than the rest, which was assumed to be the point of initial contact. The edges of the crack would stand above the level of the surrounding material, which was why sanding was required to allow operation again.

The scratches on the cylindrical surfaces of the housing and the swing arm center were a little different. On the housing side, there would be an irregular depression along the length of the surface from front to back of the compressor. On the swing arm side, the scratches would usually be uniformly shallow gouges oriented along the circumference of the cylindrical face. With a little sanding, these surfaces stopped being a problem, while the end plate scratches continued.

Eventually the device was taken to Wright Prototype to discuss troubleshooting options. The result of this meeting led to a secondary machining (free of charge) that removed the surface scratches from the end plates. Wright measured the width of the swing arm and found it to be exactly the same width as the housing, which was a large cause of the initial friction within the device, so about .0005” of material was removed from either end of the swing arm width.

After the secondary machining was completed, the device was reassembled. The swing arm moved more freely and it was then possible to operate the device using the attached electric motor. Soon after the first operation began, the device seized. After disassembly, scratches were found that showed where the swing arm had contacted the surrounding surface, again along the end plates.

Since time was a factor, it was not feasible to commute back and forth to Wright Prototype to get the device surface ground each time the swing arm seized. Consequently, sanding of scratched surfaces was once again used, this time taking off more material in order to gain more clearance and hopefully stop the rubbing. Unfortunately, the compression potential decreased each time the device was sanded. The gap between the swing arm and the surrounding surfaces was ultimately increased to between .001" and .0025".

In addition to the tight swing arm tolerances, an unfortunate event occurred that prevented the 10-hour test from being performed. The main shaft that drives the swing arm bent when the compressor seized during operation at 2000 rpm. It was speculated that the shaft failure was a result of misalignment of the coupler link in the crank-rocker linkage. Without the main shaft, it was impossible to collect any further data. A new shaft was machined and a torque limiting coupler was added to the system to prevent future damage, but slight dimensional differences once again intensified the seizing issue. At this point, further removal of material would decrease the seal significantly enough to not be worth doing.

Some data was recorded before the shaft was bent, but the quantity was very limited. Only one good run was recorded, and that at an unknown sampling rate. Using the peak rotational speed measured by the tachometer and the number of data points recorded in the highest pressure run, a sampling rate of approximately 1600 Hz was calculated, and all frequency-dependent results are based on this assumption. The next section will summarize the results of this data.

FINAL RESULTS

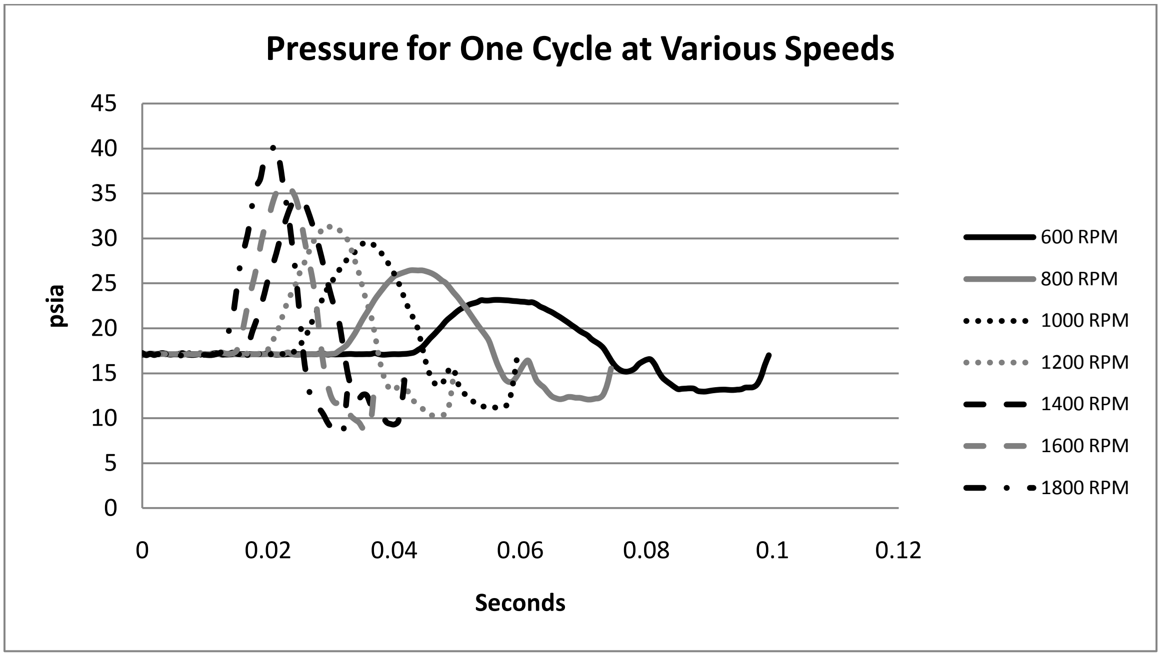


Figure 12: Pressure Data for One Cycle

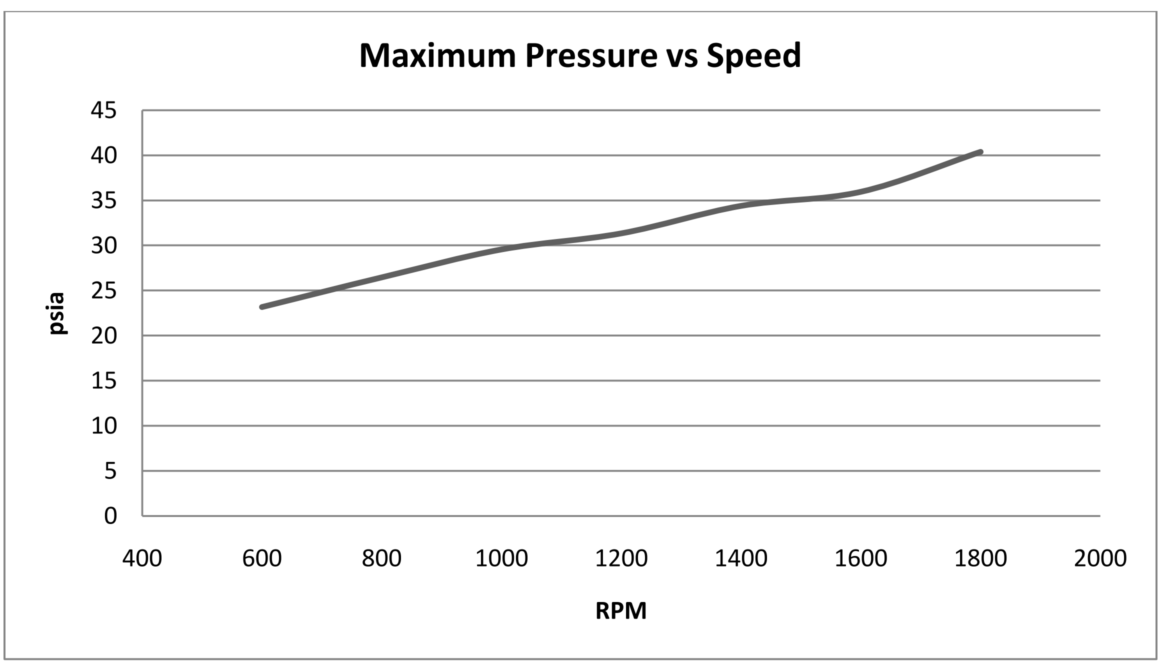


Figure 13: Pressure vs. Frequency

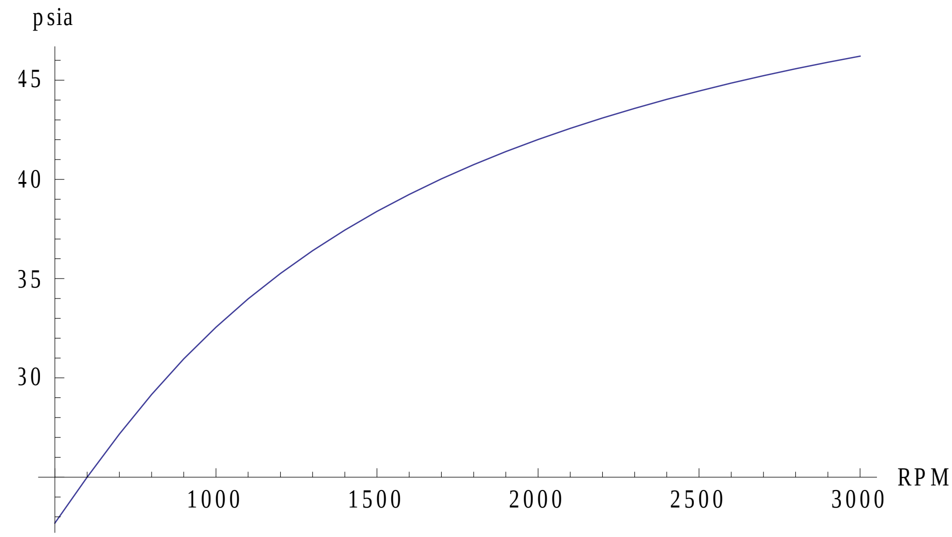


Figure 14: Leakage Model Predicted Pressure

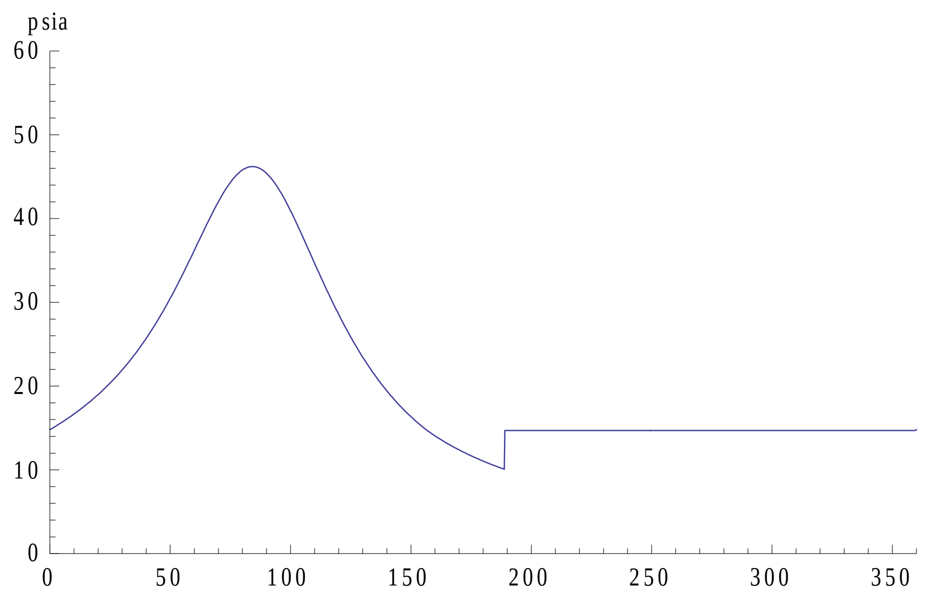


Figure 15: Leakage Model Pressure Over One Cycle at 3000 RPM

DISCUSSION

As can be seen from the limited results from testing, the pressure ratio increases with input speed. The experimental results look roughly linear, but we can see from the leakage model that with more testing, we could expect to see a more concave curve. We can now tell that some of the initial goals were not very realistic. Given that, even with the modifications we were forced to make, the clearances were still in a range that is very difficult to make any smaller, it seems that a leak rate of less than 10% at 600 RPM is not very feasible, at least with the given constraints. However, we do see that at the higher speeds, the compressor does become viable, though still not quite as good as hoped.

SUGGESTIONS FOR DESIGN IMPROVEMENT

The following are suggestions for improvement in a future iteration of this design. They come from experience gained working on this project and advice received from Dr. Peterson and the engineers and machinists at Wright Prototype. These suggestions will be very valuable if a second generation swing arm compressor is developed.

- Account for the possibility of thermal expansion of the swing arm and housing parts by adjusting part dimensions. Ideally metal-to-metal friction would not be an issue in this design, but it was found that with such tight tolerances, accounting for this expansion is necessary to alleviate the possibility of the swing arm parts expanding and binding. To overcome this difficulty some parts were re-machining and sanded down to increase clearances.

- Rethinking the process used to machine the high precision parts could create a closer fit and avoid the possibility of large tolerance stack ups. This could be done by using wire EDM to cut holes in the swing arm housing and end plates at the same time, then using that original hole to locate all other features. This would reduce tolerance stack up considerably.

- Using unlike materials for the housing and the swing arm would reduce the possibility of friction and binding. For example, using material like Oilite Bronze for the swing arm would offer some of the properties of a bearing if the part were to rub against the stainless steel housing.

- Another means of reducing friction and binding would be to use a Teflon coating on points of contact. The thickness of this coating would have to be planned into the design and probably reapplied to the parts after periods of operation.

- Using tapered dowel pins could ensure better alignment between the compressor parts.

- Replacing the locating dowel pins altogether with mating features on the end plates and housing could also simplify alignment problems, especially if used in conjunction with the suggestion to cut the housing and end plates simultaneously.

- The crank rocker linkage creates forces along the drive shaft that might have caused it to bend slightly, causing binding. Adding a gear drive mechanism such as a planetary gear could remove forces perpendicular to the shaft axis, making the design more kinematically balanced.

CONCLUSION

This project resulted in a device that, unfortunately, still has issues. More importantly, however, it resulted in a large increase in knowledge on how to solve this particular problem that will be invaluable for a second attempt at this device. It also resulted in a leakage model that will be useful for future research into swing arm compression devices. While the device itself was not totally successful, the project was successful in contributing to Dr. Peterson's research.

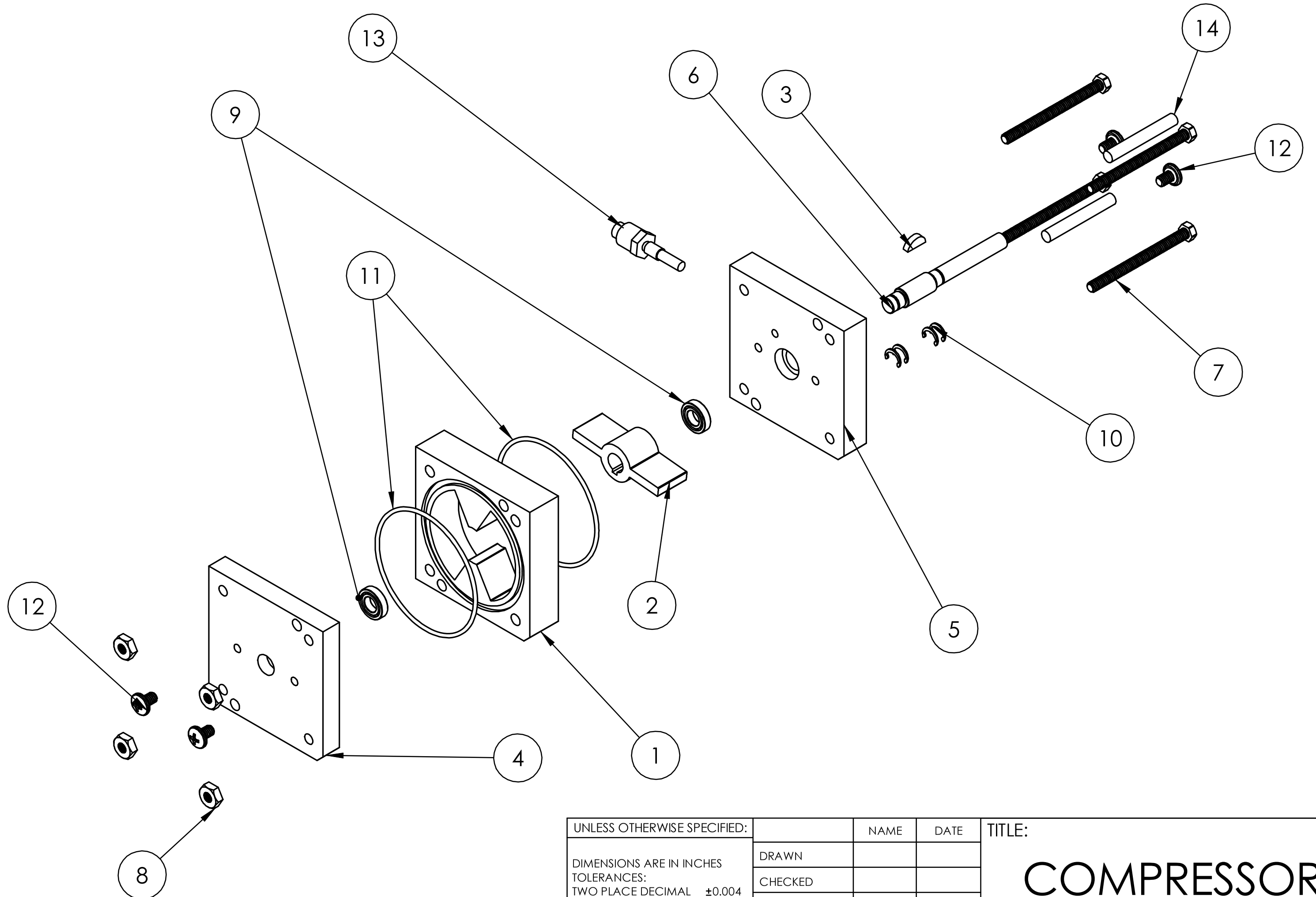
BIBLIOGRAPHY

Mijit, Kudijiang. Design, Analysis, and Experimentation of a Micro Internal Combustion Swing Engine. Detroit: University of Michigan, 2000.

Werner, Dahm J., Jun Ni, Kevin Mijit, and James R. Mayor. "Micro Internal Combustion Swing Engine (MICSE) for Portable Power Generation Systems." AIAA Aerospace Sciences Meeting. 2001.

APPENDICES

APPENDIX A: DRAWINGS



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DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

COMPRESSOR

SIZE	DWG. NO.	REV
A	SAC-A1	

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

5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Housing	COMPRESSOR HOUSING	1
2	Swing Arm	SWING ARM PISTON	1
3	97940A070	#303 SS WOODRUFF KEY	1
4	Front Plate	FRONT COVER PLATE	1
5	Back Plate	BACK COVER PLATE	1
6	Shaft	INTERNAL SHAFT	1
7	92314A205	#8-32 x 2" SS HEX HEAD MACHINE SCREW	4
8	91841A009	#8-32 HEX NUT	4
9	3826T160	1/2" OD 1/4" ID OPEN BEARING	2
10	98555A120	EXTERNAL SNAP RING FOR 1/4" OD	4
11	9396K113	2" ID 1/16" CORD SILICONE O-RING	2
12	90825A800	#8-32 x 1/4" SS SEALING PAN HEAD MACHINE SCREW	4
13	Pressure Transducer (Model 8540)	MODEL 8540 PRESSURE TRANSDUCER	1
14	98381A519	3/16" x 1 3/8" STEEL DOWEL PIN	2

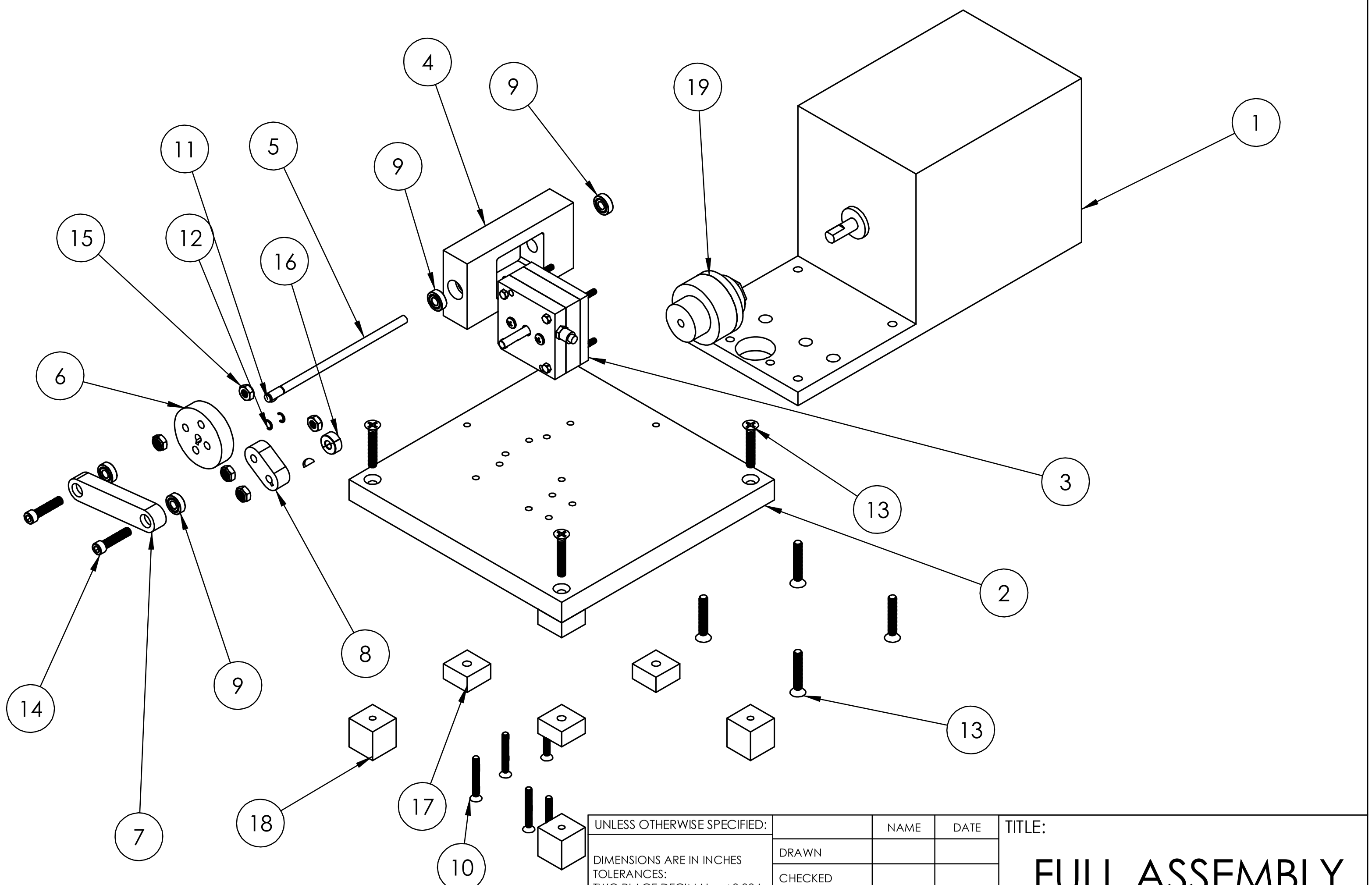
TITLE:

COMPRESSOR

SIZE A | DWG. NO. SAC-A1 | REV

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

5 4 3 2 1



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	CHECKED			
	ENG APPR.			
	MFG APPR.			
MATERIAL	Q.A.			SIZE A · DWG. NO. SAC-A2 · REV
FINISH	COMMENTS:			
DO NOT SCALE DRAWING				SCALE: 1:4 · WEIGHT: · SHEET 1 OF 2

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5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Motor	DC MOTOR	1
2	Base Plate	MOUNTING PLATE FOR COMPRESSOR PARTS	1
3	Compressor Assembly	COMPRESSOR ASSEMBLY	1
4	Drive Shaft Block	DRIVE SHAFT SUPPORT BLOCK	1
5	Drive Shaft	DRIVE SHAFT FROM MOTOR TO HUB	1
6	Crank Hub	CRANK DRIVE HUB - 2, 3, 4, 5 PRESSURE RATIO	1
7	Link	CRANK CONNECTING LINK	1
8	Follower	FOLLOWER	1
9	60355K701	5/8" OD 1/4" ID BEARING	4
10	90273A836	#10-32 x 1 1/2" FLAT HEAD MACHINE SCREW	5
11	97940A070	#303 SS WOODRUFF KEY	2
12	98555A120	EXTERNAL SNAP RING FOR 1/4" OD	2
13	90273A546	1/4"-20 x 1 1/2" FLAT HEAD MACHINE SCREW	7
14	92196A543	1/4"-20 x 1 1/8" SS SOCKET HEAD CAP SCREW	2
15	90101A230	1/4"-20 LOCK NUT	5
16	9961K13	1/4" BORE CLAMP ON SHAFT COLLAR	1
17	Motor Offset Block	OFFSET BLOCK	4
18	Base Leg	LEG	3
19	6291K13	TORQUE LIMITING SHAFT COUPLER	1

TITLE:

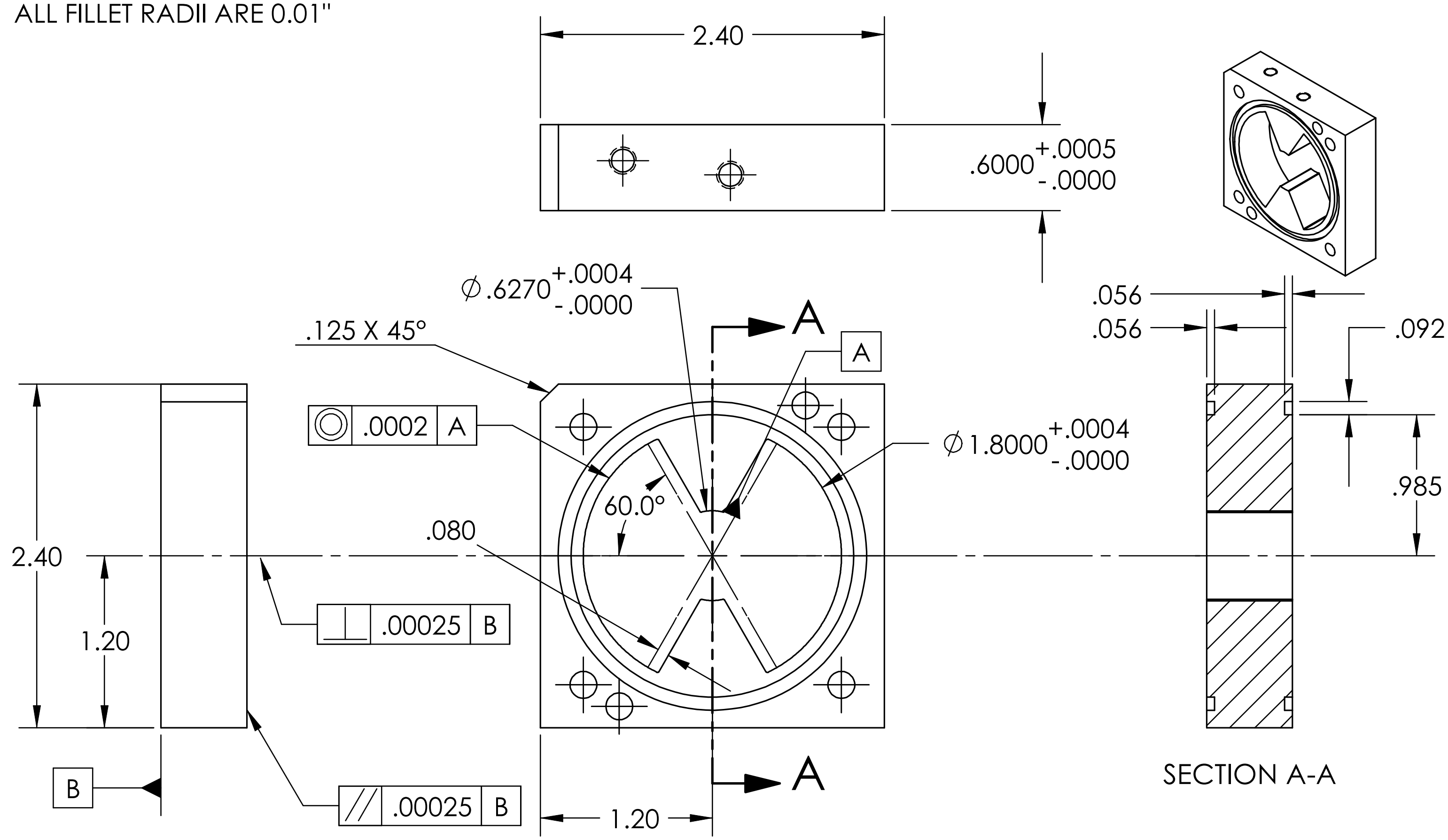
FULL ASSEMBLY

SIZE	DWG. NO.	REV
A	SAC-A2	

SCALE: 1:4	WEIGHT:	SHEET 2 OF 2

5 4 3 2 1

ALL FILLET RADII ARE 0.01"



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TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL
304 STAINLESS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
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CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

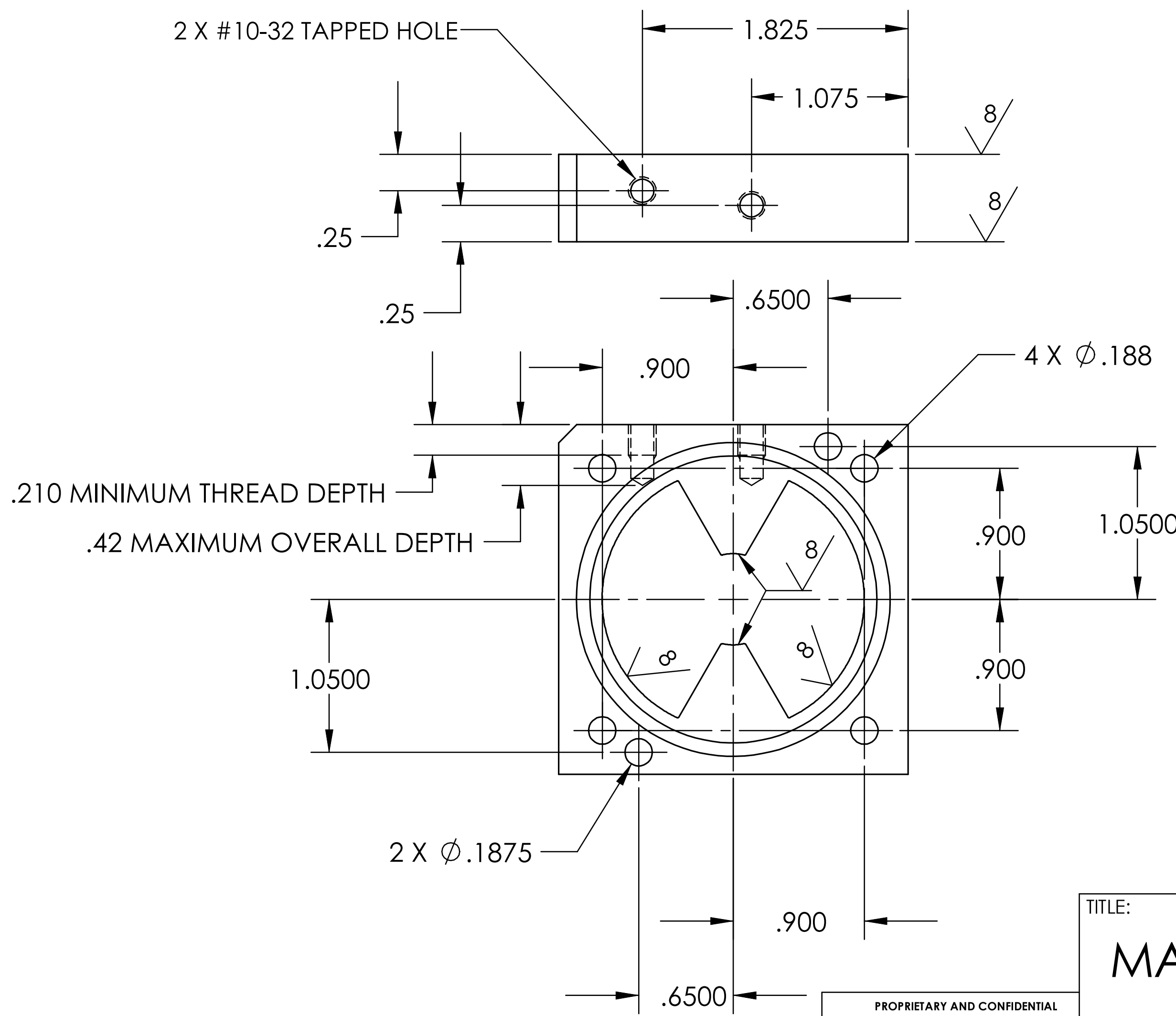
TITLE:

MAIN HOUSING

SIZE	DWG. NO.	REV
A	SAC01	

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

5 4 3 2 1



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TITLE: MAIN HOUSING		
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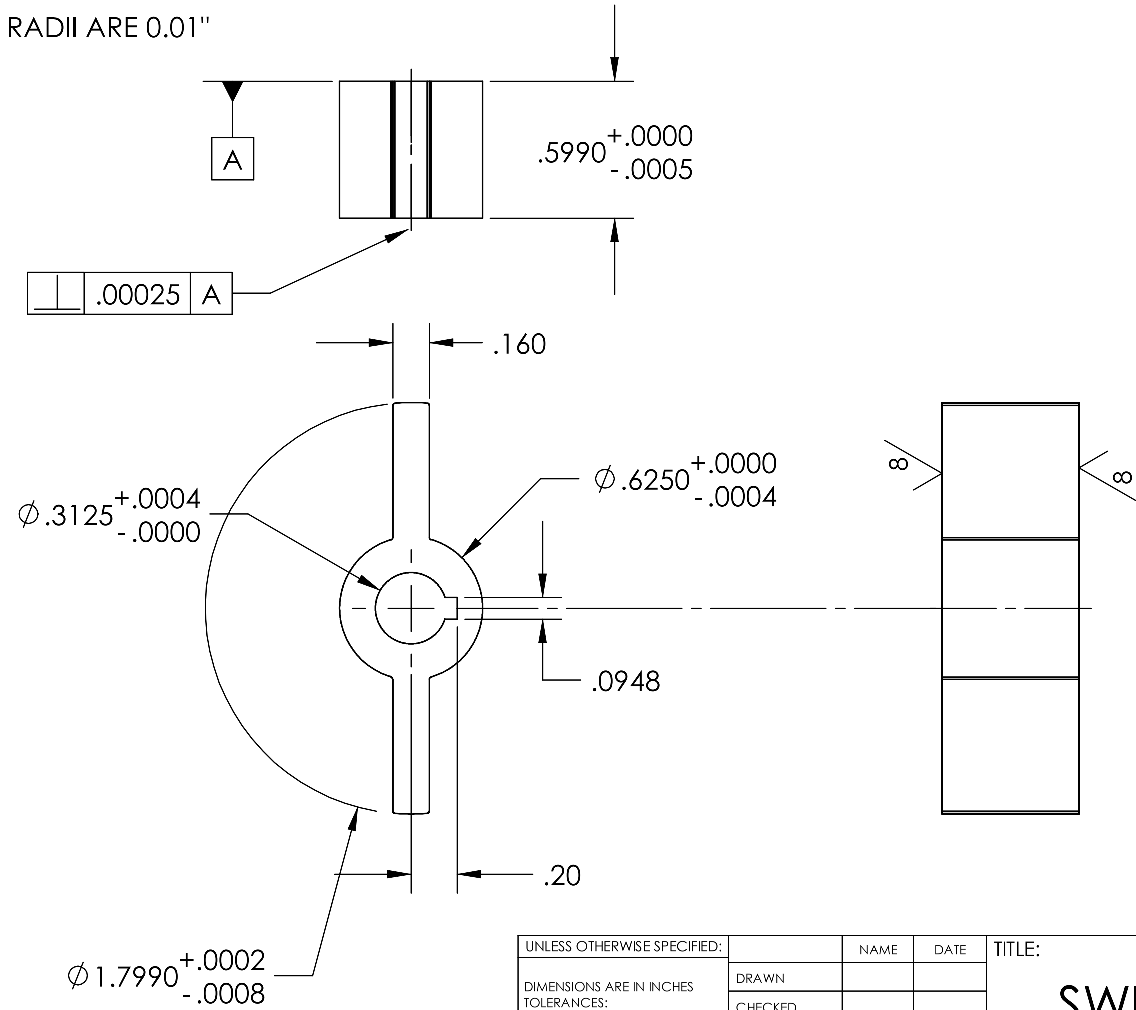
SCALE: 1:1	WEIGHT:	SHEET 2 OF 2

5 4 3 2 1

ALL FILLET RADII ARE 0.01"



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TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL
304 STAINLESS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

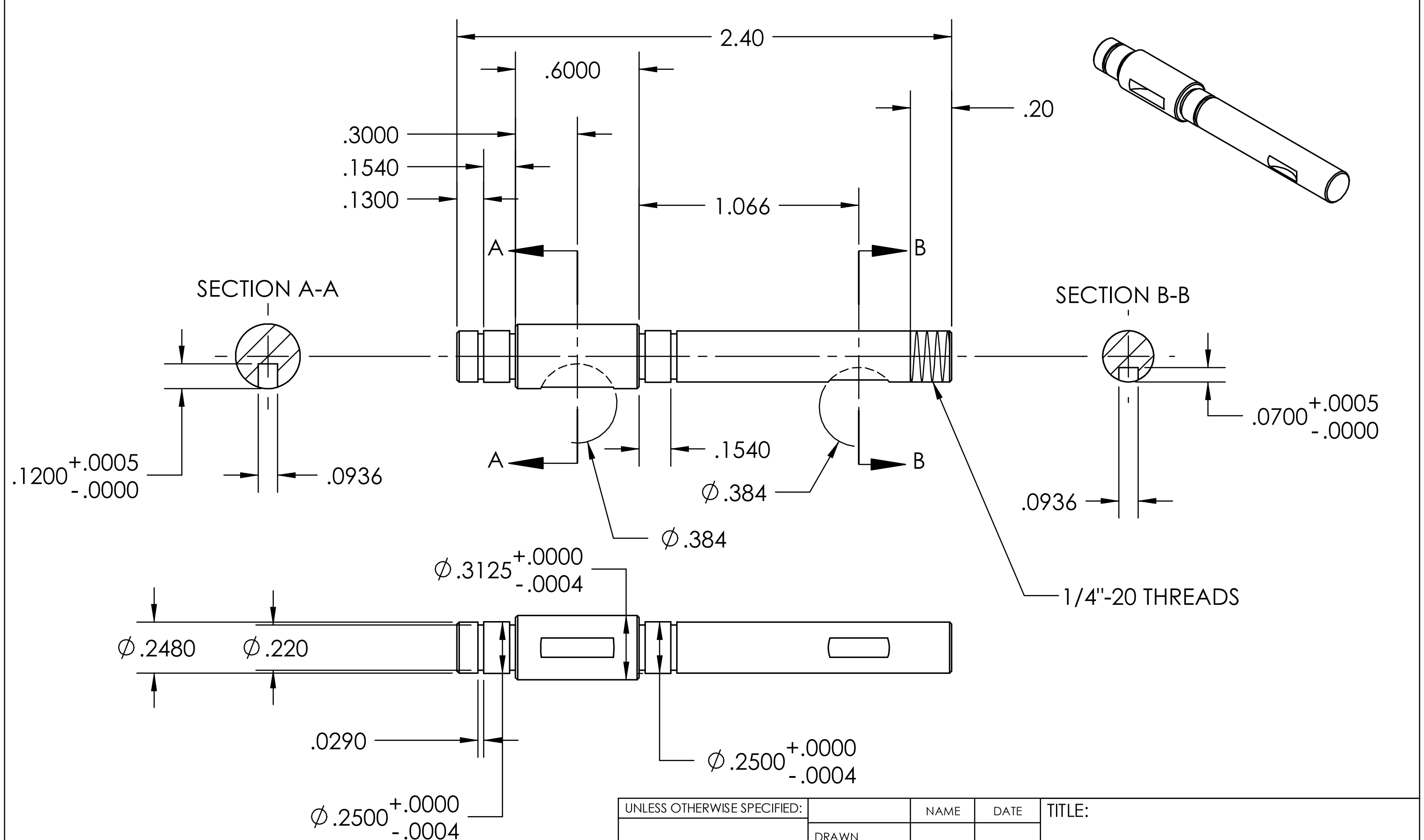
SWING ARM

SIZE A | DWG. NO. SAC02 | REV

SCALE: 3:2 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

ALL CHAMFERS ARE 0.01" X 45°



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MATERIAL 304 STAINLESS	MFG APPR.			SIZE A · DWG. NO. SAC03 · REV
FINISH	Q.A.			
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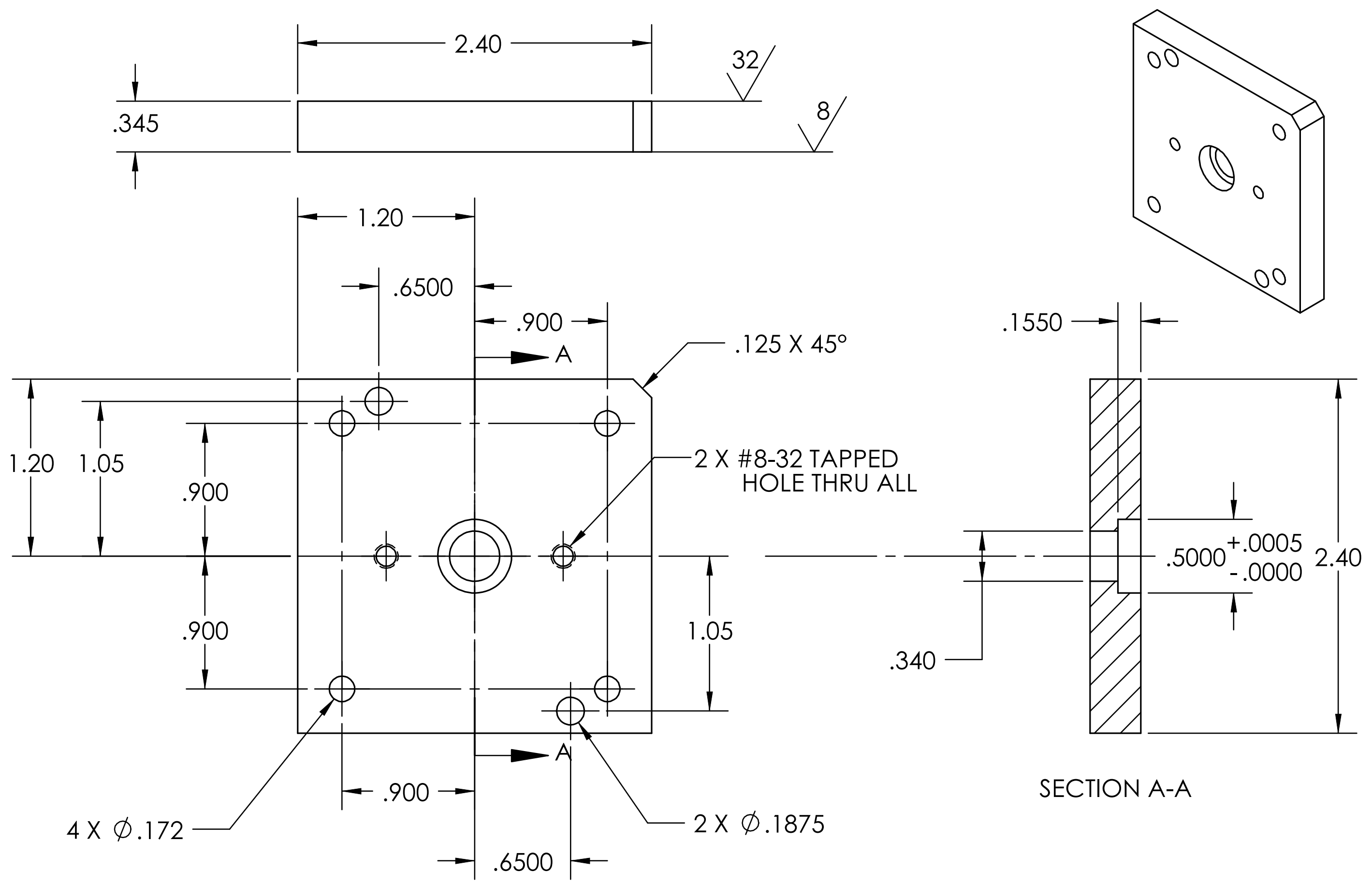
5 4 3 2 1



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TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL
304 STAINLESS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

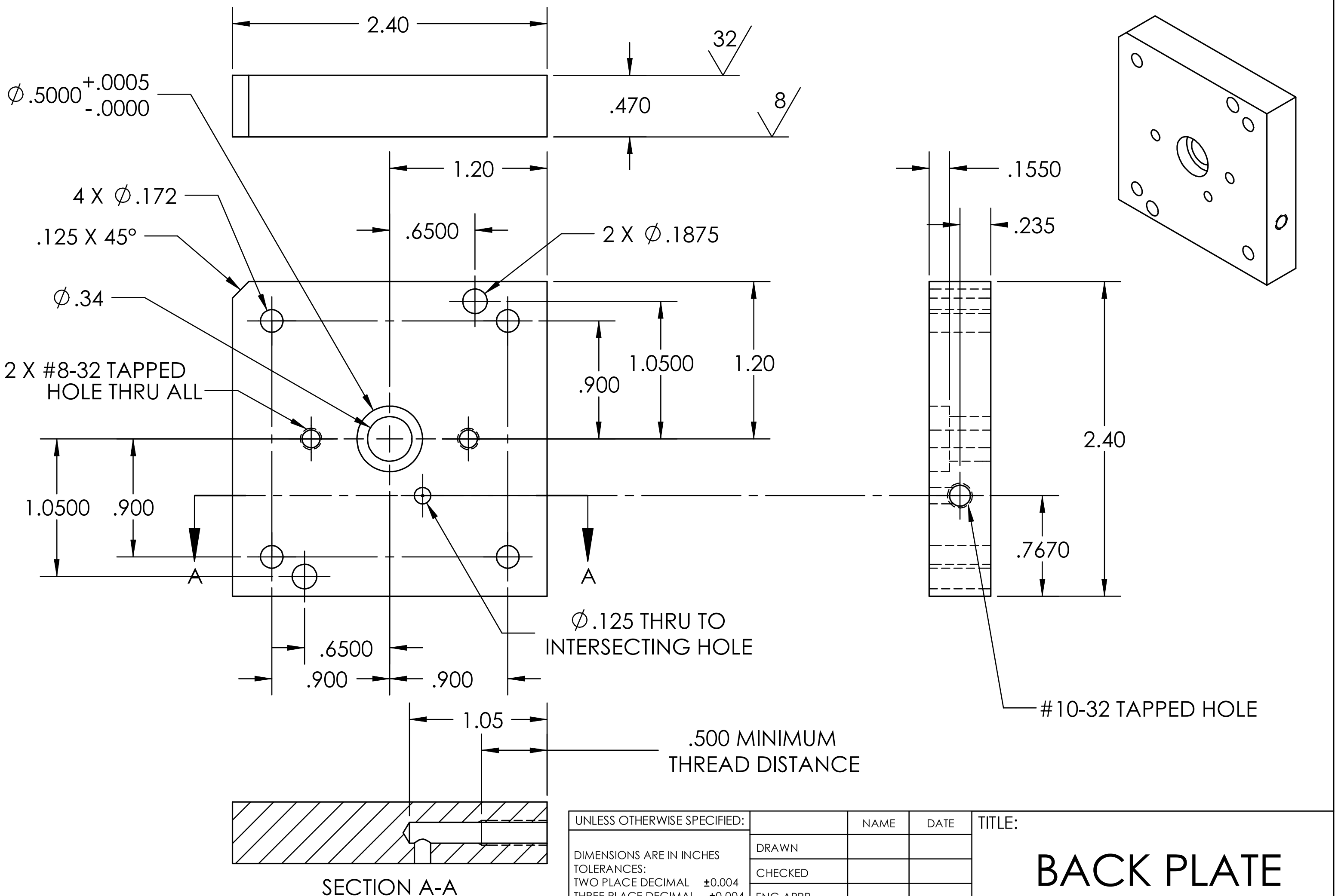
TITLE:

FRONT PLATE

SIZE A | DWG. NO. SAC04 | REV

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

5 4 3 2 1



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TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL
304 STAINLESS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

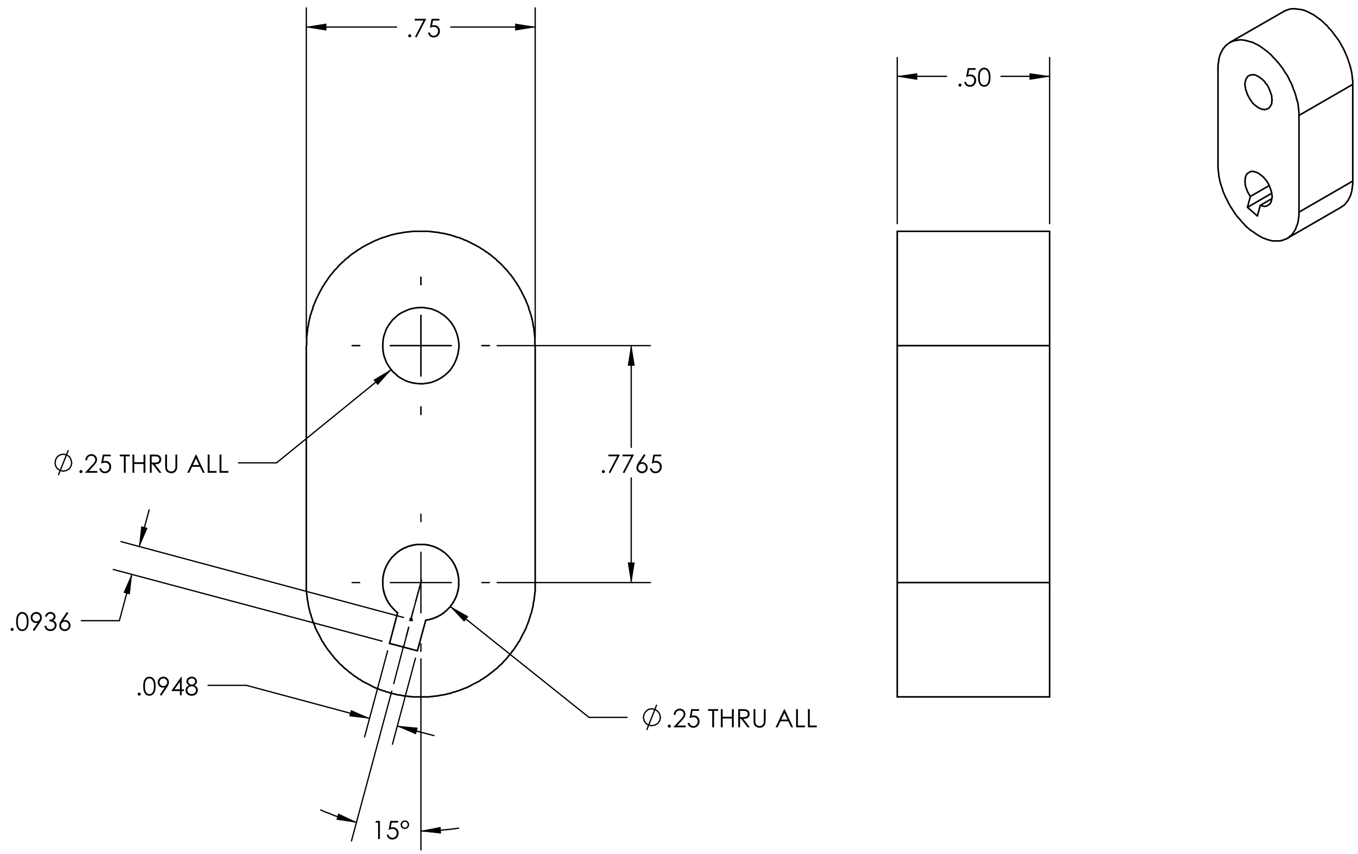
TITLE:

BACK PLATE

SIZE	DWG. NO.	REV
A	SAC05	

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

5 4 3 2 1



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	MFG APPR.		
MATERIAL ALUMINUM	Q.A.		
FINISH	COMMENTS:		
DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

TITLE:

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SIZE	DWG. NO.	REV
A	SAC06	
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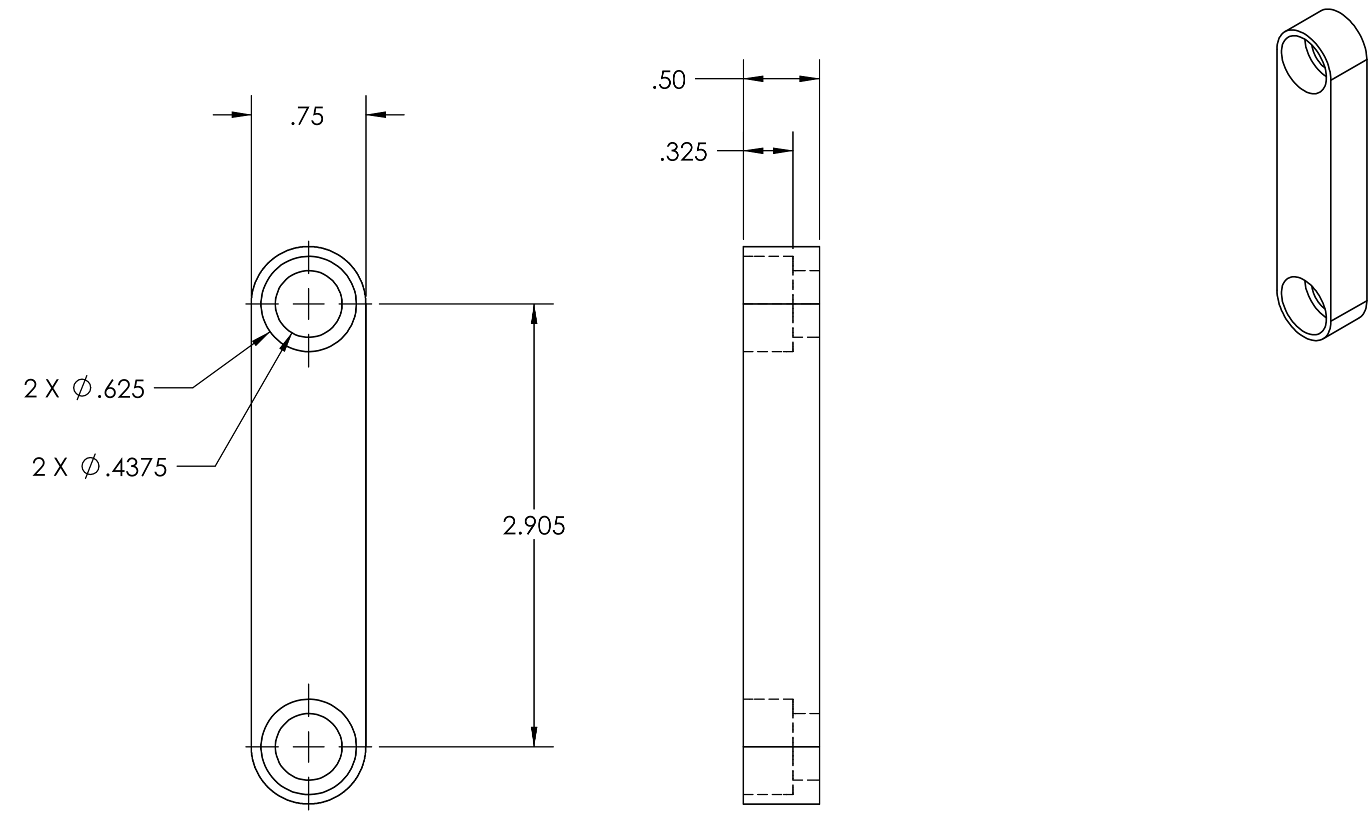
5 4 3 2 1



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	CHECKED			
	ENG APPR.			
MATERIAL ALUMINUM	MFG APPR.			SIZE A — DWG. NO. SAC07 — REV
	Q.A.			
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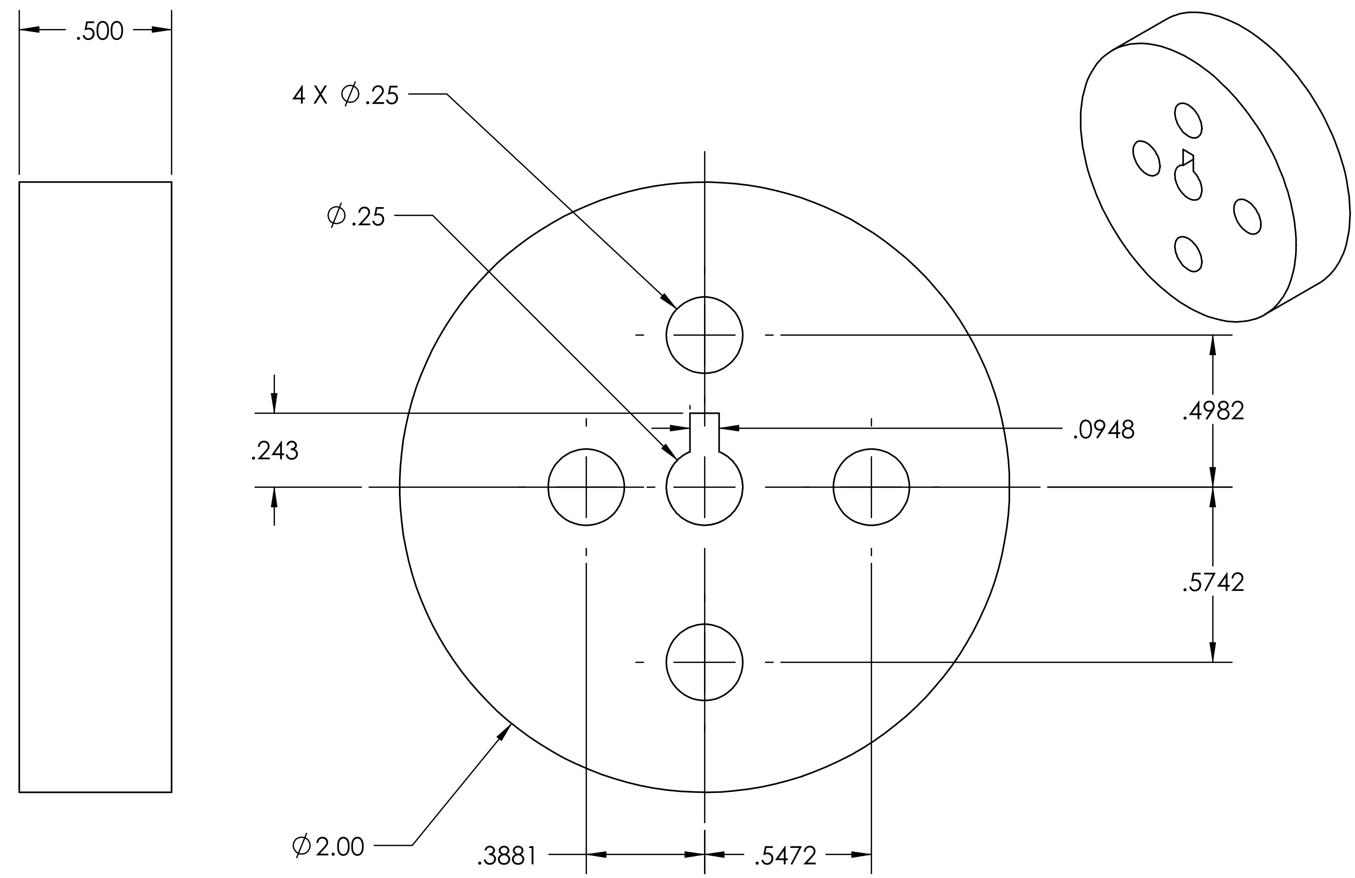
5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
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	CHECKED		
	ENG APPR.		
	MFG APPR.		
MATERIAL ALUMINUM	Q.A.		
FINISH	COMMENTS:		
DO NOT SCALE DRAWING			

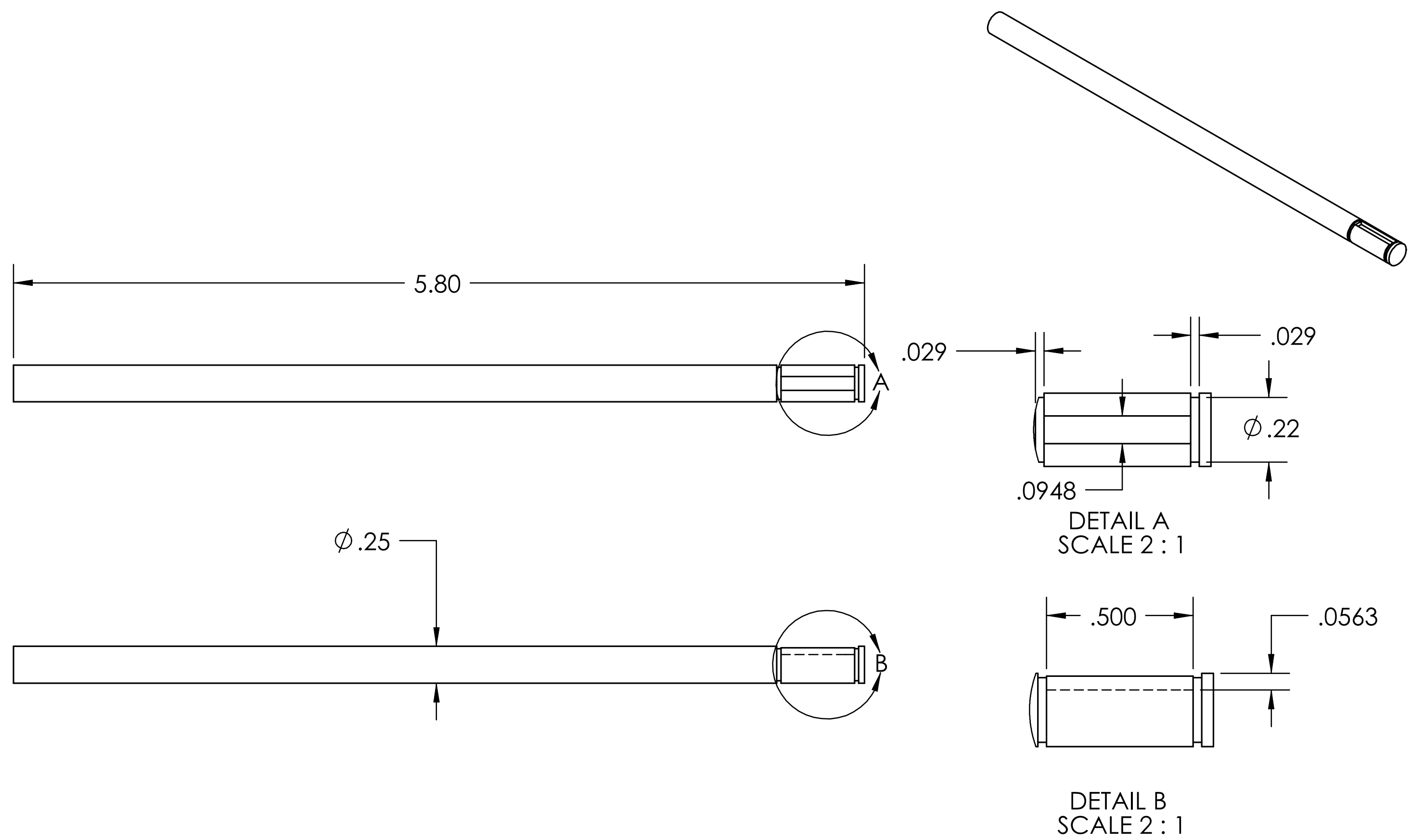
PROPRIETARY AND CONFIDENTIAL

TITLE:

CRANK HUB

SIZE	DWG. NO.	REV
A	SAC08	
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

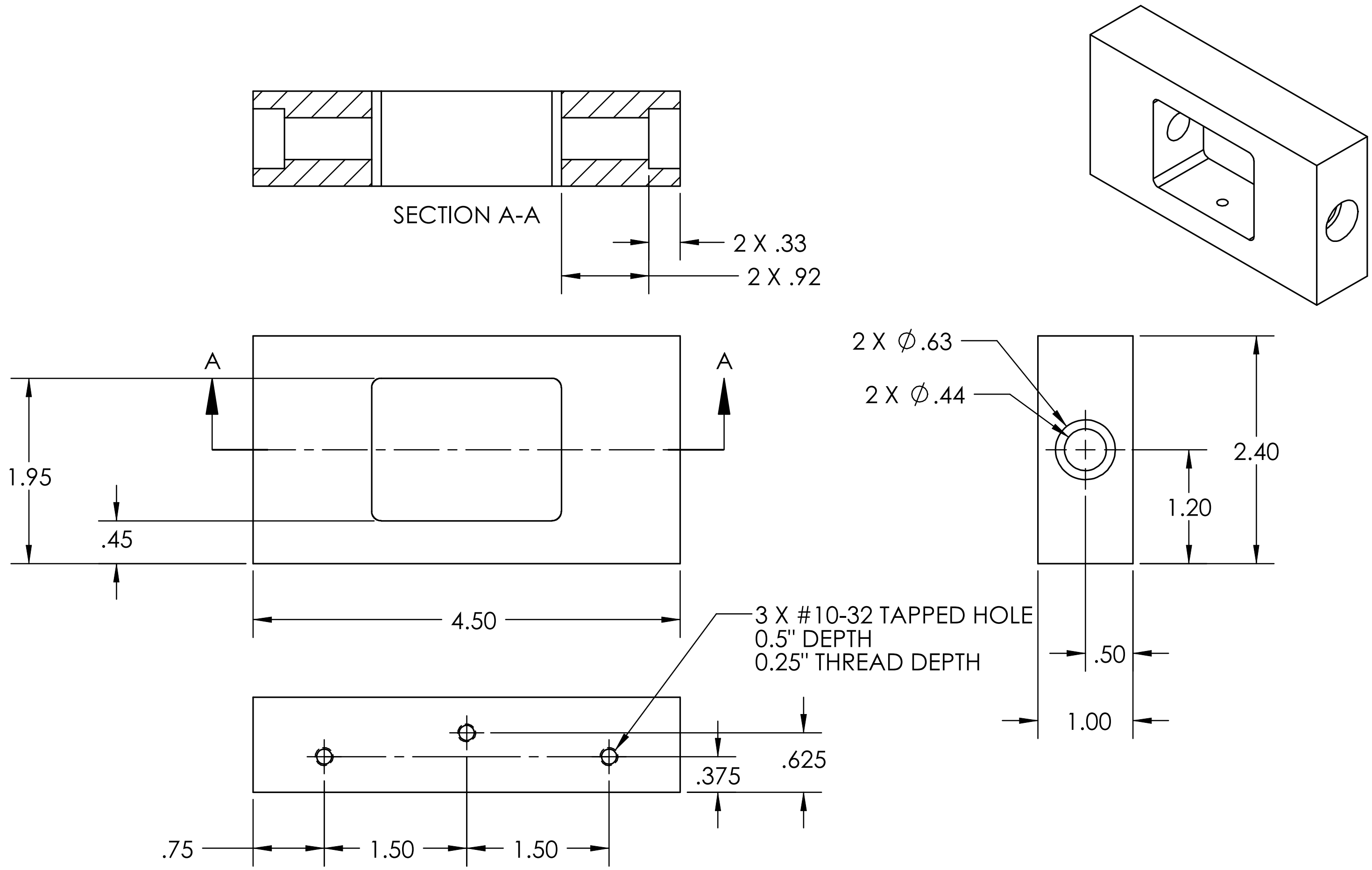
TITLE:

DRIVE SHAFT

SIZE	DWG. NO.	REV
A	SAC09	

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

5 4 3 2 1



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	CHECKED			
	ENG APPR.			
MATERIAL ALUMINUM	MFG APPR.			SIZE A
	Q.A.			DWG. NO. SAC10
FINISH	COMMENTS:			REV
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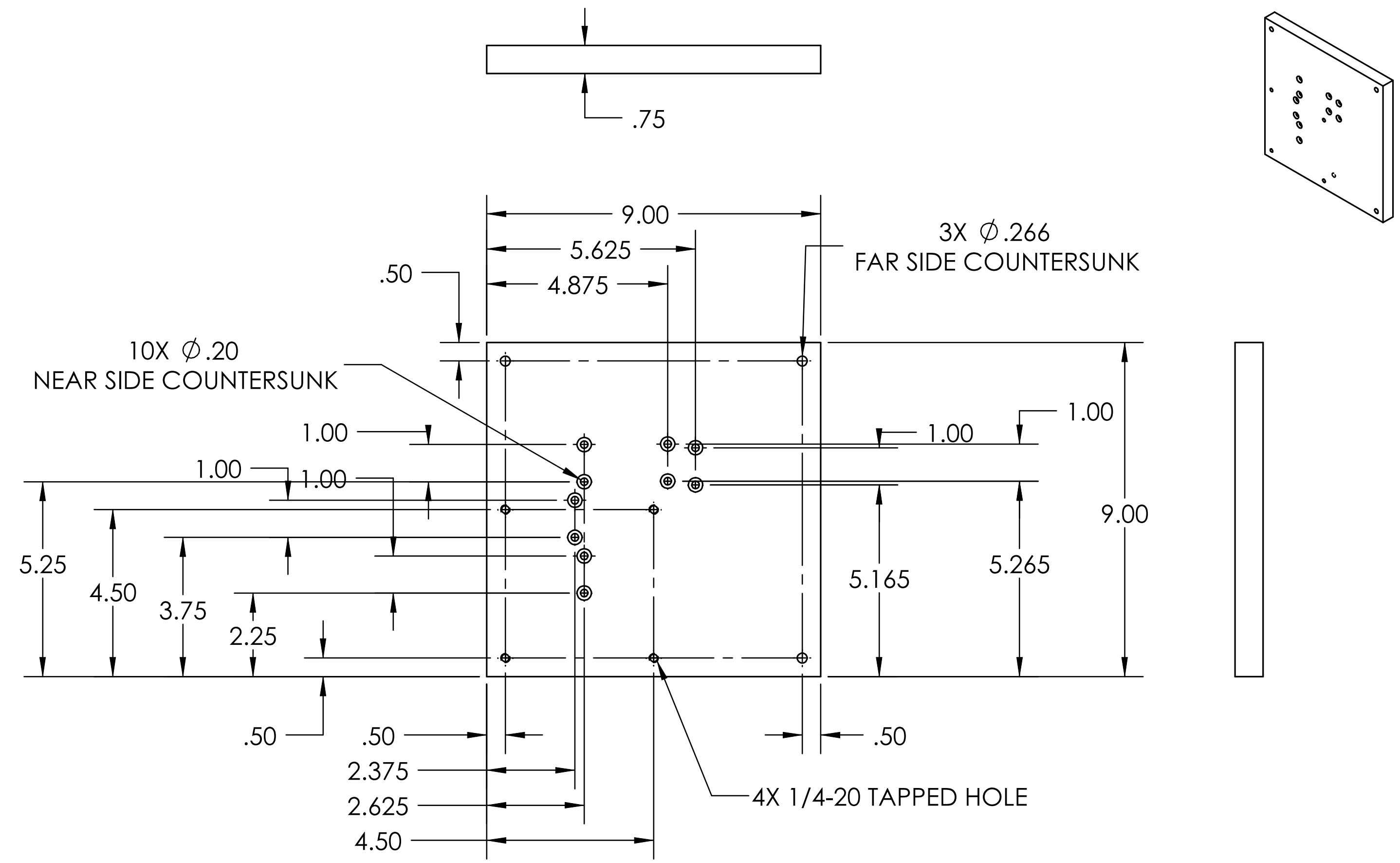

PROPRIETARY AND CONFIDENTIAL

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DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.004
THREE PLACE DECIMAL ±0.004
FOUR PLACE DECIMAL ±0.0004"

MATERIAL
ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

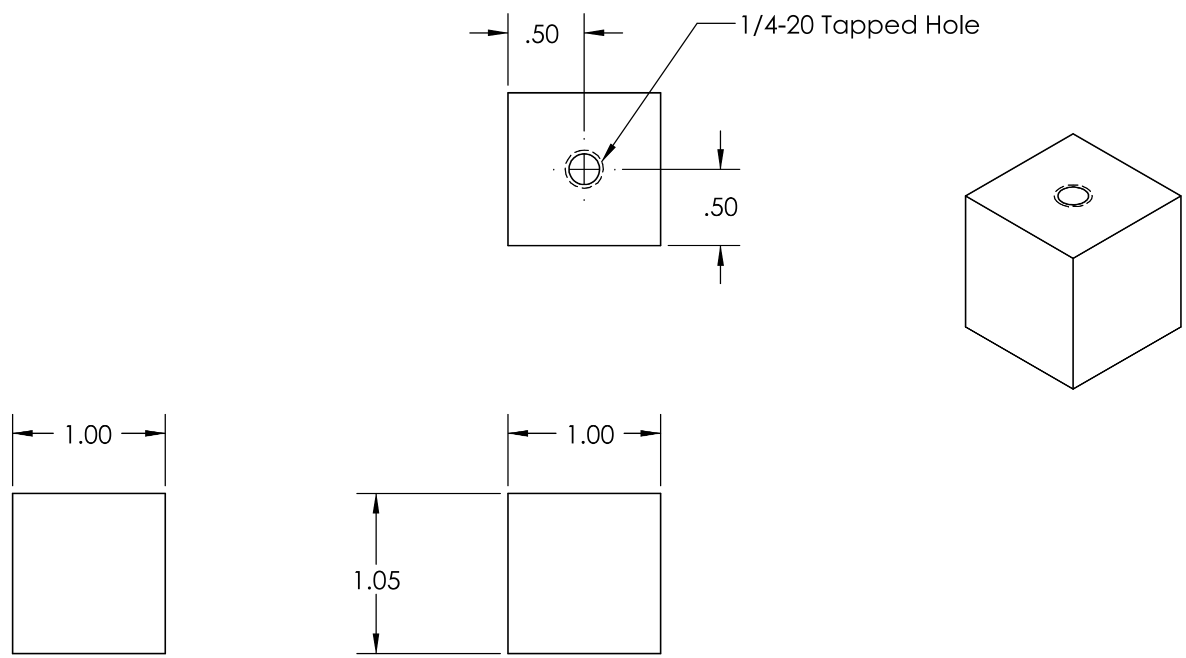
TITLE:

BASE PLATE

SIZE A | DWG. NO. SAC11 | REV

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

5 4 3 2 1



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	CHECKED			
	ENG APPR.			
MATERIAL 6061 ALUMINUM	MFG APPR.			SIZE A — DWG. NO. SAC12 — REV
	Q.A.			
FINISH	COMMENTS:			
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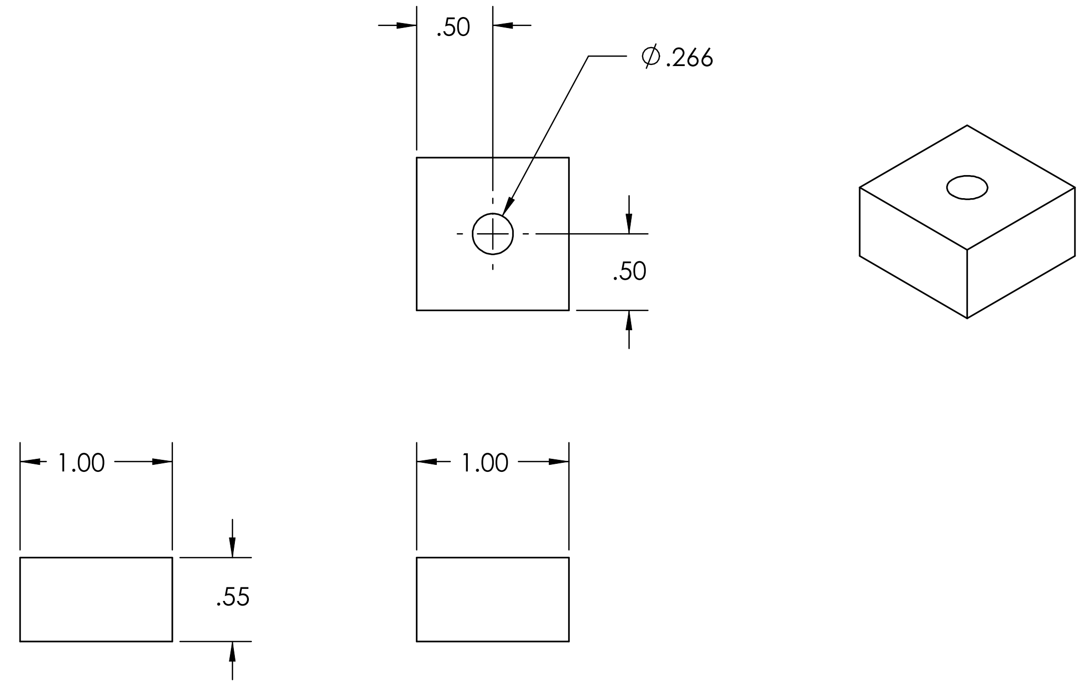

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	CHECKED		
	ENG APPR.		
	MFG APPR.		
MATERIAL 6061 ALUMINUM	Q.A.		
FINISH	COMMENTS:		
DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

TITLE:

MOTOR OFFSET

SIZE	DWG. NO.	REV
A	SAC13	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1

APPENDIX B: LEAKAGE MODEL

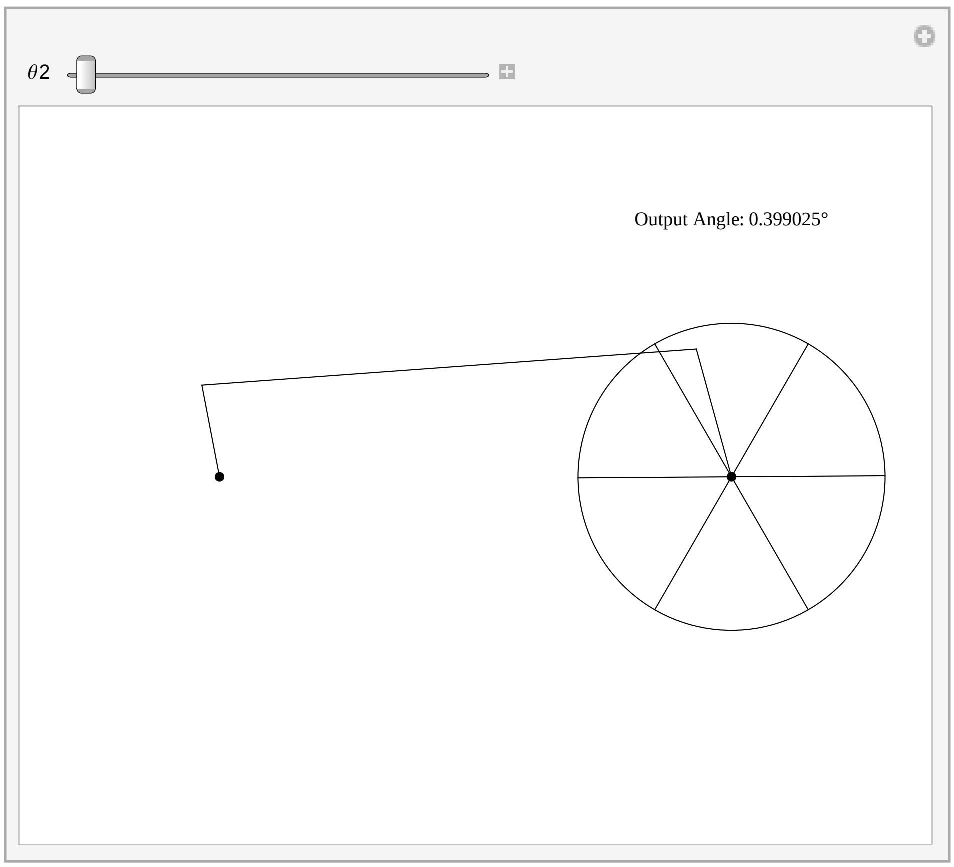
```
In[1]:= fourbar[R_, θ_] := Module[{R1 = R[[1]], R2 = R[[2]], R3 = R[[3]],
    R4 = R[[4]], θ1 = θ[[1]], θ2 = θ[[2]] - θ[[1]], θ3 = {0, 0}, θ4 = {0, 0}},
   θ3[[1]] = -2 ArcTan[(R2 R3 (2 Sin[θ2] +
          Sqrt[(4 Sin[θ2]^2 - 1/(R2^2 R3^2) (R2^2 + 2 (R3 - R1) Cos[θ2] R2 + (R1 - R3)^2 - R4^2)
              (R2^2 - 2 (R1 + R3) Cos[θ2] R2 + (R1 + R3)^2 - R4^2))]))/
       (R2^2 - 2 (R1 + R3) Cos[θ2] R2 + (R1 + R3)^2 - R4^2)];
   θ4[[1]] = 2 ArcTan[(R2 R4 (2 Sin[θ2] + Sqrt[(4 Sin[θ2]^2 -
              1/(R2^2 R4^2) (R2^2 + 2 (R4 - R1) Cos[θ2] R2 - R3^2 + (R1 - R4)^2)
              (R2^2 - 2 (R1 + R4) Cos[θ2] R2 - R3^2 + (R1 + R4)^2))]))/
       (R2^2 + 2 (R4 - R1) Cos[θ2] R2 - R3^2 + (R1 - R4)^2)];

   θ3[[2]] = -2 ArcTan[(R2 R3 (2 Sin[θ2] -
          Sqrt[(4 Sin[θ2]^2 - 1/(R2^2 R3^2) (R2^2 + 2 (R3 - R1) Cos[θ2] R2 + (R1 - R3)^2 - R4^2)
              (R2^2 - 2 (R1 + R3) Cos[θ2] R2 + (R1 + R3)^2 - R4^2))]))/
       (R2^2 - 2 (R1 + R3) Cos[θ2] R2 + (R1 + R3)^2 - R4^2)];
   θ4[[2]] = 2 ArcTan[(R2 R4 (2 Sin[θ2] - Sqrt[(4 Sin[θ2]^2 -
              1/(R2^2 R4^2) (R2^2 + 2 (R4 - R1) Cos[θ2] R2 - R3^2 + (R1 - R4)^2)
              (R2^2 - 2 (R1 + R4) Cos[θ2] R2 - R3^2 + (R1 + R4)^2))]))/
       (R2^2 + 2 (R4 - R1) Cos[θ2] R2 - R3^2 + (R1 - R4)^2)];
   Return[{{θ1, θ2 + θ1, θ3[[1]] + θ1, θ4[[1]] + θ1},
     {θ1, θ2 + θ1, θ3[[2]] + θ1, θ4[[2]] + θ1}}]
```

```
 ];

Origin = {0, 0};
R1 = 3.0;
R2 = {0.388, 0.498, 0.547, 0.574};
R3 = 2.905;
R4 = 0.7765;
θ1 = 0 °;
Lengths = {{R1, R2⟦1⟧, R3, R4},
   {R1, R2⟦2⟧, R3, R4}, {R1, R2⟦3⟧, R3, R4}, {R1, R2⟦4⟧, R3, R4}};
θ2Start = 100.905 °;
θ2Inc = 0.25 °;
θ2Max = 360.0 °;
RArm = 0.90 - 0.001;


PressureRatio = 4;

inversion = 2;

dataList = {{}, {}};
outputAngle = {};
inputAngle = {};


For[θ2 = θ2Start, θ2 < θ2Max + θ2Start, θ2 += θ2Inc,
 sol = fourbar[Lengths⟦PressureRatio - 1⟧, {θ1, θ2}];
 AppendTo[dataList⟦1⟧, # / ° & /@ {θ1, θ2, sol⟦1⟧⟦3⟧, sol⟦1⟧⟦4⟧}];
 AppendTo[dataList⟦2⟧, # / ° & /@ {θ1, θ2, sol⟦2⟧⟦3⟧, sol⟦2⟧⟦4⟧}];
 AppendTo[outputAngle, (sol⟦inversion⟧⟦4⟧ - 15 ° - 90 °)];
 AppendTo[inputAngle, θ2 - θ2Start];
]
dataCount = Length[dataList⟦1⟧];
Clear[θ2];

myGraphics[Inv_, θIndex_, mySize_] :=
 Module[{Inversion = Inv, θ2 = θIndex, size = mySize},
  Return[
    Graphics[{
      (*Drive Linkage*)
      Line[{
```

```
    {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °],
      R1 Sin[dataList[[Inversion]][[θ2]][[1]] °]} + Origin,
    {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] + R4 Cos[dataList[[Inversion]][[
             θ2]][[4]] °], R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] +
       R4 Sin[dataList[[Inversion]][[θ2]][[4]] °]} + Origin
   }],
  Line[{
    {0, 0} + Origin,
    {R2[[PressureRatio - 1]] Cos[dataList[[Inversion]][[θ2]][[2]] °],
      R2[[PressureRatio - 1]] Sin[dataList[[Inversion]][[θ2]][[2]] °]} + Origin,
    {R2[[PressureRatio - 1]] Cos[dataList[[Inversion]][[θ2]][[2]] °] +
       R3 Cos[dataList[[Inversion]][[θ2]][[3]] °],
      R2[[PressureRatio - 1]] Sin[dataList[[Inversion]][[θ2]][[2]] °] +
       R3 Sin[dataList[[Inversion]][[θ2]][[3]] °]} + Origin
   }],
  {PointSize[Medium], Point[{0, 0} + Origin]},
  {PointSize[Medium], Point[{R1 Cos[dataList[[Inversion]][[θ2]][[1]] °],
      R1 Sin[dataList[[Inversion]][[θ2]][[1]] °]} + Origin]},
  (*Swing Arm*)
  Circle[{R1 Cos[dataList[[Inversion]][[θ2]][[1]] °],
     R1 Sin[dataList[[Inversion]][[θ2]][[1]] °]} + Origin, RArm + .001 / 2],
  Line[{
    {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] + RArm Cos[outputAngle[[θ2]]],
      R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] +
       RArm Sin[outputAngle[[θ2]]]} + Origin,
    {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] - RArm Cos[outputAngle[[θ2]]],
      R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] -
       RArm Sin[outputAngle[[θ2]]]} + Origin
   }],
  Line[{
    {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] + (RArm + .001 / 2) Cos[60 °],
      R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] +
       (RArm + .001 / 2) Sin[60 °]} + Origin,
    {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] - (RArm + .001 / 2) Cos[60 °],
      R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] -
       (RArm + .001 / 2) Sin[60 °]} + Origin
   }],
  Line[{
```

```
        {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] + (RArm + .001 / 2) Cos[-60 °],
          R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] +
            (RArm + .001 / 2) Sin[-60 °]} + Origin,
        {R1 Cos[dataList[[Inversion]][[θ2]][[1]] °] - (RArm + .001 / 2) Cos[-60 °],
          R1 Sin[dataList[[Inversion]][[θ2]][[1]] °] -
            (RArm + .001 / 2) Sin[-60 °]} + Origin
      }],
    Text[StringJoin["Output Angle: ",
        ToString[outputAngle[[θ2]] / °], "°"], {3.0, 1.5}]
   }, PlotRange → {{-1, 4}, {-2, 2}}, ImageSize → mySize]
  ];
]

Manipulate[
 myGraphics[inversion, θ2, 400], {θ2, 1, dataCount, 1}
]
```

Out[22]=



In[23]:=
```
PAmbient = 14.7; (*psia*)
FullVolume = .37296464 * 0.6;(*in^3*)
ExtraVolume = 0.0072612625 - 0.004332; (*in^3*)
AirDensity = 4.35333869 * 10^(-5); (*lbm/in^3*)
FullMass = AirDensity * (FullVolume + ExtraVolume);(*lbm*)
T = 529.67; (*°R*)

EndGapWidth = 0.001; (*in*)
EndGapLength = 0.60; (*in*)
RArm = 0.90 - EndGapWidth; (*in*)
SideGapWidth = 0.0006;(*in*)
SideGapLength = RArm - 0.625 / 2;

massLossTop[i_] := Module[{Q, Z = 1, R = 1545.3, M = 28.97,
    mloss, gc, k, C, A, v, p, m, P = PAmbient 12^2 (*lb/ft^2*)},

   p = If[i == 1, P, pressure[[i - 1]] 12^2]; (*lb/ft^2*)
   C = 0.3; (*Discharge Coefficient - Dimensionless*)
   gc = 32.17; (*Gravitational Conversion Factor - ft/s^2*)
   A = (EndGapWidth / 12) * (EndGapLength / 12); (*Discharge Area - ft^2*)
   k = 1.40; (*cp/cv - Dimensionless*)
   m = If[i == 1, FullMass, mass[[i - 1]]]; (*lb/ft^2*)
   If[p < P,
```

$$\text{If}\left[P / p < \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}},\right.$$

$$Q = -C\,A\,P\sqrt{\left(\frac{2\,gc\,M}{Z\,R\,T}\right)\left(\frac{k}{k-1}\right)\left(\left(\frac{p}{P}\right)^{\left(\frac{2}{k}\right)} - \left(\frac{p}{P}\right)^{\frac{k+1}{k}}\right)};$$

,

$$Q = -C\,A\,P\sqrt{\left(\frac{gc\,k\,M}{Z\,R\,T}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}};$$

],

$$\text{If}\left[p / P < \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}},\right.$$

$$Q = C\,A\,p\sqrt{\left(\frac{2\,gc\,M}{Z\,R\,T}\right)\left(\frac{k}{k-1}\right)\left(\left(\frac{P}{p}\right)^{\left(\frac{2}{k}\right)} - \left(\frac{P}{p}\right)^{\frac{k+1}{k}}\right)};$$

,

$$Q = C\,A\,p\sqrt{\left(\frac{gc\,k\,M}{Z\,R\,T}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}};$$

```
    ]
  ];

  mloss = (Q + (outputTipVelocity[[i]] / 12) A If[outputTipVelocity[[i]] > 0,
        (m / (volume[[i]] / 12^3)), AirDensity 12^3]) dt;
  Return[If[outputAngle[[i]] < 0, 0, mloss]];

 ];

massLossSides[i_] := Module[{Q, Z = 1, R = 1545.3, M = 28.97,
    mloss, gc, k, C, A, v, p, m, P = PAmbient 12^2 (*lb/ft^2*)},

  p = If[i == 1, P, pressure[[i - 1]] 12^2]; (*lb/ft^2*)
  C = 0.3; (*Discharge Coefficient - Dimensionless*)
  gc = 32.17; (*Gravitational Conversion Factor - ft/s^2*)
  A = (SideGapWidth / 12) * (SideGapLength / 12); (*Discharge Area - ft^2*)
  k = 1.40; (*cp/cv - Dimensionless*)
  m = If[i == 1, FullMass, mass[[i - 1]]]; (*lb/ft^2*)

  If[p < P,
```

$$\text{If}\left[P / p < \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}},\right.$$

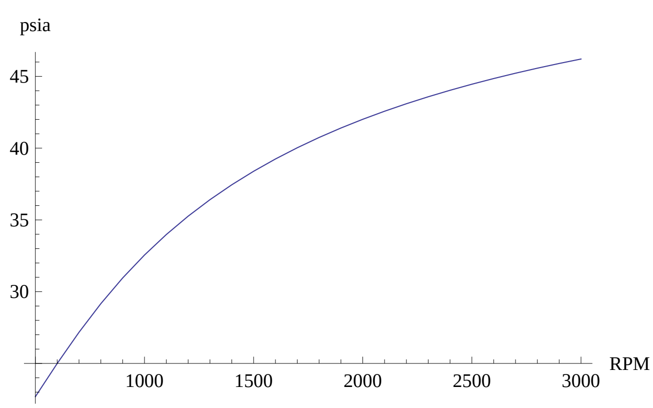
$$Q = -C\,A\,P\sqrt{\left(\frac{2\,gc\,M}{Z\,R\,T}\right)\left(\frac{k}{k-1}\right)\left(\left(\frac{p}{P}\right)^{\left(\frac{2}{k}\right)} - \left(\frac{p}{P}\right)^{\frac{k+1}{k}}\right)};$$

,

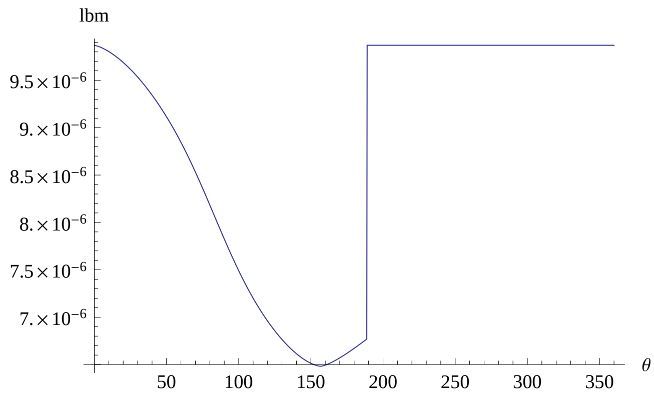
```
      Q = -C A P Sqrt[((gc k M)/(Z R T)) (2/(k + 1))^((k+1)/(k-1))];
     ],
     If[p / P < ((k + 1)/2)^(k/(k-1)),
      Q = C A p Sqrt[((2 gc M)/(Z R T)) (k/(k - 1)) ((P/p)^(2/k) - (P/p)^((k+1)/k))];
      ,
      Q = C A p Sqrt[((gc k M)/(Z R T)) (2/(k + 1))^((k+1)/(k-1))];
     ]
    ];

   mloss = (Q + (outputAngularVelocity[[i]] (SideGapWidth / 12)
          ((RArm^2 - ((RArm - SideGapLength) / 2)^2) / 2) / 12^2)
        If[outputTipVelocity[[i]] > 0, (m / (volume[[i]] / 12^3)),
         AirDensity 12^3]) dt;
   Return[If[outputAngle[[i]] < 0, 0, 2 * mloss]];

  ];

calcPressures[] := Module[{},
   outputAngularVelocity = {};
   outputTipVelocity = {};
   volume = {};
   pressure = {};
   losslessPressure = {};
   mass = {};

   Frequency = RPM / 60;
   dt = (1 / Frequency) / (360 ° / θ2Inc);

   For[i = 1, i ≤ dataCount, i += 1,
```

```
      AppendTo[outputAngularVelocity,
       (outputAngle[[If[i == dataCount, 1, i + 1]]] -
          outputAngle[[i - If[i == 1, 2, 1]]]) / (2 dt)];
      AppendTo[outputTipVelocity, outputAngularVelocity[[i]] * RArm];
      AppendTo[volume, If[outputAngle[[i]] < 0, FullVolume + ExtraVolume,
        (1 - outputAngle[[i]] / (60 °)) * FullVolume + ExtraVolume]];

      AppendTo[mass, If[i == 1 || outputAngle[[i]] < 0, FullMass, mass[[i - 1]]] -
        massLossTop[i] - 2 * massLossSides[i]];

      AppendTo[losslessPressure,
       PAmbient * ((FullVolume + ExtraVolume) / volume[[i]])];
      AppendTo[pressure, PAmbient * ((FullVolume + ExtraVolume) / volume[[i]]) *
        (mass[[i]] / FullMass)];
     ]

     Return[];
   ];

maxPList = {};

For[j = 500, j ≤ 3000, j += 100,
 RPM = j;
 calcPressures[];
 AppendTo[maxPList, {RPM, Max[pressure]}];
]


ListLinePlot[maxPList, PlotRange → Automatic, AxesLabel → {"RPM", "psia"}]
ListLinePlot[Partition[Riffle[(# / ° &/@inputAngle), mass], 2],
 PlotRange → Automatic, AxesLabel → {"θ", "lbm"}]
ListLinePlot[Partition[Riffle[(# / ° &/@inputAngle), volume], 2],
 PlotRange → {{0, 360}, {0, .25}}, AxesLabel → {"θ", "in^3"}]
ListLinePlot[Partition[Riffle[(# / ° &/@inputAngle), losslessPressure], 2],
 PlotRange → {{0, 360}, {0, 60}}, AxesLabel → {"θ", "psia"}]
ListLinePlot[Partition[Riffle[(# / ° &/@inputAngle), pressure], 2],
 PlotRange → {{0, 360}, {0, 60}}, AxesLabel → {"θ", "psia"}]
```

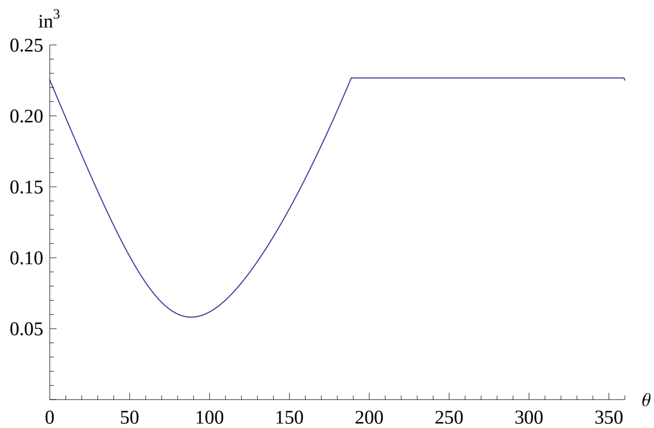
Out[39]=



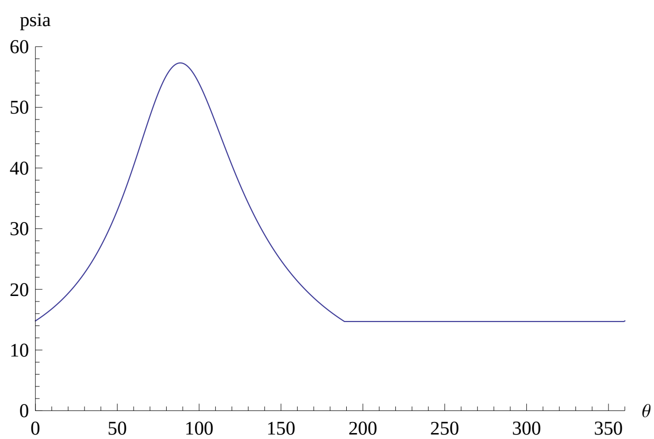
Out[40]=



Out[41]=



Out[42]=



Out[43]=