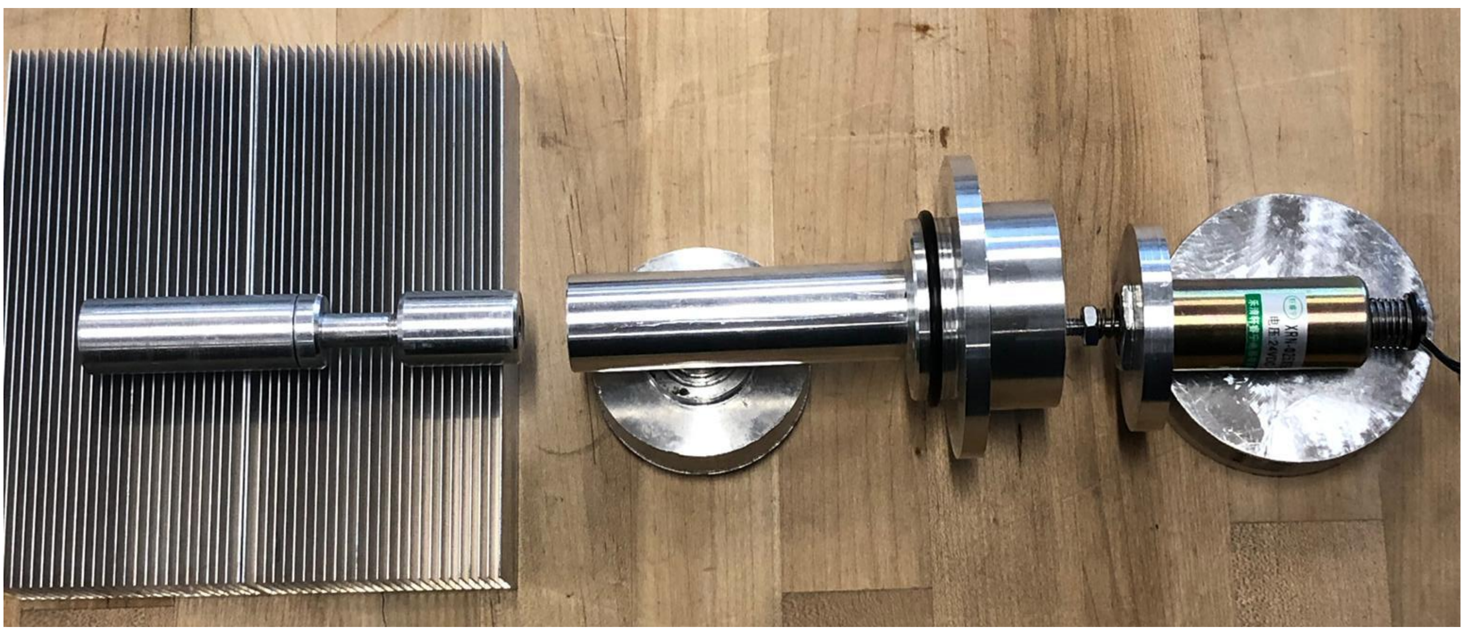
NORTHERN ARIZONA UNIVERSITY

Stirling Free Piston Cooler

(FPSC)

Operations Manual



1 December 2018

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1 Manufacturing

The assembly section of the cooler maintenance covers the complete construction of the free piston Stirling cooler (FPSC), with the assumption that the reader is interested in either fabricating & recreating the cooler, doing so with the intention of improving upon it, or that the reader is invested in this project in some other capacity (e.g. research, interest etc.). The majority of the provided assembly process was completed with the help of the mechanical lathe in the machine shop (located in building 98C) at Northern Arizona University (NAU). It should be noted that a four-jaw chuck was employed for most turning operations in this project due to the need for more traction on our parts, namely, the inner cylinder, grander cylinder, and motor housing. Additionally, all parts discussed in this manual have specifications in Appendix A under the bill of materials.

1.1 Inner Cylinder

The internal cylinder of the FPSC is created by using a mechanical lathe with a high-speed steel tool. The material used in this case is aluminum. The stock purchased was provided in the form of cylindrical work pieces with dimensions of $3.5" \ x \ 8"$. With 3 of these blocks, one can create everything described in this section. The first procedure is to turn down the cylindrical work to the diameter (in the previously mentioned drawing). This cylinder will be responsible for guiding the piston-displacer apparatus that warrants further discussion in a future section. The long and smallest cylinder (i.e. inner cylinder) should be turned down with the knowledge that one will have to allow for a small length at one of its ends to have two different diameters as specified in the drawing. Additionally, a section just before this abrupt step in diameter (along the length of the cylinder) will accommodate an O-ring to eventually pressurize the *grander* cylinder. Please see Figure 1 for a representation of the inner cylinder. Finally, the inner diameter for this inner cylinder is removed by virtue of the drill-chuck on the tail stock of the mechanical lathe. Equation 1 below, shows how to relate the feed rate to the rotational speed, where f_r, N, and f correspond to the feed rate $\left(\frac{in}{min}\right)$, rotational speed $\left(\frac{rev}{min}\right)$, and feed $\left(\frac{in}{rev}\right)$. Additionally, Equation 2 shows how the RPM (revolutions per minute) can be determined based on one's desired cutting speed, v $\left(\frac{in}{min}\right)$, and original diameter D_0.

$$f_r = Nf \quad (1)$$

$$N = \frac{v}{\pi D_0} \quad (2)$$

The final task with this part is to machine holes about the base of the smallest cylinder in the "inner cylinder" part. These holes can be machined with either a drill press (roughly) or with a CNC machine. It should be noted that the CNC route will require a sophisticated mounting system for this part, while a drill press is more difficult to use for accuracy.

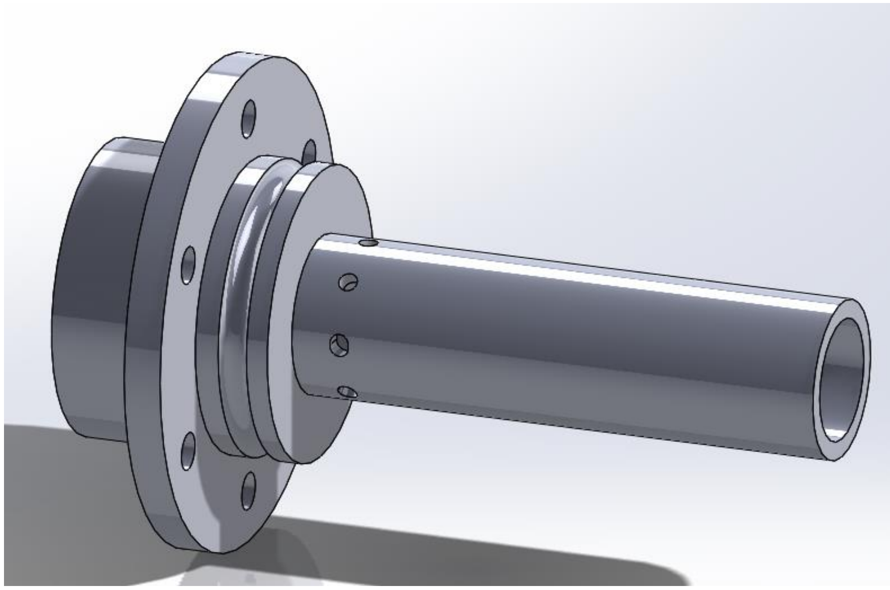

Figure 1 Inner Cylinder CAD

1.2 Grander Cylinder

The Grander Cylinder of this cooler corresponds to the pressurized vessel that ultimately contains the bulk of the components associated with Stirling coolers. Namely, the *grander* cylinder will contain the cold (expansion) space, hot (compression) space, regenerator material and the piston-displacer assembly. This part was created by using the remaining material that was mentioned in the previous section. Figure 2 shows the grander cylinder with the heat sink and flanges. The inner diameter of this cylinder was removed with a boring tool, since the work needs to be turned along its entire length, within the limits established by the inner diameter dimensioning. In order to complete this task, one must first drill multiple “pilot” holes in order to reach a large enough diameter to use the boring tool. This is in part, due to the geometry of the boring tool and the way it cuts material with a single-point tool. This problem should be approached similarly with the bore(s) and drilling tool(s) available to you. With respect to the heat sink, the appropriate amount of material thickness should be omitted from turning as shown in Figure 2. The three equally spaced fins were turned by using a parting tool.

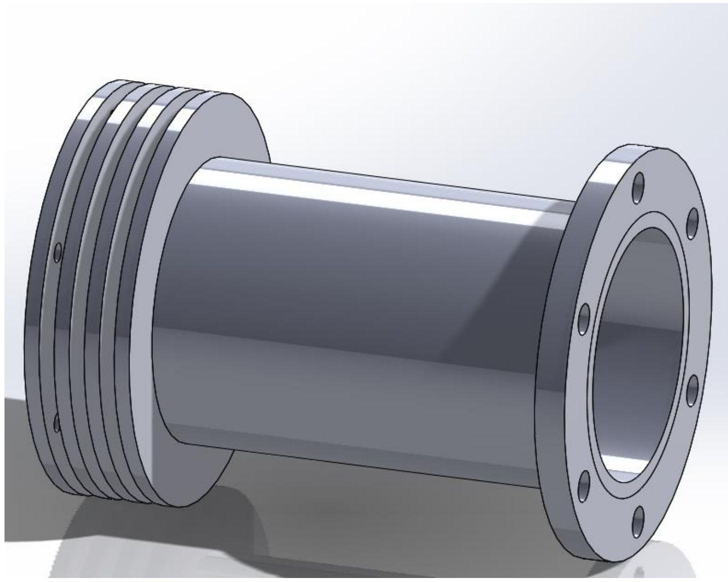

Figure 2 Grander Cylinder

1.3 Displacer Shell

The displacer shell is actually two parts because of its requirement to be interfaced with a magnet configuration ensuring continuous linear motion without “knocking” from any one part of the piston-displacer assembly. The displacer shell was turned down to its outer diameter for the length specified. An additional length should be added to account for the fabrication (and length) of the displacer shell cap. At this point one should use the tail stock and drill chuck to drill an appropriately sized hole for the cap and deep enough for its linear motion in the working system. Of course, the displacer shell will be hollow and open from one end and closed on the other to reduce airflow in & out of the displacer. The displacer shell and its cap is shown below in Figures 3 & 4.

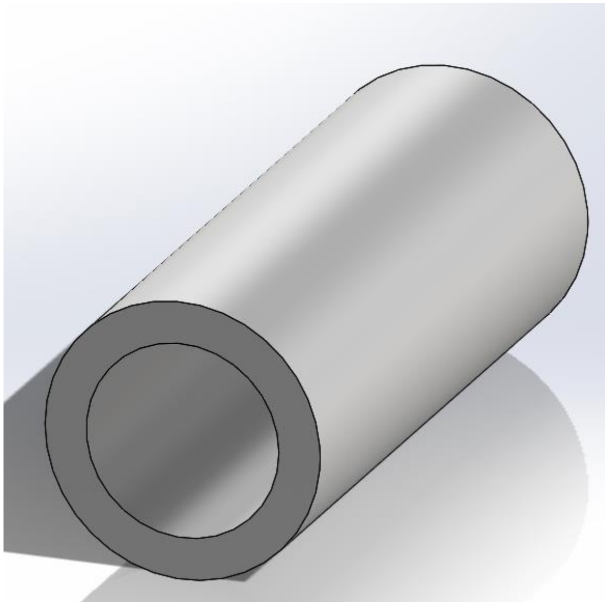

Figure 3 Displacer shell

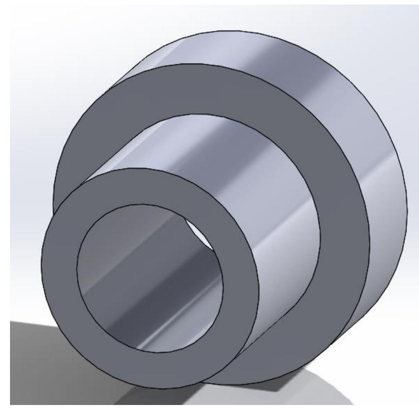

Figure 4 Displacer Shell Cap

1.4 Piston-Displacer Shaft

The piston-displacer is created by turning down aluminum to the diameter specified and threading the end of it to eventually connect with the piston-solenoid assembly. The end of the shaft should also be drilled into, with intentions of creating a hole for threading. This will serve to hold an appropriately sized screw to retain the “displacer” cylindrical ring magnet(s).

1.5 Piston-Solenoid Assembly

The piston is the simplest part to be manufactured yet, with no internal turning (i.e. boring) required. The piston requires holes on either end to be threaded. These threads should be completed to match the external threading completed on the displacer-piston & displacer-solenoid shaft. The solenoid used in this manual is specified in the BOM (Appendix A). The solenoid-piston shaft should be threaded with the aforementioned considerations in mind. Figure 5 shows the physical solenoid-piston-displacer assembly (with the solenoid retainer included), whereas Figure 6 shows the CAD view of the piston.

Figure 5 Physical Solenoid-Piston-Displacer Assembly

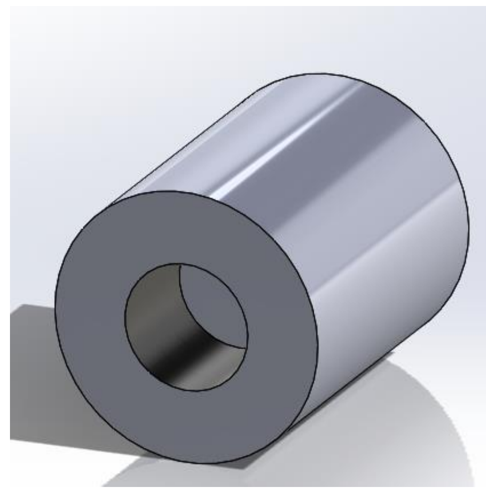

Figure 6 Piston CAD representation

1.6 Regenerator Cap, Motor Housing Cap & Solenoid Retainer

The solenoid retainer was created by turning down a piece of aluminum to a diameter that would fit inside the Motor Housing. The work was turned down to the appropriate diameter and was cut with a band saw (also in building 98c), with a thickness of approximately $\frac{1}{4}$". Finally, this piece was drilled into to supply a path for the solenoid plunger to travel linearly. The bore into this piece was started with a drill bit attached to the tail stock of the Lathe and finished with a boring tool (also attached to the tail stock of the Lathe).

The regenerator and motor housing cap are completed with a nearly identical procedure on the lathe, by turning down the stock and drilling the specified holes. The pressure sensor and compressor inlet valve will also be interfacing directly with the motor housing cap, meaning holes need to be drilled, followed by threading with a tap. The solenoid, regenerator cap and motor housing caps are provided in the manufacturing CAD images in Figures 7, 8 and 9.

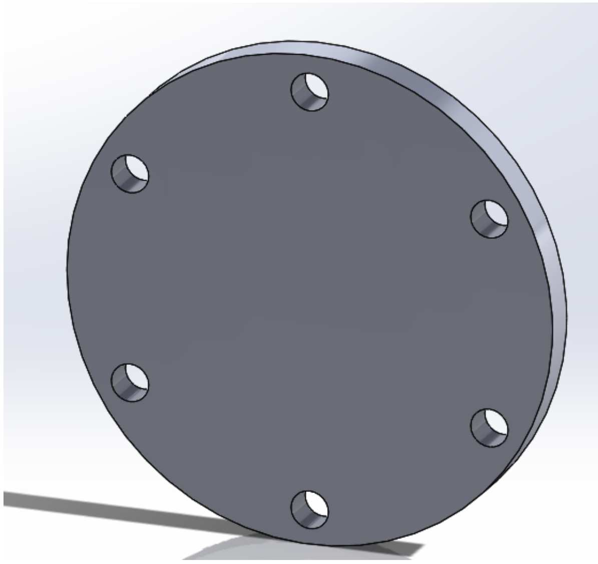

Figure 7 Regenerator Cap

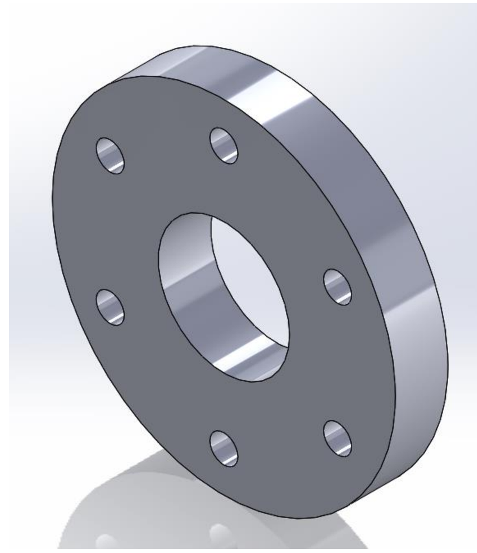

Figure 8 Solenoid Retainer

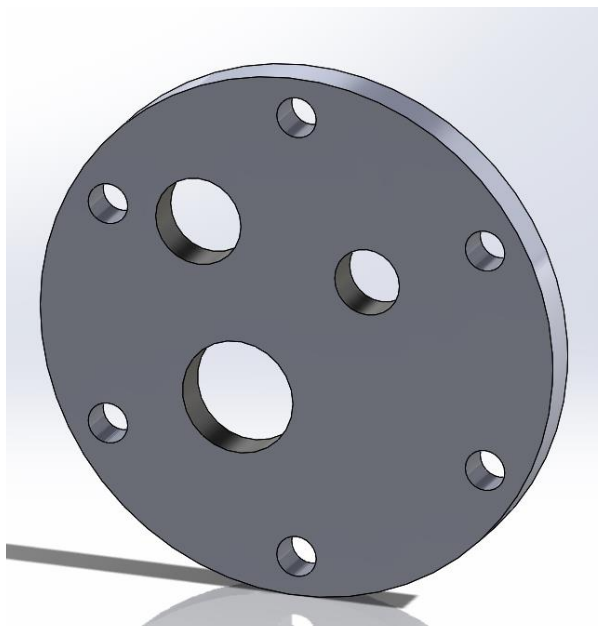

Figure 9 Motor Housing Cap

1.7 Motor Housing Cylinder

The motor housing was completed per Figure 10. The external turning was completed in the same way as the previous part. The internal turning (boring) was completed in the same manner as the *grand* cylinder was completed. The procedure using the drill chuck (attached to the tail stock) and eventually the boring tool, is necessary to prolong the life of the tools used and remove material as quickly as reasonable possible.

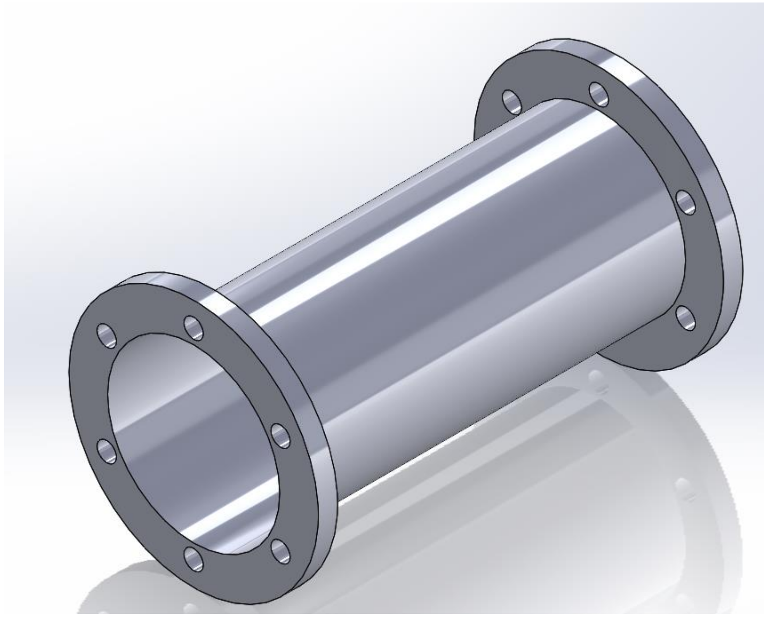

Figure 10 Motor Housing Cylinder

1.8 Wire Feed-Through Seal

In order to pressurize the entire vessel (i.e. the motor housing and *grander* cylinder), the motor wiring needs to penetrate the through the wall of the motor housing without any air/pressure dissipation. Hermetically sealed wire feedthroughs are sold and available commercially, but in this system, the seal created was modeled based on the configuration of commercial hermetic seals. Additionally, JB Weld was used in place of potting material to seal the wire feedthrough.

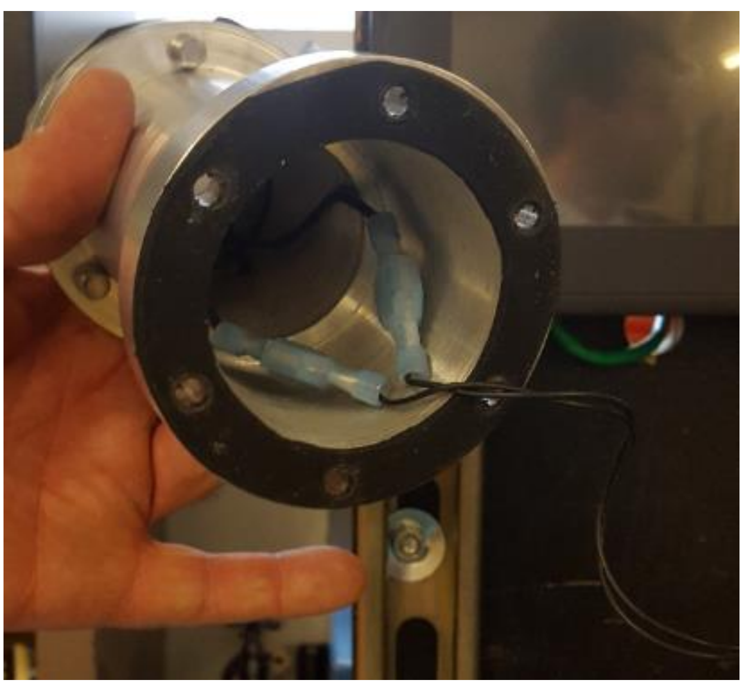

Figure 11 Interior Hermetic Seal Figure

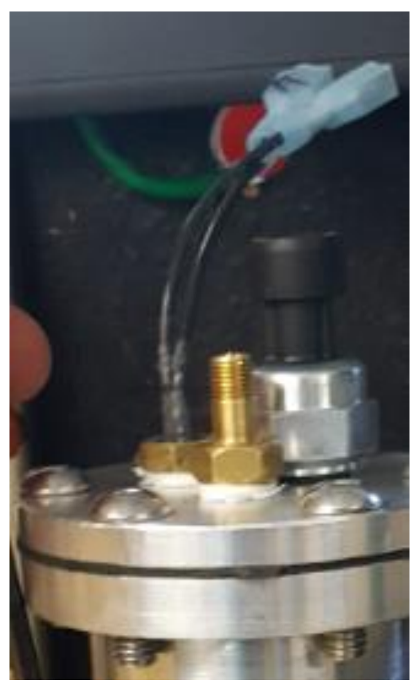

Figure 12 Exterior Hermetic Seal

1.9 Arduino Casing

The Arduino and its associated wiring was hidden and contained in repurposed electrical box. This electrical box was modified by cutting rectangles on the back of it, where the LCD displays would protrude. These rectangles were cut by programming & using a CNC machine. The final mounted Arduino case is shown below in Figure 13.

Figure 13 Arduino-LCD Casing

1.10 Cooler Space

The cooler space depicted in Figure X is required to allow for the cold head to protrude into the cooler. In order to achieve this, a CNC machine must be programmed and operated to cut a large hole in the side of the cooler space. This hole must supply ample clearance for the cold head to protrude into the cooling space.

2 Assembly

This section will explain how to assemble the final manufactured and purchased parts in the system. Additional considerations related to performance and programming are provided in detail in the Operation section on this manual.

2.1 Screws & Bolts

With respect to the Allen screws and bolts, an Allen wrench should be used to tighten and loosen as appropriate. In the case that one needs to adjust Allen screws that aren't conveniently accessible, one should use a ball end Allen wrench. Figure 14 shows the ball end Allen wrench in action.on the motor housing-inner cylinder flange screws.

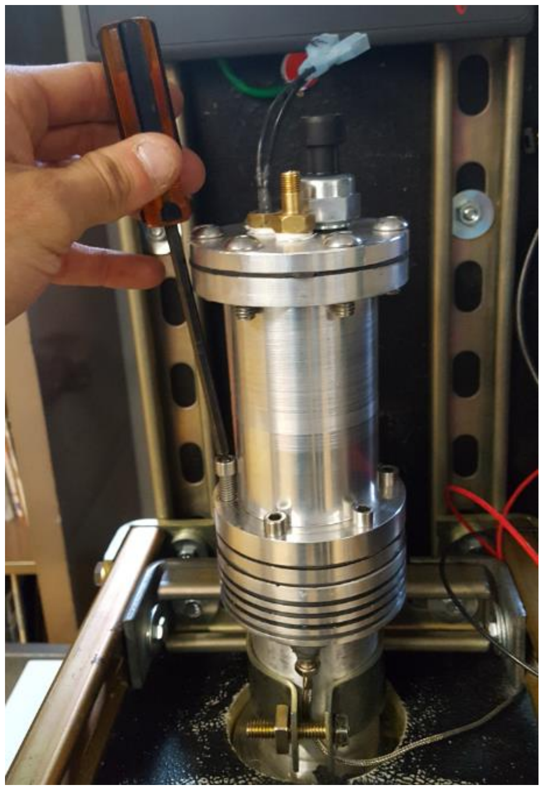

Figure 14 Ball end Allen wrench

2.2 External Framework and Structure

As can be inferred, the external framework, serving as the support and aesthetic for this final design, was constructed with wood from an old pair of cabinets as well as Unistrut. The Unistrut was bolted and screwed in a manner that allowed for the Stirling cooler to stand up straight.

Two short pieces of Unistrut were cut to fit onto the wooden framework in order to mount the Human Machine Interface (HMI), Stirling cooler and cooler space. The Stirling cooler was additionally supported by 3 more pieces of Unistrut as well as standard Unistrut braces (that physically held the Stirling cooler). The cooler space was attached to the two previously mentioned pieces of Unistrut by using screws bolts and washers. Four holes on each corner of the cooler space were drilled for these screws, where the cooler space was ultimately mounted. A drawer slide is repurposed to hold the power supply and I/O controller with more bolts and screws. Finally, 3 L-shaped Unistrut frameworks were constructed by using an L-shaped bracket on two pieces of Unistrut. Two of the three L-shaped Unistrut pieces are the same size while the last is slightly larger. In order to construct these

L-shaped Unistrut segments, the ends of all 6 pieces of Unistrut needed to be cut at a 45-degree angle to accommodate for bracket's need to bolt in. The two smaller pieces were responsible for supporting the two pieces of wood, to which the entire apparatus is mounted to. These pieces were mounted on the bottom and top of the two pieces of wood, in order to orient them at a 90-degree angle (with respect to one another). Finally, three rubber bumpers were attached at the bottom of the 3 corners of the larger L-shaped Unistrut to prevent any damage to furniture and tabletops. These were screwed into the Unistrut just the same as the other brackets and braces mentioned previously. The Unistrut on the front side of the apparatus is mostly visible in Figure 15, whereas the two smaller L-shaped Unistrut parts are located directly behind the two wooden panels (on the bottom and top of the panels).

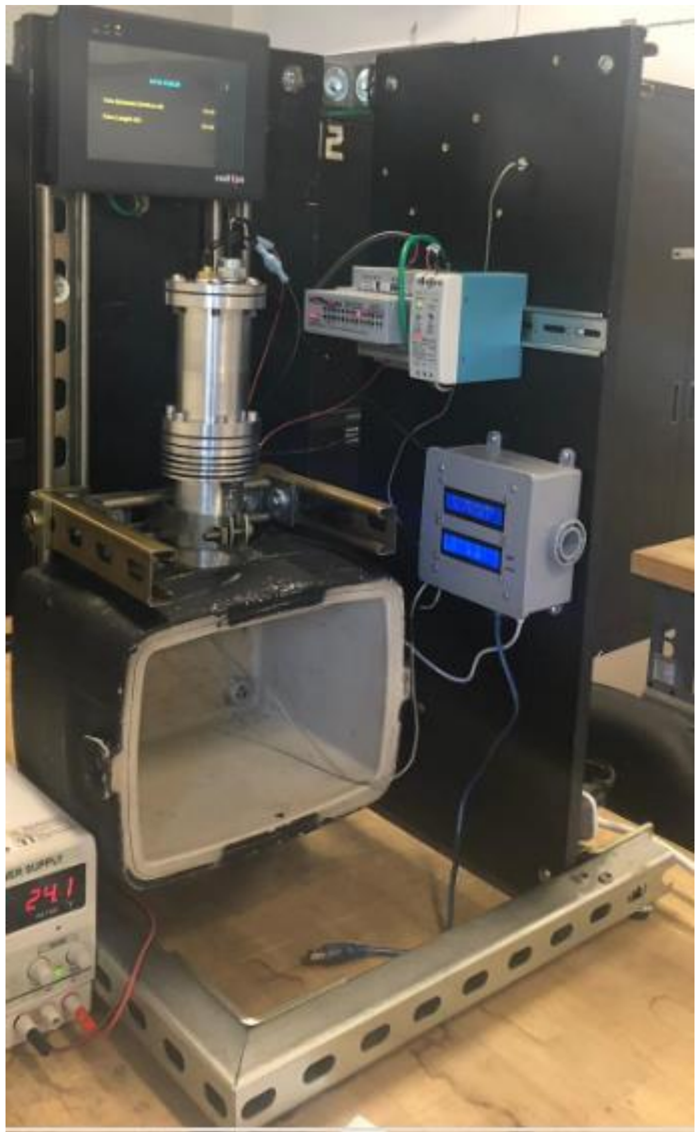

Figure 15 Final Assembly showing the Unistrut

2.3 Threaded Interfaces

The piston interfaces with both the solenoid's plunger shaft and the displacer shaft. Since both ends are constantly in tension and compression, Lock-tight is used to ensure rigid connections.

2.4 Magnet Interface

The shaft directly threaded to the piston is responsible for the motion of the displacer and by extension, air. Before proceeding any further, two cylindrical magnets were placed around the base of the shaft near the piston with one oriented on the same shaft in a manner that allowed for repulsion between the magnets. After sliding the shaft into the displacer cap, two pairs of magnets were put on the shaft (on the other side of the displacer cap), in a manner that facilitates repulsion. Figure 16 partially shows this configuration of magnets with respect to the piston and displacer. The internal pair of magnets closer to the end of the shaft is magnetically attached to a washer, which is screwed at the end of the shaft, where the accommodating internal threading is already present.

2.4.1 Adhesion Methodology

As just mentioned, the displacer cap is being retained by the magnet and/o washer assembly on either side of it. This displacer cap is "stuck" to the displacer shell by using electrical tape. Namely, electrical tape is stretched and wrapped (inside-out) around the smaller diameter portion of the displacer cap. This is subsequently squeezed into the displacer shell as seen in Figure 16 below.

Figure 17 Solenoid-Piston-Displacer Assembly with a visual of the disc magnets

2.4.2 Additional "Bounce-back" Material

Rubber gasket material is cut in the shape of an "O" and sized according to the magnets. This is then glued to one of the groups of magnets on either side of the displacer cap. These two circular cut rubber pieces were oriented on the magnets in a manner that would prevent the magnets from colliding into one another.

2.5 Gaskets

Four circular gaskets were cut to accommodate for 6 annular holes (per the regenerator cap, motor housing cap and inner cylinder flange. Each gasket is cut identically since each flange connection is identical. After some rough tracing with a pen a razor blade can be used to cut out the shape of the gaskets from rubber gasket material. Figure 11 (provided below for convenience) shows one of the four gaskets, while Figure 18 explicitly shows where each gasket is placed.

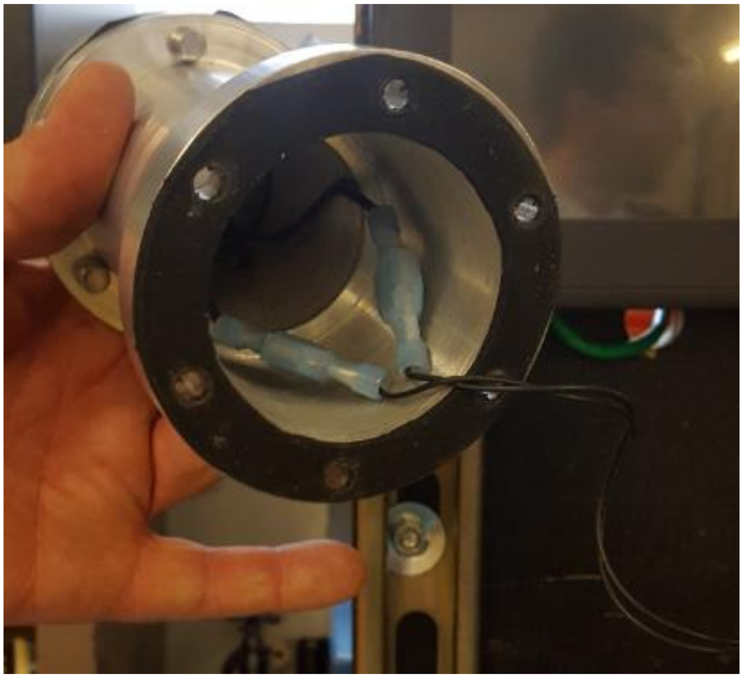

Figure 11 An example of a cut rubber gasket

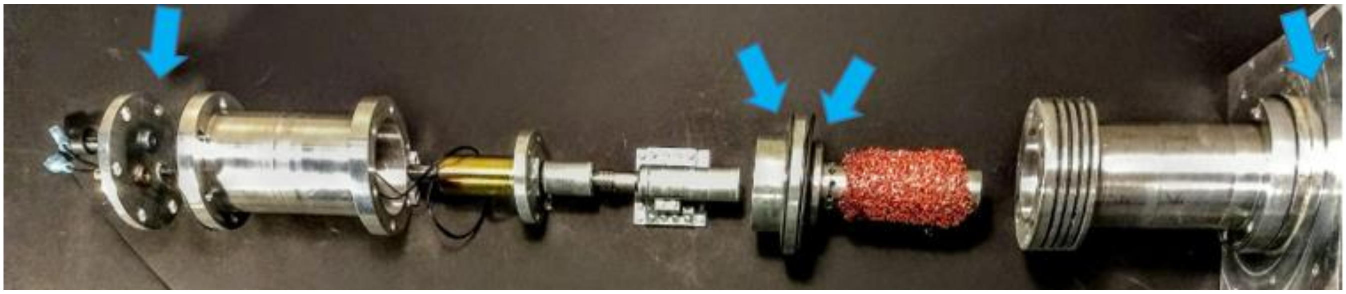

Figure 18 "Exploded View" of Stirling cooler with arrows pointing at gaskets

2.6 Inner-Grander Cylinder Interface

The inner-grander cylinder interface consists of a cut rubber gasket, an O-ring and Allen screws & bolts on the flange holes. The cut rubber gasket must first be oriented with the flange holes on the inner cylinder and the O-ring must be seated in the indentation along the base of the inner cylinder.

Before meshing the cylinders together with the correct orientation of the O-ring and rubber gasket, the regenerator material must be uniformly wrapped around the inner cylinder. The material used for the regenerator in this case is copper (wire mesh). Figure 18 above shows an acceptable distribution of copper mesh around the inner cylinder.

After completing these tasks, the cylinders are then meshed together, with some reluctance from the O-ring. One should be weary of the orientation of the copper wire while meshing the inner & grander cylinder together. One should be sure to have the copper mesh uniformly distributed along the length of the inner cylinder, even after putting together the inner and grander cylinder. Figures 19 & 20 show the inner and grander cylinder being constructed.

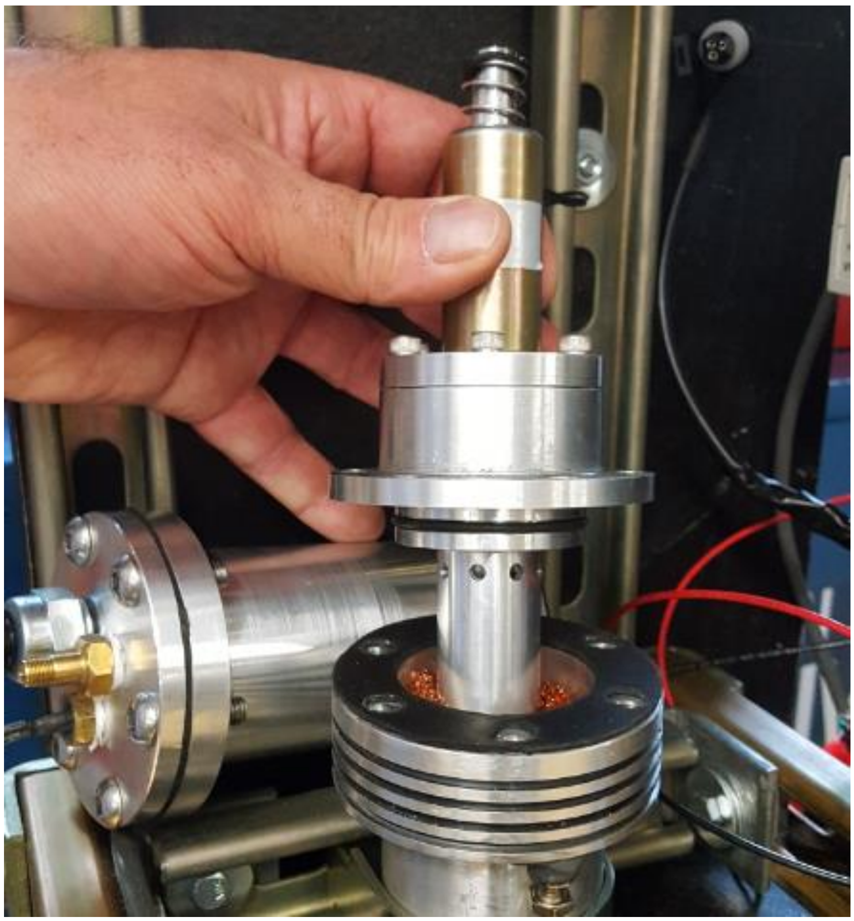

Figure 19 Inner-Grander Cylinder Interface with Flange screws removed

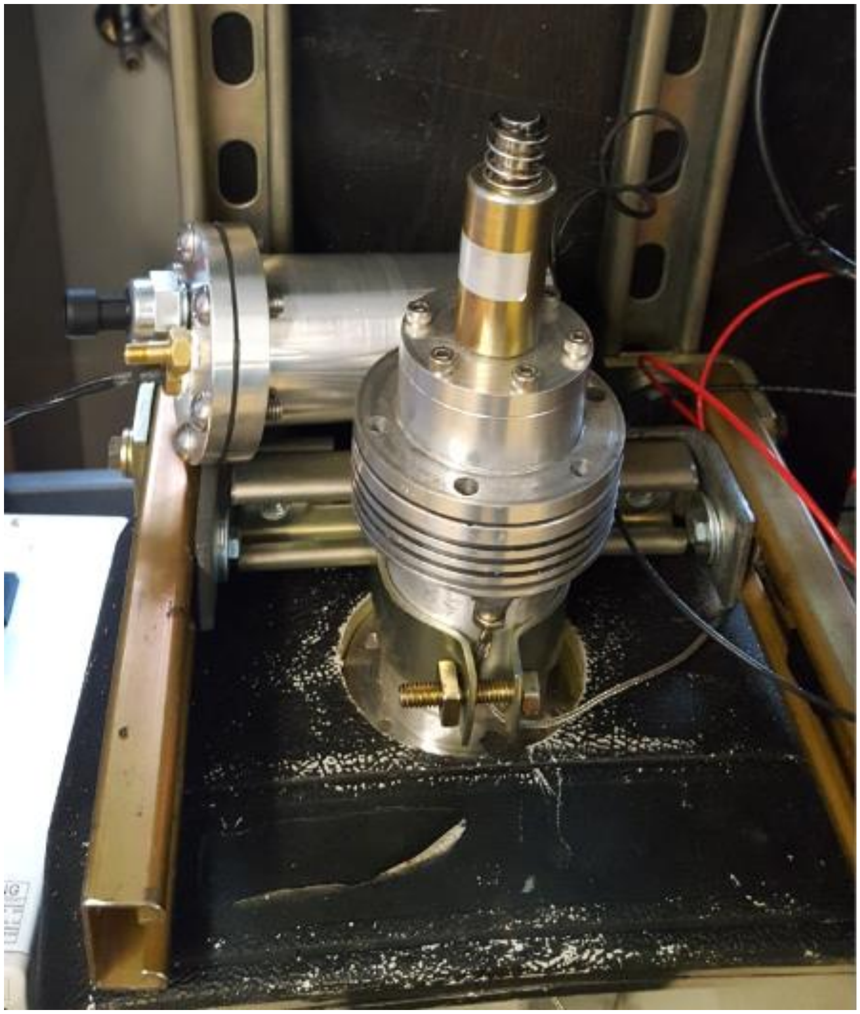

Figure 20 Inner-Grander Cylinder Deconstruction

2.7 Grander Cylinder

With the grander cylinder in place, the bottom portion needs to be sealed with the aforementioned regenerator cap. The regenerator cap, like the inner cylinder and motor housing cap, has 6 annular holes where bolts and Allen screws will be used to seal this end of the grander cylinder. Prior to screwing on the regenerator cap, be sure to orient a cut rubber gasket with the 6 holes to ensure the vessel stays sealed. Figure 18 above, shows the regenerator cap on the far-right side (with a blue arrow pointing at it).

2.8 Solenoid Retainer

The solenoid retainer is placed on the inside of the hexagonal nut attached to solenoid. This hexagonal nut can be removed and screwed on with an adjustable wrench. One should be careful to tighten this nut only when the orientation of the retainer is centered with the solenoid itself. Figure 21 shows the orientation of the hexagonal nut with respect to the solenoid and retainer.

Figure 21 Solenoid Retainer assembly

After mounting the retainer to the solenoid, it must be subsequently mounted to the inner cylinder. On the opposite side of the grander cylinder, the solenoid retainer is mounted/screwed into an inner flange. This is a critical procedure in the assembly of this apparatus because if not done correctly, the piston-displacer assembly will not be free to move due to misalignment of the shaft. One must initially only mount the retainer with two Allen screws on opposing sides of the retainer to check for alignment issues. Then one can continue to screw in the retainer to the inner cylinder. Figure 22 shows the Solenoid retainer being assembled with the inner cylinder.

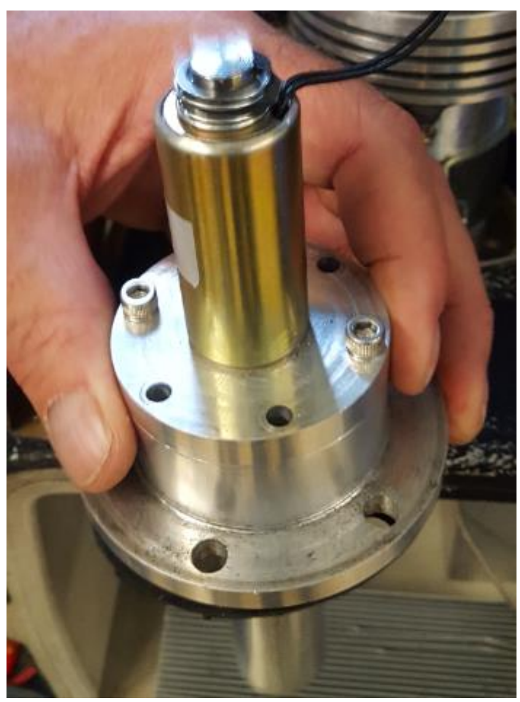

Figure 22 Solenoid Retainer alignments

2.9 Motor Housing

With the inner cylinder fully mounted to the solenoid, one can now mount the motor housing cylinder, seen in Figure 23. To do this, one must first orient the third cut rubber gasket with the holes on the inner cylinder flange (on the opposite side of the grander cylinder). Subsequently, one can fit the motor housing together with the inner cylinder flange. Again, be sure to align the gasket with the holes on the motor housing and inner cylinder flange. Finally, the motor housing cylinder is mounted to the inner cylinder by using screws and bolts to seal this connection.

2.9.1 Motor Housing Cap

Finally, to completely seal the pressure vessel, one must mount the motor housing cap at the open end of the motor housing cylinder. As previously mentioned, one must first orient the fourth and final cut rubber gasket to fit with the holes in the motor housing cap and the motor housing cylinder flange. Then one can align and bolt the motor housing to the motor housing cap. This cap has a preinstalled hermetic seal as well as two threaded holes for the pressure sensor and Schrader valve. The pressure sensor and Schrader valve are tightened into their respective holes only after applying lock tight to the external threads. Figure 23 shows the motor housing cylinder and its respective cap connected while disconnected from the rest of the assembly. Figure 24 shows the motor housing assembly completely connected to the remaining system.

Figure 23 Disconnected Motor Housing Assembly

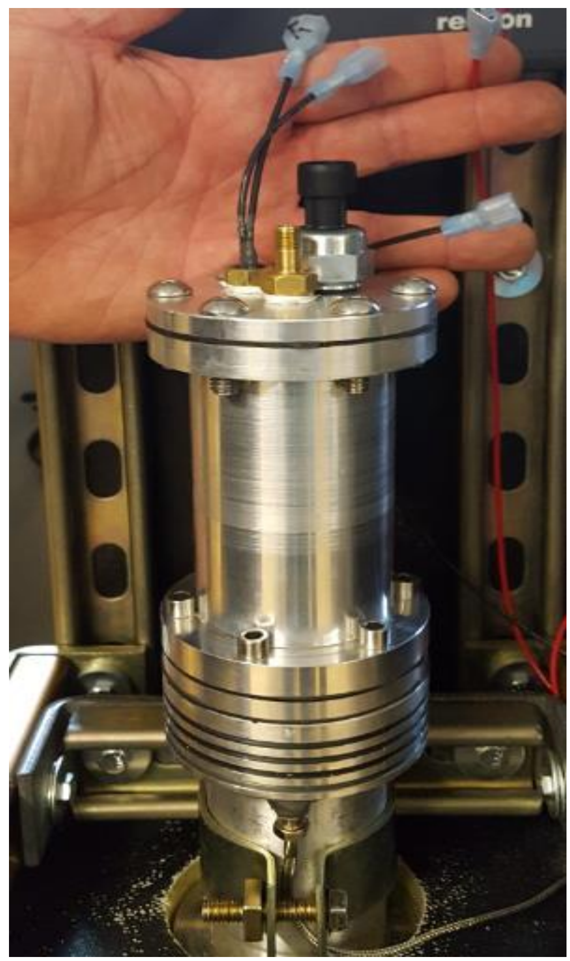

Figure 24 Completely Connected Motor Housing Assembly

2.10 Cooler Space

The cooler space has four holes inside it for screws to mount it to the Unistrut framework as well as one larger sized hole on its side for the cold head to installed. The cooler should be oriented in a manner that allows for the cold head to fit in the side of the cooler space (i.e. in the hole) while also ensuring that the four holes inside the cooler space are aligned with locations on the Unistrut that can be used to anchor the Cooler Space.

2.11 Arduino Implementation of the Pressure Sensor & Thermocouples

Two LCD displays, one pressure transducer and three thermocouples were controlled with the Arduino micro-controller. Three MAX6675 thermocouple break-out boards were used in this apparatus to measure the room temperature, the hot and cold side of the Stirling cooler. The LCD display is wired to show the pressure and temperature, in real time. The code that runs the pressure sensor, thermocouples & LCD displays is accounted for in Appendix B. The pressure sensor used in this design only requires 3 connections: 5-volt power, ground and an analog output connection. The analog output connection is fed directly into port A1 on the Arduino board, per the aforementioned code in Appendix B. The power and ground connections were fed into a miniature breadboard, in correspondence with wires that were connected to the ground and 5-volt power ports on the Arduino board. The MAX6675 thermocouples were mounted on the Arduino casing, where their breakout-board's protruding connections were connected to the ports specified in Table 1 below. The connections labeled GND and VCC correspond to ground and 5-volt ports on the Arduino, which was circumvented with a breadboard earlier. Figure 13 (shown below for convenience) shows how the LCD displays are oriented in the final design as well as the Arduino casing that prevents wiring from being altered unintentionally.

Table 1 Arduino Port Numbers for the Thermocouples

Break-out Board Connection	**Thermocouples**		
	Ambient	Heat Sink	Cold Head
SCK	40	46	50
CS	41	47	51
SO	42	48	52

Figure 13 Arduino-LCD Casing

With respect to the LCD displays, they were wired in a similar fashion, with only 6 unique connections per display. Figure 26 shows how the wiring for both LCD displays is connected. Each wire in the figure has letters and/or numbers associated with the functionality of the display connection. These connections are tabulated in Table 2, where the Arduino port numbers are specified.

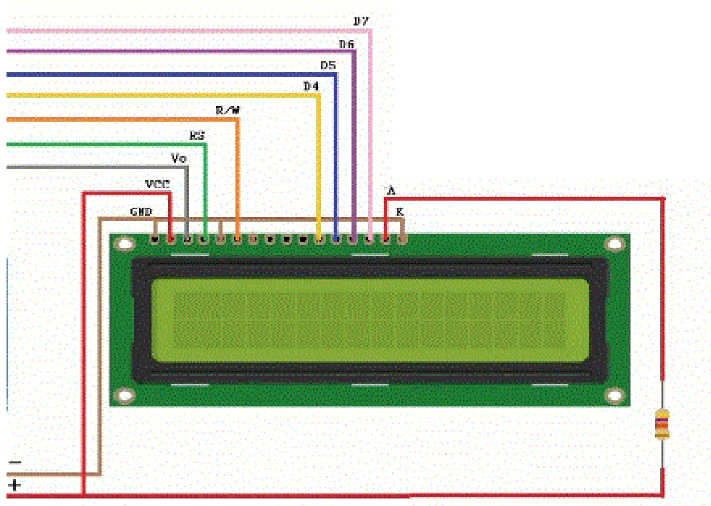

Figure 25 LCD Display Wiring Schematic

Table 2 LCD-Arduino Wiring

LCD Connection	**Display #1**	**Display #2**
GND	Ground	Ground
VCC	5 V	5 V
V_0	Digital 6	Digital 7
RS	26	12
R/W	Ground	Ground
D4	28	22
D5	29	23
D6	30	24
D7	31	35
A	9	8
K	Ground	Ground

The thermocouples used in this apparatus are threaded and as such, were exploited to be mounted onto the cooler in reasonable locations (i.e. the hot & cold head). Namely, appropriately sized bolts were used to mount the thermocouples on the bottom side of the heat sink & cold head. The thermocouple responsible for measuring ambient temperature is drilled into the wooden board serving as the infrastructure for the apparatus. The bolts were attached to the hot and cold head with thermal paste as well as JB Weld.

2.12 Motor Control

The solenoid in this system is controlled with a Sixnet RTU/PLC and a Red Lion HMI, both of which are slightly damaged. The HMI is damaged in the way that it cannot be pinged (because of damaged network functionalities) and must be worked with serially or with other methods.

Crimson software is used for programming the HMI in this cooler. Programming and integration of the Sixnet PLC was completed with I/O Toolkit and Isagraf 3.47. Something to note is that the HMI is programmed to exchange data with the Sixnet PLC with Modbus TCP/IP protocol.While Isagraf and Sixnet support all IEEE programming languages (Ladder Logic, Structured Text, Function Block Diagram, etc), FBD was used in this case. Figure 13 shows the Function block diagram.

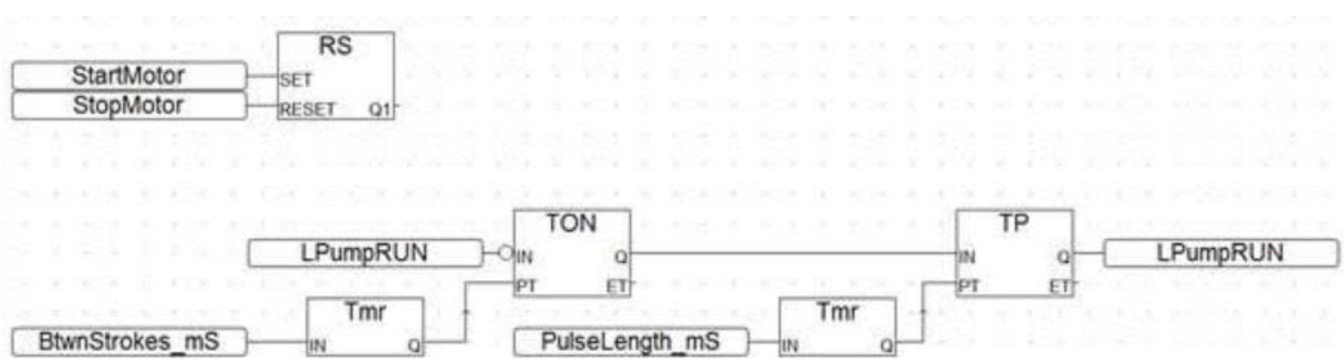

Figure 26 Function block diagram

The RS block output was connected to LPumpRUN during some preliminary testing of the electronics, but the variable was later removed from the RS function block output.

With respect to the rest of the FBD in Figure 13 The Tmr function blocks (FB) convert the values of the BtwnStrokes_ms & PulseLength_ms integer variables to time variables (ms). These values are subsequently used as inputs to the TON ("time on") and TP ("pulse timer") function blocks. It should be noted that the circle next to the TON input indicates negation. The implication of this is that when LPumpRUN is False, the TON timer is started which represents the portion of the characteristic "period" when the motor is not being delivered power. After the TON timer reaches its user-specified "wait time", the output of the TON function block, the input of the TP function block (LPumpRUN), and the output to the TP function block become TRUE. Once the TP function block's timer elapses, the value of LPumpRUN goes FALSE and the TON function block starts the cycle over again. The amount of time elapsed between wait times, specified by the PulseLength_ms variable, is representative of the time when a 24 Volt DC pulse is delivered to the linear motor. The HMI and PLC (programmable logic control) units are captured in Figure 14

3 Operation

3.1 HMI Interface

The HMI, located on one of the wood panels, should have two setting being displayed: pulse length & time between strokes. The pulse length refers to the amount of time the motor is being delivered power, while the time between strokes refers to the amount of time the motor is not delivered power. The sum of these two numbers is equal to the period (T), which is also related to the frequency. Equations 3, 4 & 5 show how duty cycle (D_c) and frequency (f) can be determined.

$$T = [Pulse\ Length] + [Time\ Between\ Strokes] \quad (3)$$

$$f = \frac{1}{T} \quad (4)$$

$$D_c = \frac{[Pulse\ Length]}{T} \quad (5)$$

The pulse length & time between strokes settings were set to 15 and 25 milliseconds respectively during the final testing proof for this apparatus, which is associated with a functional system. Different frequencies and duty cycles can be specified if desired.

It should be noted that most commercial Stirling coolers operate around 70 Hertz @ a 50% duty cycle.

3.2 Compressing the System

This section will explain the procedure for compressing the pressure vessel.

3.2.1 Pressure Specification & Implication

The pressure should be raised to a pressure of approximately one megapascal to match the operating conditions of the cooler during the final testing proof. Typically, greater pressure within the vessel implicates more heat transfer, but not necessarily higher coefficients of performance. The pressure can be adjusted by using a compressor with an attachment compatible with a Schrader valve. By using the compressor and the pressure being displayed on the LCD, one can adjust the pressure within the vessel as needed/desired. It should be noted that some time should be given for the vessel to equilibrate before one finished compressing. The pressure will decrease slightly after initially compressing due to the design of the solenoid retainer.

3.3 Arduino Temperature and Pressure Results

With respect to data collection, one can perform data analysis on the system with the temperature and pressure data. The provided code (in Appendix G) allows for the temperatures and pressures to be printed onto the serial monitor in the Arduino IDE platform. If one wants to perform analysis data collected during operation, one only needs to open the serial monitor with the Arduino connected to the computer. Once one is done collecting data during the Stirling cooler's operation, the data can be copied and pasted into Excel. Since this data that was just copied is already in tab delimited format, one can use Excel's built-in "Text to Columns" function to correctly format the data.

4 Maintenance & Troubleshooting

4.1 Motor Control

4.1.1 Replacing the Motor used

One can replace the motor in this design by only changing the solenoid retainer to one that accommodates the shape of the new motor. Assuming the motor fits within the motor housing, the same methodology for installing the solenoid can be followed to install a different motor.

The hole for the solenoid plunger may need to be adjusted for a different motor. In order to complete this, one can either use a drill press, or a lathe. Either way, one must elect the correct sized drill bit according to the size of the plunger associated with the new motor.

4.2 Regenerator Material

Regenerator material is a characteristic of this system that can be manipulated, changed and/or replaced if need be (or desired). Section 2.6 above describes how the regenerator is installed within the system. The same methodology should be followed when attempting to change the material being used. Additionally, it is important to make sure that there isn't so much regenerator material that it is impeding the flow within the vessel significantly.

4.3 Replacing Thermocouples & the Pressure Sensor

If one wanted to replace the thermocouples in this design, one only needs to unscrew the three mounted thermocouple break-out boars as well as the threaded thermocouple junctions in the bolts and wood panel. The thermocouple junction can be removed by using an adjustable wrench, which can also be used to install the new MAX6675 thermocouple head and break-out board. The pressure sensor can be replaced by unscrewing the transducer from the motor housing cap and unplugging the wire connectors from the Arduino. In order to disconnect the wiring from the Arduino, the Arduino casing must be unscrewed and carefully removed (without unplugging any wires). The housing can then be remounted

4.4 Pressure Leaks

In the case of a pressure leak, indicated by the pressure sensor, one can troubleshoot the leaks by virtue of a spray bottle. The gaskets between the regenerator cap & the grander cylinder, the inner & grander cylinder, the inner & motor housing cylinder and the motor cap & cylinder should be sprayed and observed individually. If any bubbles come to fruition, one can conclude closest gasket is not uniformly bolted down, in which one should tighten the Allen screws around the region of bubbles. This methodology can be repeated for any bubbles that arise from any gasket in the apparatus.

In the case that tightening the flanges around the gaskets doesn't work, replacing the gasket in question is the next step to fixing your Stirling cooler. The gasket manufacturing plan was outlined in section 2.5 and can be repeated for replacement gaskets.

4.5 Solenoid Won't Actuate

4.5.1 Solenoid Retainer Alignment

If the solenoid is turned on but is not actuating, chances are the solenoid retainer isn't tightened uniformly across all 6 bolts, or all 6 bolts weren't sufficiently tight f to or a rigid connection. In either case, take apart the apparatus down to the retainer and put the retainer back on by only screwing in two screws (like in Figure 22). Turn on the cooler and observe whether or not the piston-displacer assembly is moving freely, without binding to the inner cylinder (due misalignment). If it isn't moving freely, tighten one of the screws more to apply equivalent force on either of the threads within each hole.

4.5.2 Displacer Shell lubrication

In order to decrease friction between the inner cylinder and displacer shell, graphite can be applied to the outside of the shell.

4.6 Loud Knocking Noise coming from the Cooler

In the event that the cooler is making a loud knocking noise, there is probably only one solution but there are several scenarios that could lead up to this problem. As such, this manual will provide multiple solutions.

The first of which is that the motor is receiving too much power and is not able to sustain such high loads, let alone perform as expected. In other words, make sure to only deliver an amount of power that is less than or equal to the rated power for the motor. In this cooler, the solenoid is rated for 24-volts which is easily targeted by the DC power supply.

The second possible explanation is that the piston, piston-displacer shaft, or solenoid-piston shaft, disconnected during operation due to high speeds and forces. In order to find out one must deconstruct the cooler vessel to investigate the rigidity of connections. A possible solution to this would be to reapply Lock-tight to the threads and to retighten any of the aforementioned threaded connections. Another possible explanation would be that some (or all) of the magnets shattered within the vessel, preventing the magnets from absorbing some of the load. This case requires a deconstruction of the piston-displacer interface. If this turns out to be true, promptly replace the batteries and follow section 2.4 for specific instructions on the orientation of magnets.

APPENDIX A: BILL OF MATERIALS

PART #	PART NAME	QTY.	DESCRIPTION	MATERIAL	COST/UNIT($)	SOURCE	ACTUAL COST ($)
9	Black Laminated Wood Shelving	2	Used To Support Instrumentation	Laminated Particleboard	9.98	HomeDepot	19.96
10	2-Hole 90 degree angle bracket	10	Used To Join Unistrut Frame	Steel	14.10	HomeDepot	14.1
11	UniStrut Spring Nuts	5	5 pc/unit Springnut for joining Unistrut	Steel	5.00	HomeDepot	25.00
12	Unistrut Bracing	1	Structural Frame for Display Mounting	Steel	15.00	HomeDepot	15.00
13	Bolts	50	Box of 1/4" x 1" coarse thread	Steel	15.00	HomeDepot	15.00
14	Pull Push Type Linear Motion Solenoid Electromagnet	2	uxcell XRN-25x50TL DC 24V 0.7A 17W 20N 10mm	Steel	19.97	Amazon	39.94
15	Aluminum Material for fabrication	4	3-1/2" x 8" solid aluminum stock	Aluminum	38.89	Stoner Metal	155.56
16	SAE Flat washers	100	#10	Zinc	2.49	HomCo	2.49
17	SAE Flat washers	100	3/16" X 3/4" Fender Washers	Zinc	3.50	HomCo	3.5
18	Phillips Pan Machine Screws	100	10-32 X 1" Fine Thread	Zinc	5.49	HomCo	5.49
19	Phillips Pan Machine Screws	100	10-32 X 1-1/4" Fine Thread	Zinc	5.49	HomCo	5.49
20	Nylon Insert Hex Lock Nuts	100	Oct-32	Zinc/Nylon	7.99	HomCo	7.99
21	Coarse Hex Nuts	100	1/4"-20	Zinc	3.19	HomCo	3.19
22	Pressure Transducer	1	1.2 Mpa 1/4" 5v	Misc. Electronics	17.99	Amazon	17.99
23	Copper mesh for regenerator material	1	Copper Mesh	Copper	6.99	Amazon	6.99
24	Neodymium Magnets	10	1/2" X 3/8" X 1/8" Ni coated	Neodymium	8.99	Apex Mag.	8.99
	Rubber Gasket Material	4	1/16" X 6" X 6"	Rubber	0.79	HomCo	3.16
25	Aluminum Heatsink	4	150 X 69 X 37 mm	Aluminum	18.37	Amazon	97.44
26	40 W, Single Output, 24 V @1.7A AC-DC Power Supply	1	Mean Well MDR-40-24	Plastic Case/Electronics	17.10	On-line	0
27	Touch Screen, KADET 2, Model G307K2	1	RedLion Human Machine Interface (HMI)	Touchscreen/Electronics	833.40	redLion	0
28	BMXCPS2000 Modicon X80 PowerSupply	1	Power Supply for Process Logic Control (PLC)	Plastic Case/Electronics	140.71	Ebay	0
29	BMX-P34-100 Processor Module	1	Schneider Elect. Main PLC motor controller	Plastic Case/Electronics	878.00	Ebay	0
30	4-Slot Backplane	1	Schneider Elect. BMXXBP0400	Stainless/Electronics	211.00	Ebay	0
31	DIN Rail	1	Small Lengths approx. (2Feet)	Stainless	6.55	Ebay	0
32	DIN Rail Terminal Block,	5	30 A/ 600V 30-10 AWG terminal block	Plastic	2.50	On-line	0
3	Module + K Type Thermocouple Temperature Sensor	4	Arduino Thermocouple Sensors	Steel Braided	6.99	Amazon	27.96
						Total Cost =	475.24

APPENDIX B: ARDUINO CODE

```
#include <LiquidCrystal.h>
#include "max6675.h"
//thermocouple 1
int ktcSO = 40;
int ktcCS = 41;
int ktcCLK = 42;
//thermocouple 2
int ktcSO2 = 46;
int ktcCS2 = 47;
int ktcCLK2 = 48;
//thermocouple 3
int ktcSO3 = 50;
int ktcCS3 = 51;
int ktcCLK3 = 52;

MAX6675 ktc1(ktcCLK, ktcCS, ktcSO);
MAX6675 ktc2(ktcCLK2, ktcCS2, ktcSO2);
MAX6675 ktc3(ktcCLK3, ktcCS3, ktcSO3);
LiquidCrystal lcd(26, 27, 28, 29, 30, 31);
LiquidCrystal lcd2(12, 11, 22, 23, 24, 25);

void setup(){
  lcd.begin(16,2);
  lcd2.begin(16,2);

  analogWrite(6,57);  //lcd (these are here in place of potentiometers)
  analogWrite(7,87);  //lcd2
  analogWrite(9,35);  //lcd
  analogWrite(8,65);  //lcd2

  Serial.begin(9600);
  delay(500);
}
void loop(){
  int sensorvalue = analogRead(1);
  float voltage = sensorvalue*5/1024; //5 Volts for every 1023 bits
  float kPa = voltage*3 + 80.15582; //pressure calibration equation
  lcd.setCursor(1,0);
  lcd.print("P =  ");
  lcd.setCursor(5,0);
  lcd.print(kPa);
  lcd.print(" kPa");
  lcd.setCursor(1,1);
  lcd.print("T1 = ");
  lcd.setCursor(6,1);
  lcd.print(ktc1.readCelsius());
  lcd.print(" C");
  lcd2.setCursor(1,0);
  lcd2.print("T2 = ");
  lcd2.setCursor(6,0);
  lcd2.print(ktc2.readCelsius());
  lcd2.print(" C");
  lcd2.setCursor(1,1);
  lcd2.print("T3 = ");
  lcd2.setCursor(6,1);
  lcd2.print(ktc3.readCelsius());
  lcd2.print(" C");
  Serial.print(ktc1.readCelsius());
  Serial.print("  ");
  Serial.print(ktc2.readCelsius());
  Serial.print("  ");
  Serial.print(ktc3.readCelsius());
  Serial.println("");
  delay(2500);
}
```

APPENDIX C: COMPUTER AIDED DESIGN IMAGES

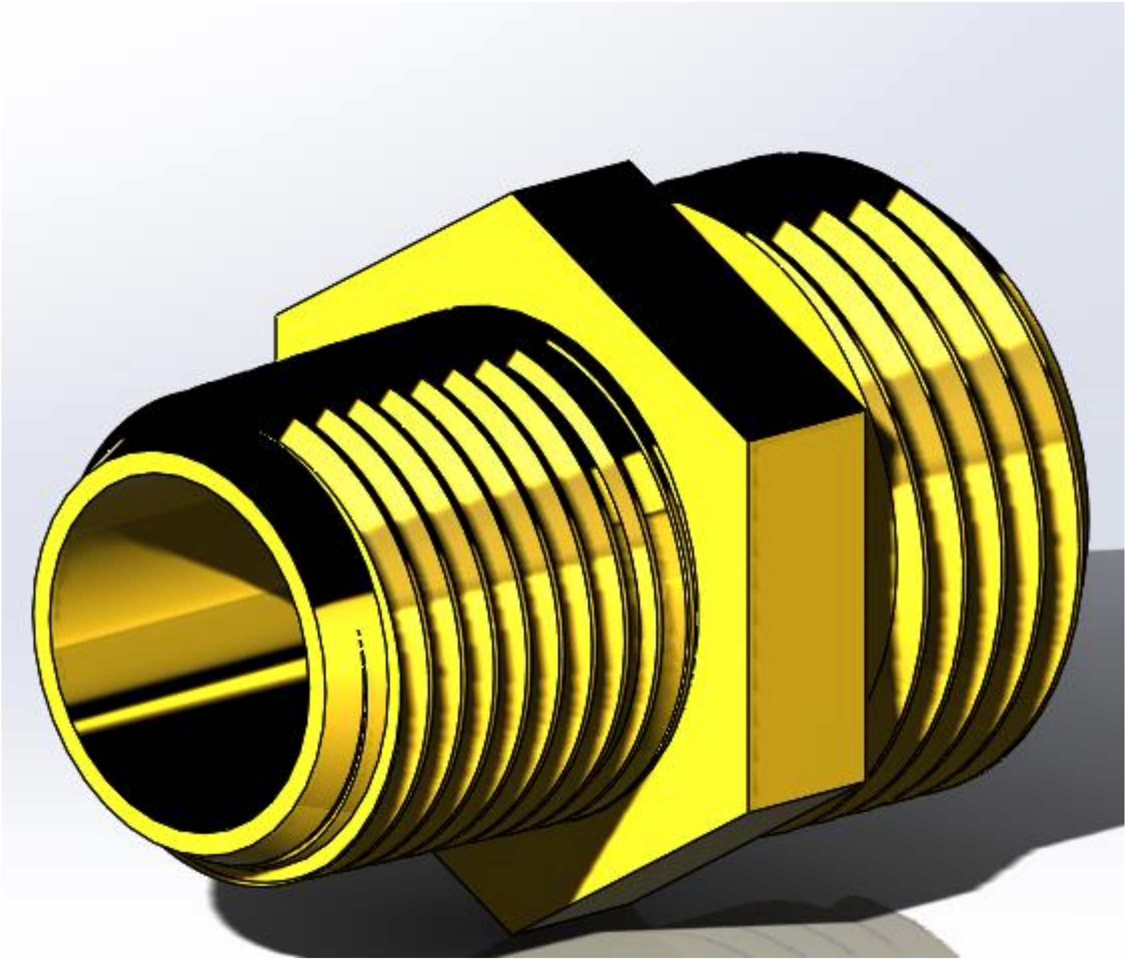

Figure 27 Hermetic Seal

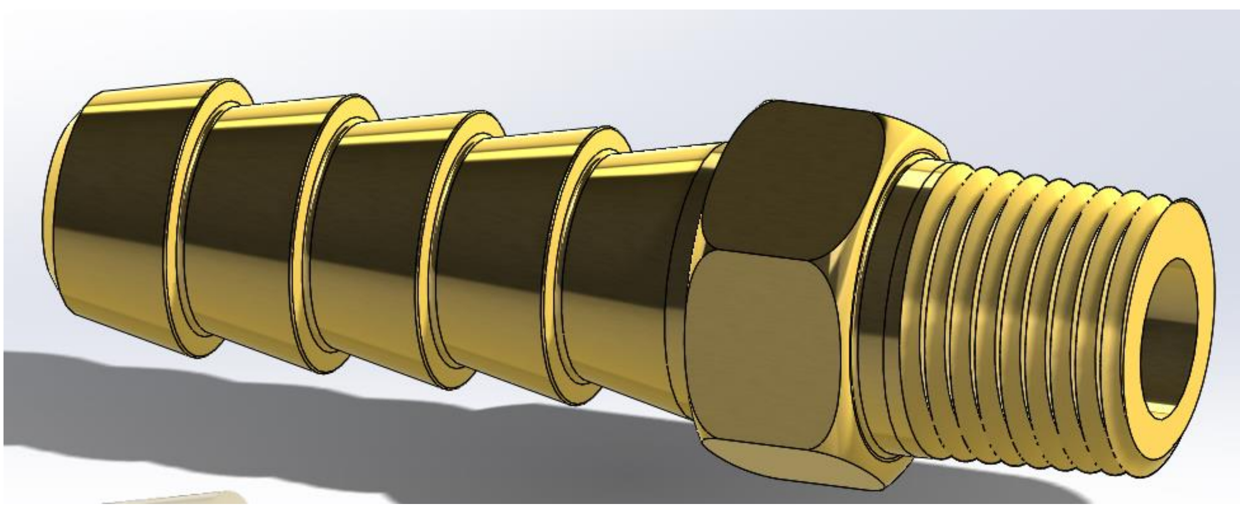

Figure 28 Schrader Valve

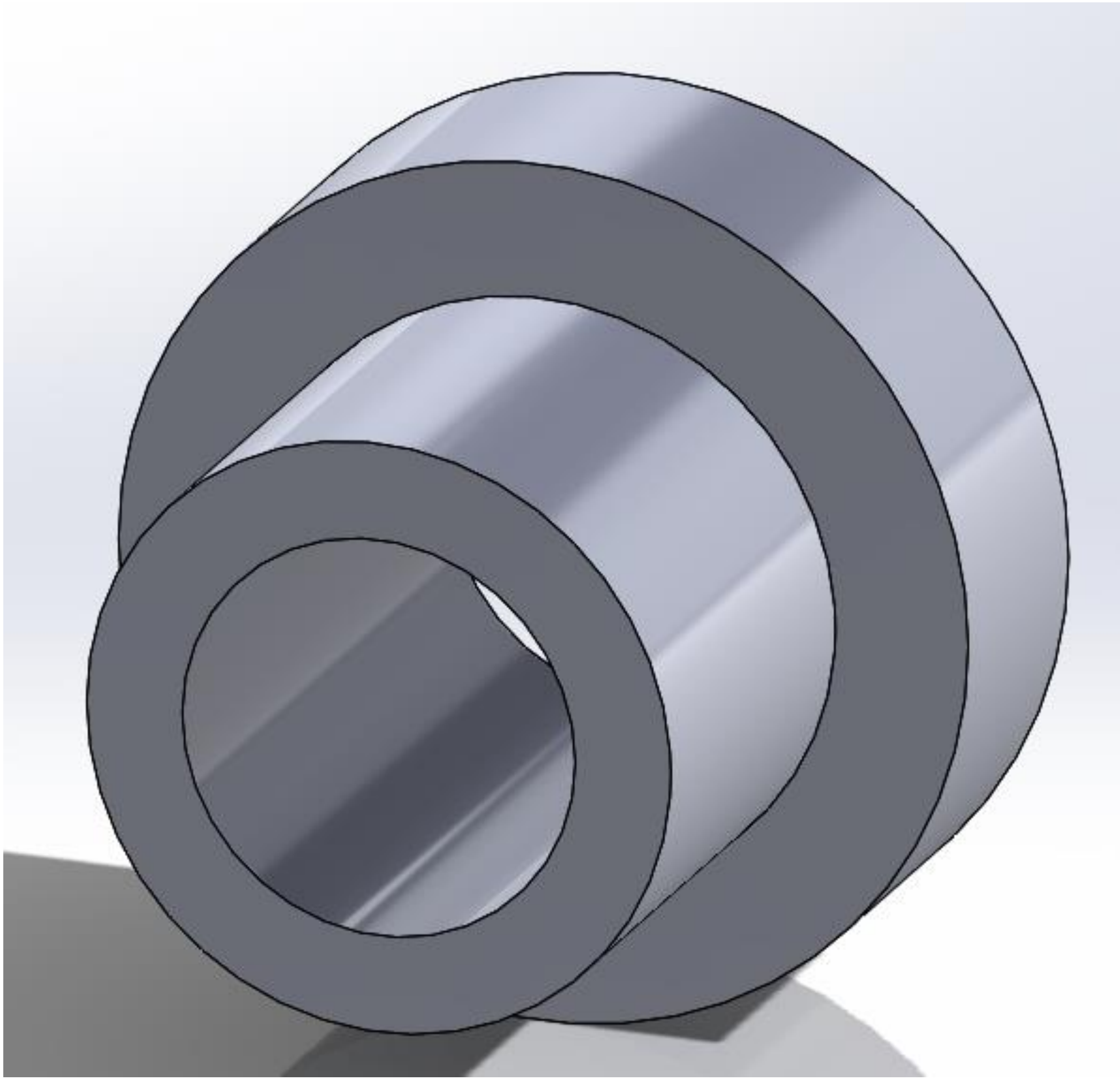

Figure 29 Displacer shell cap

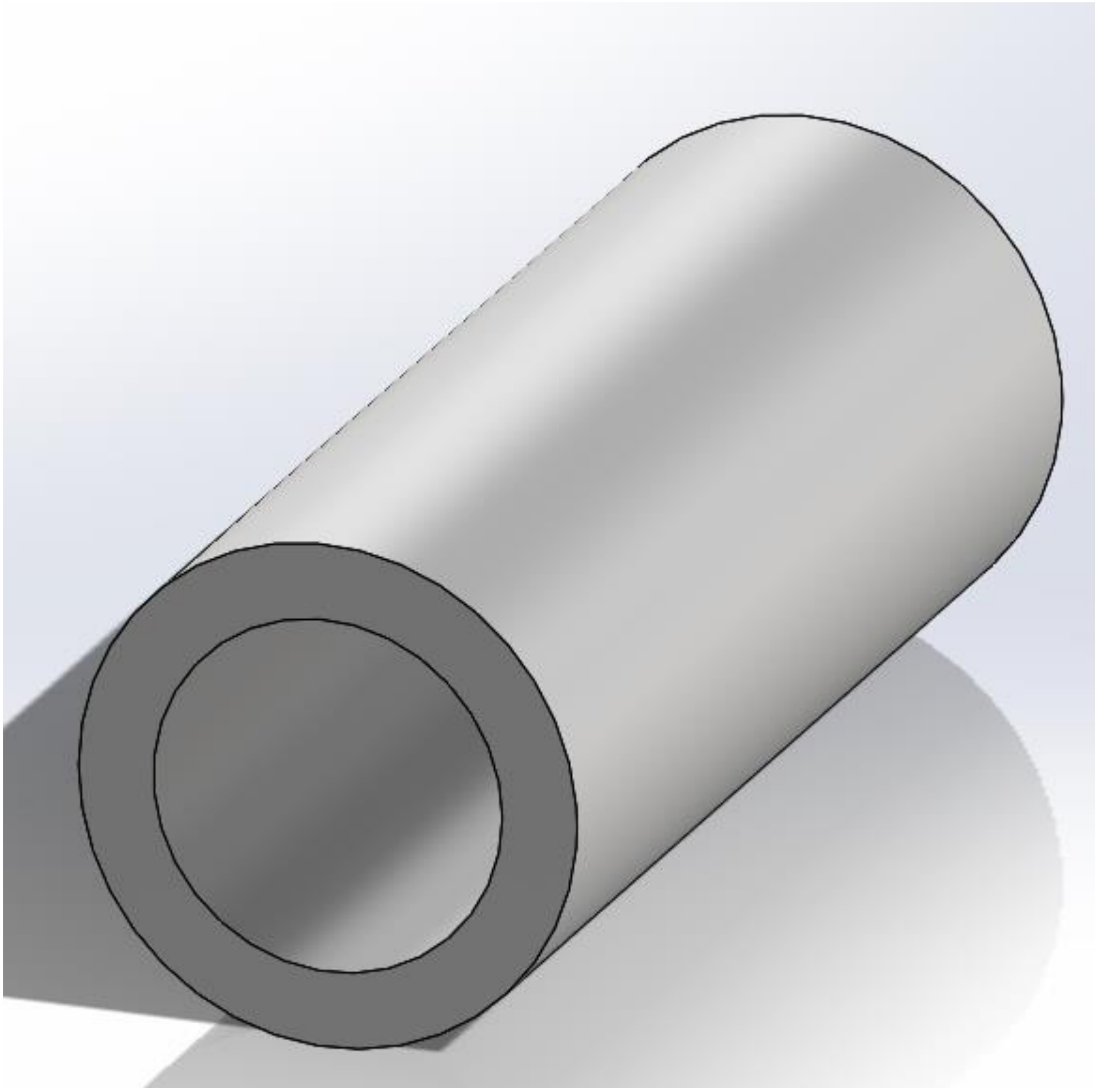

Figure 30 Displacer Shell

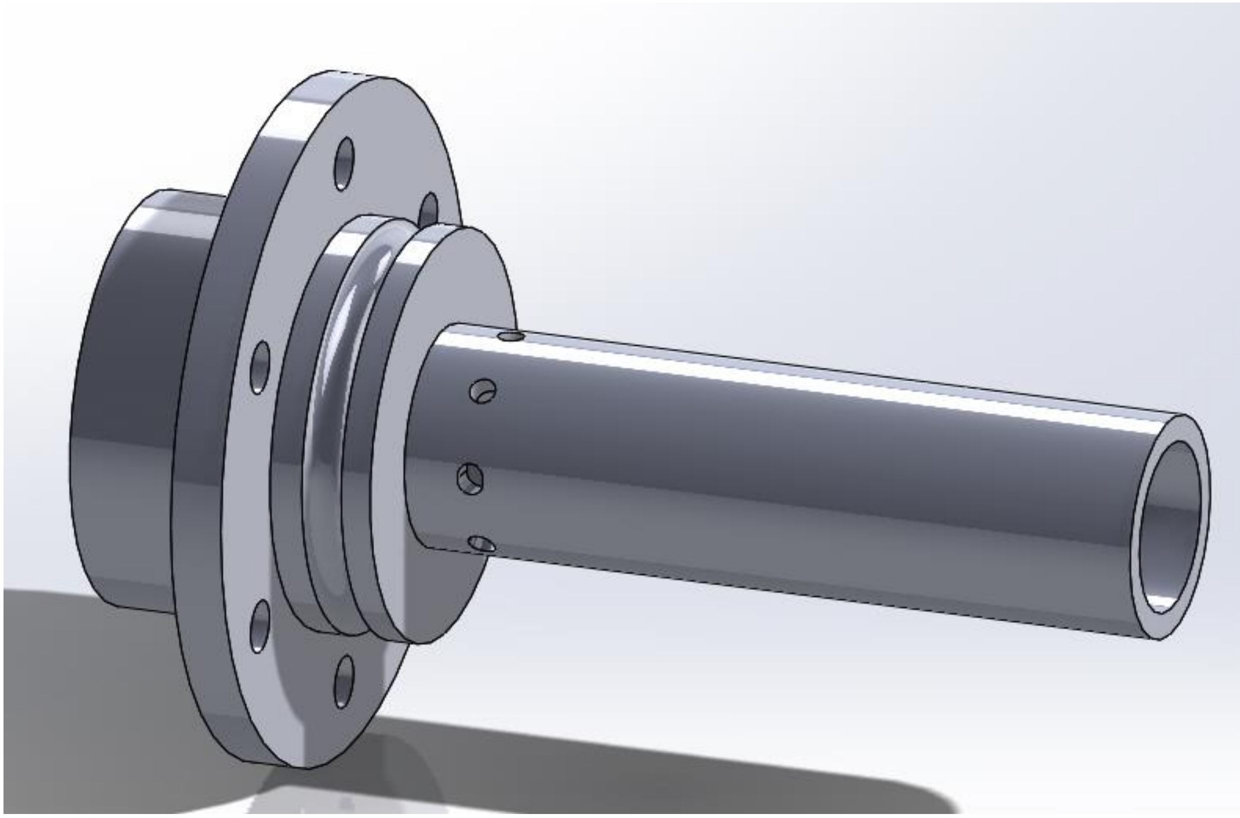

Figure 316 Inner Cylinder

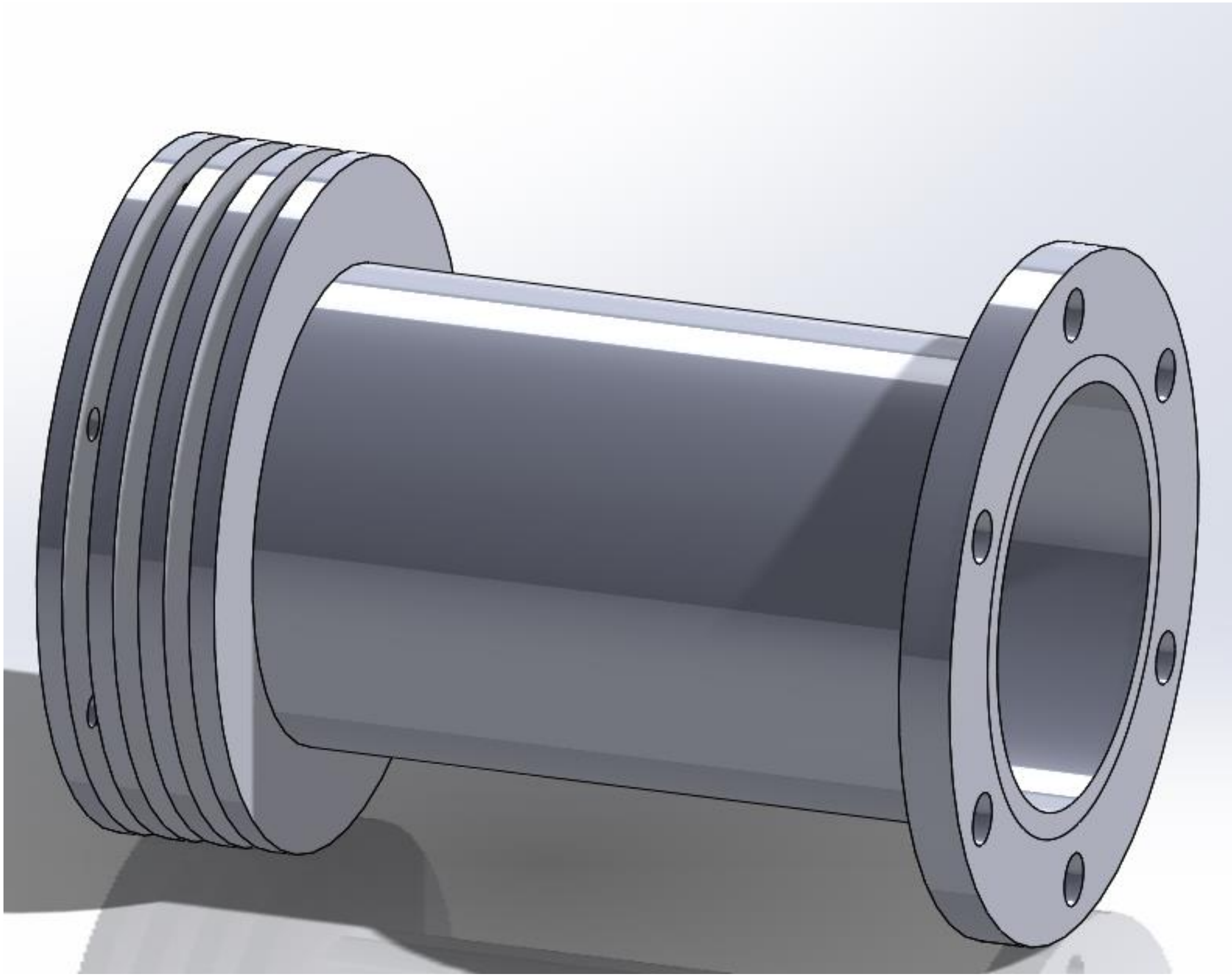

Figure 32 Grander Cylinder

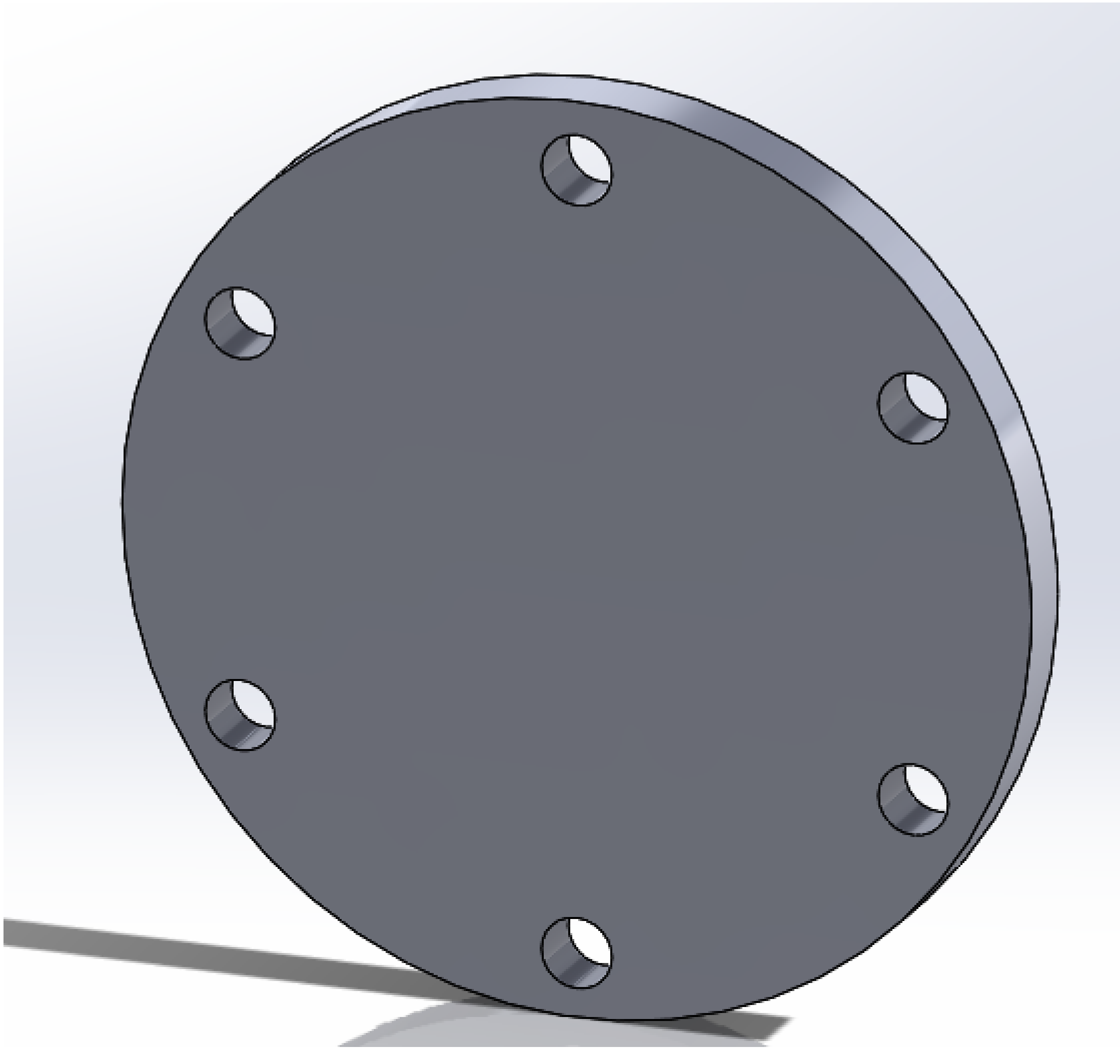

Figure 33 Regenerator Cap

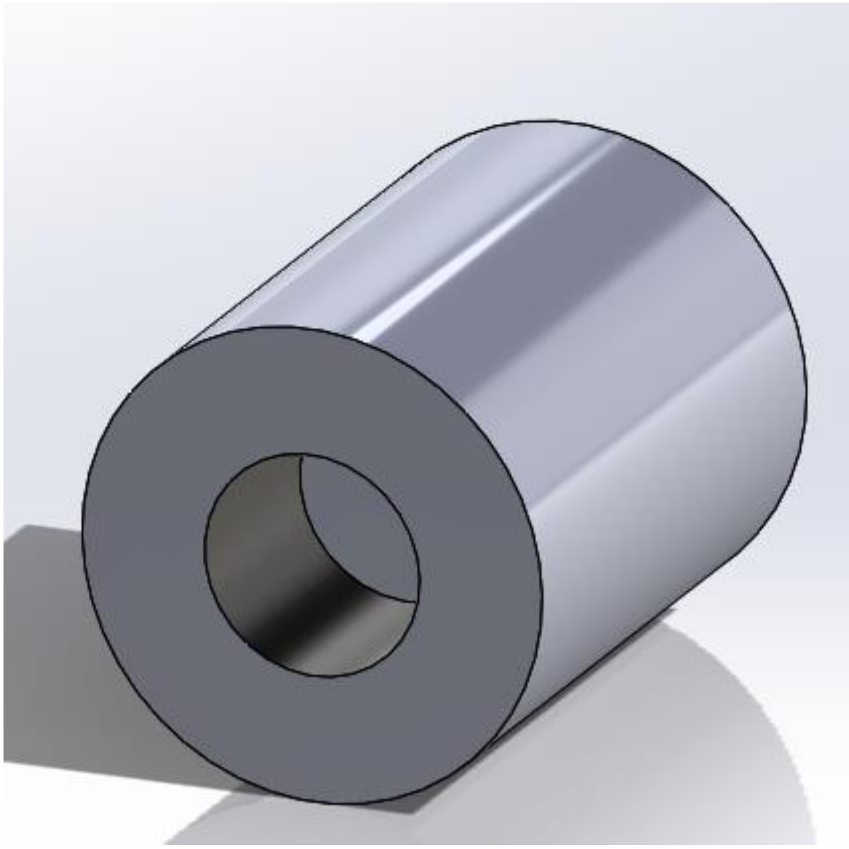

Figure 34 Piston

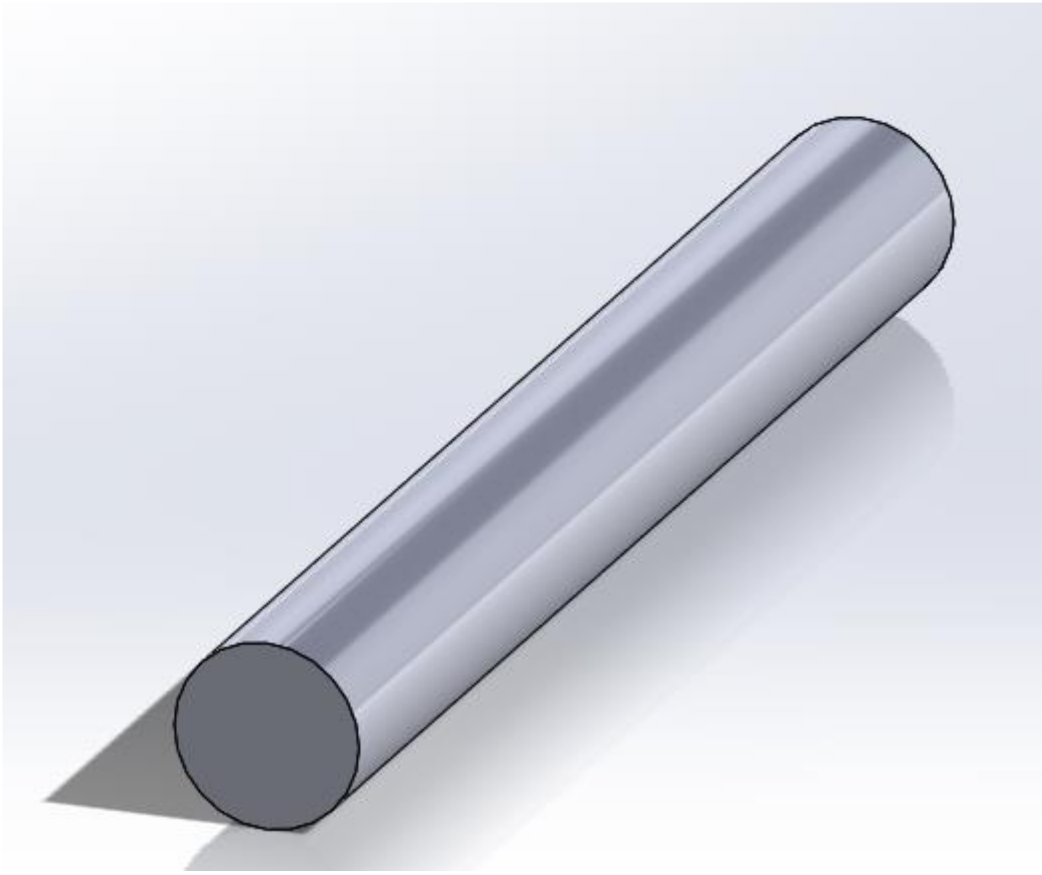

Figure 35 Piston-Displacer Shaft

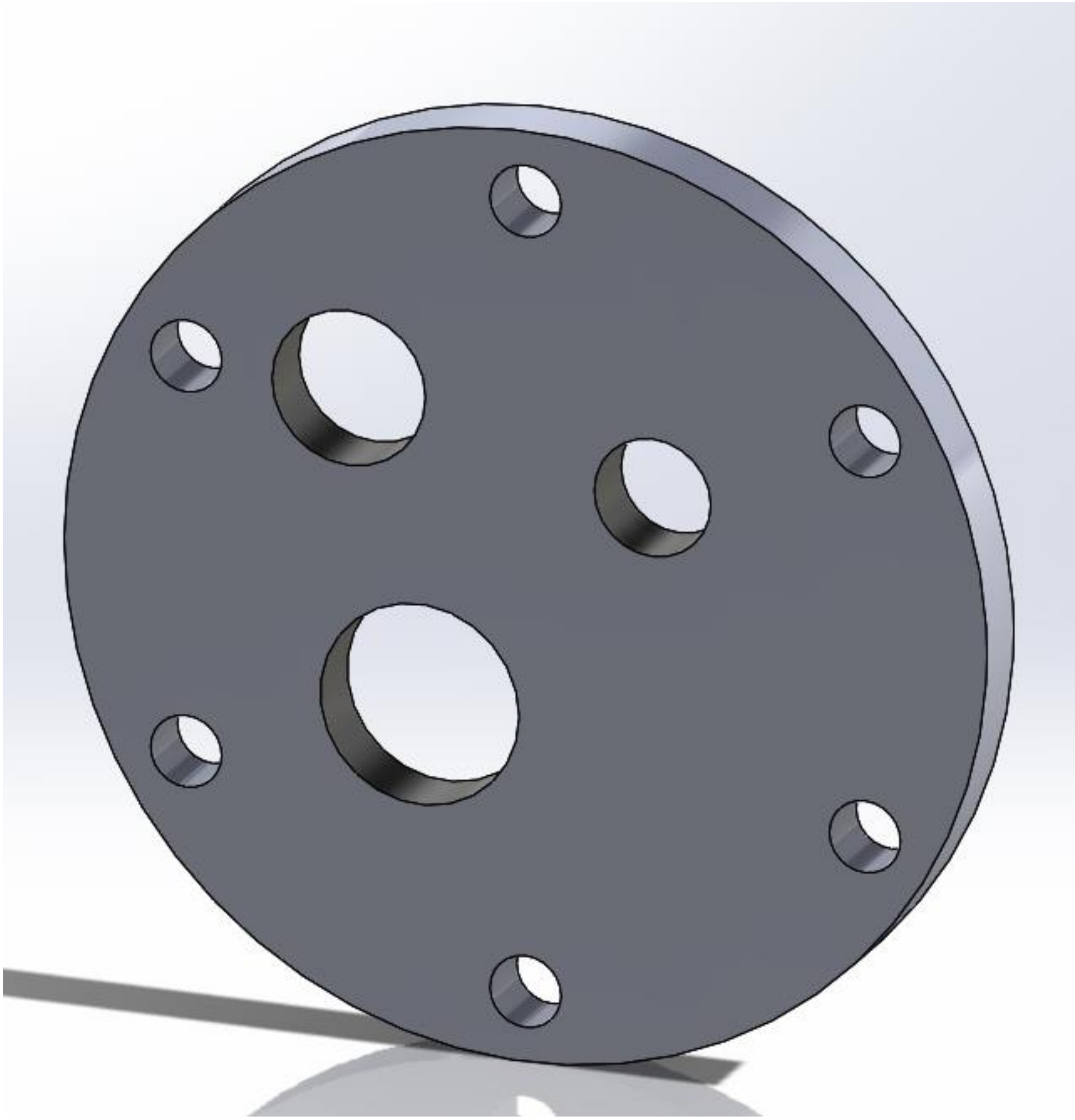

Figure 36 Motor Housing Cap

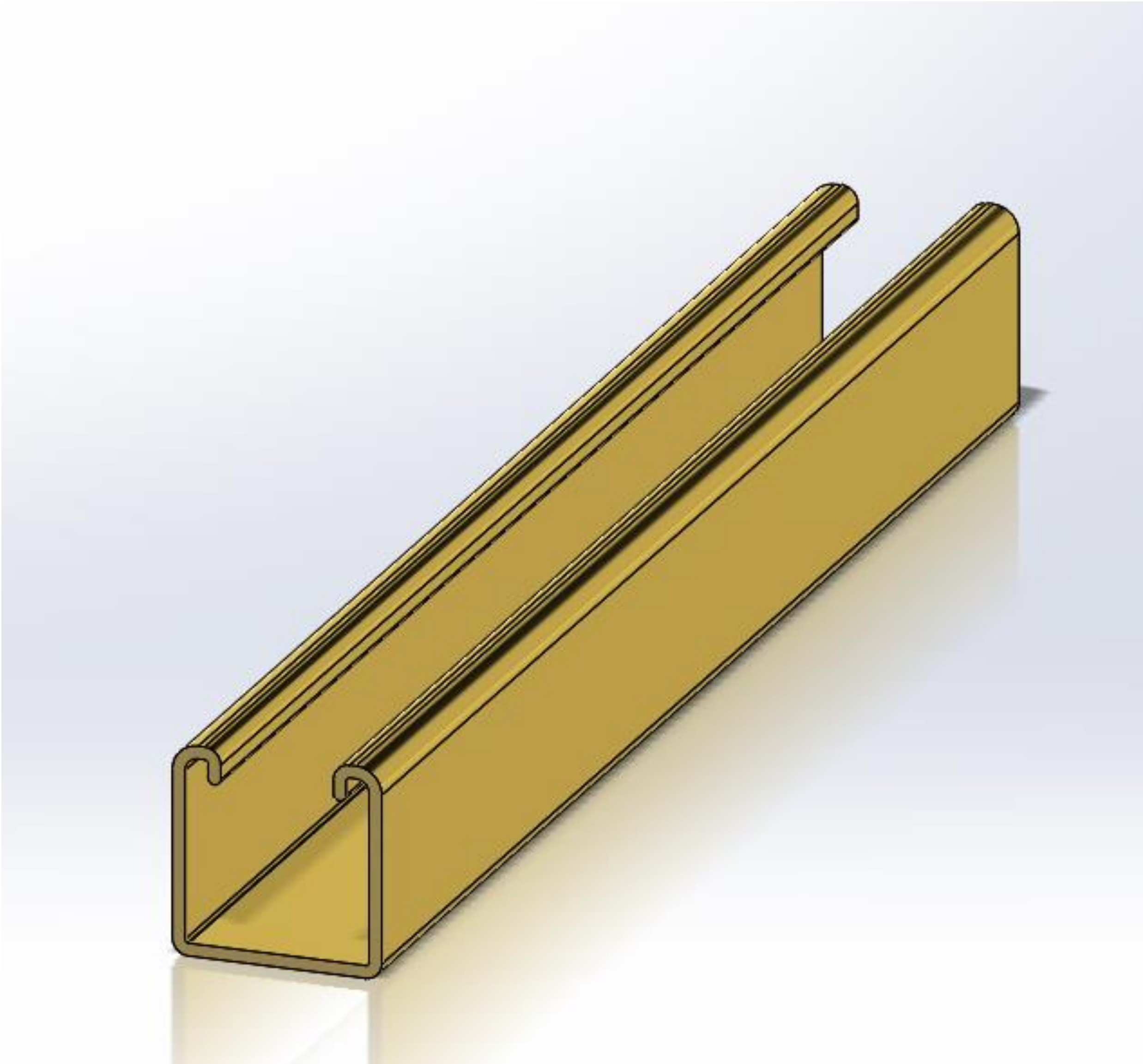

Figure 37 Unaltered Unistrut

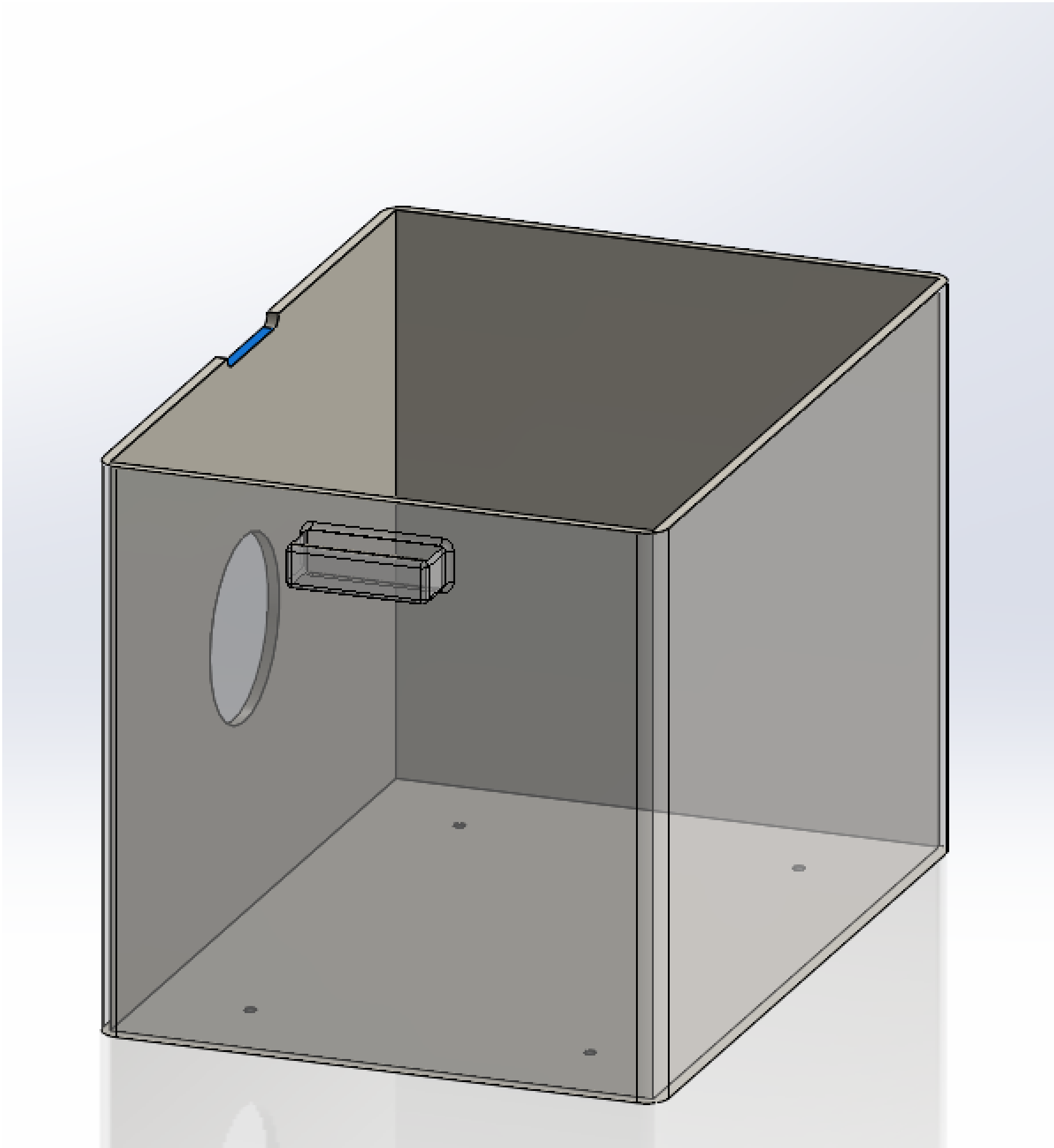

Figure 38 Cooling Space

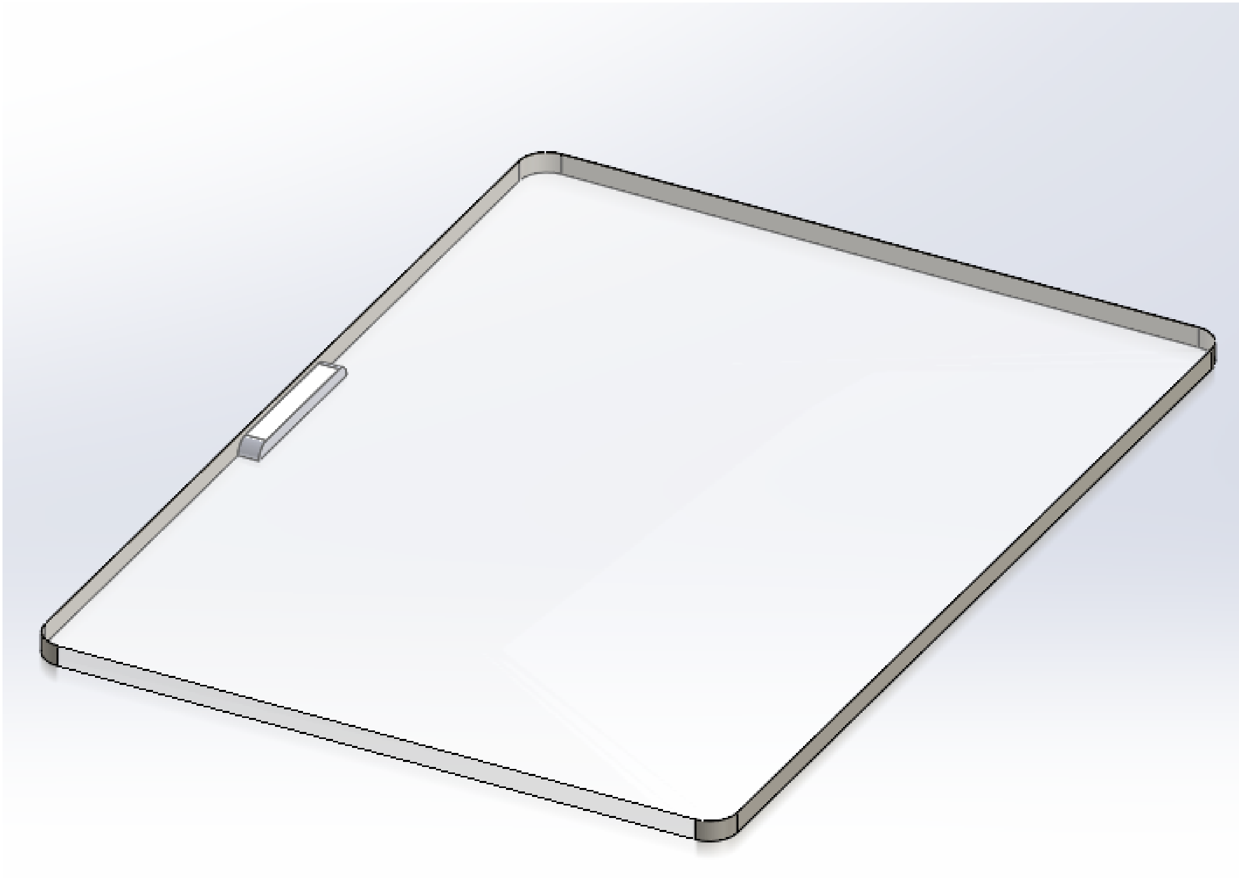

Figure 39 Cooling Space Lid

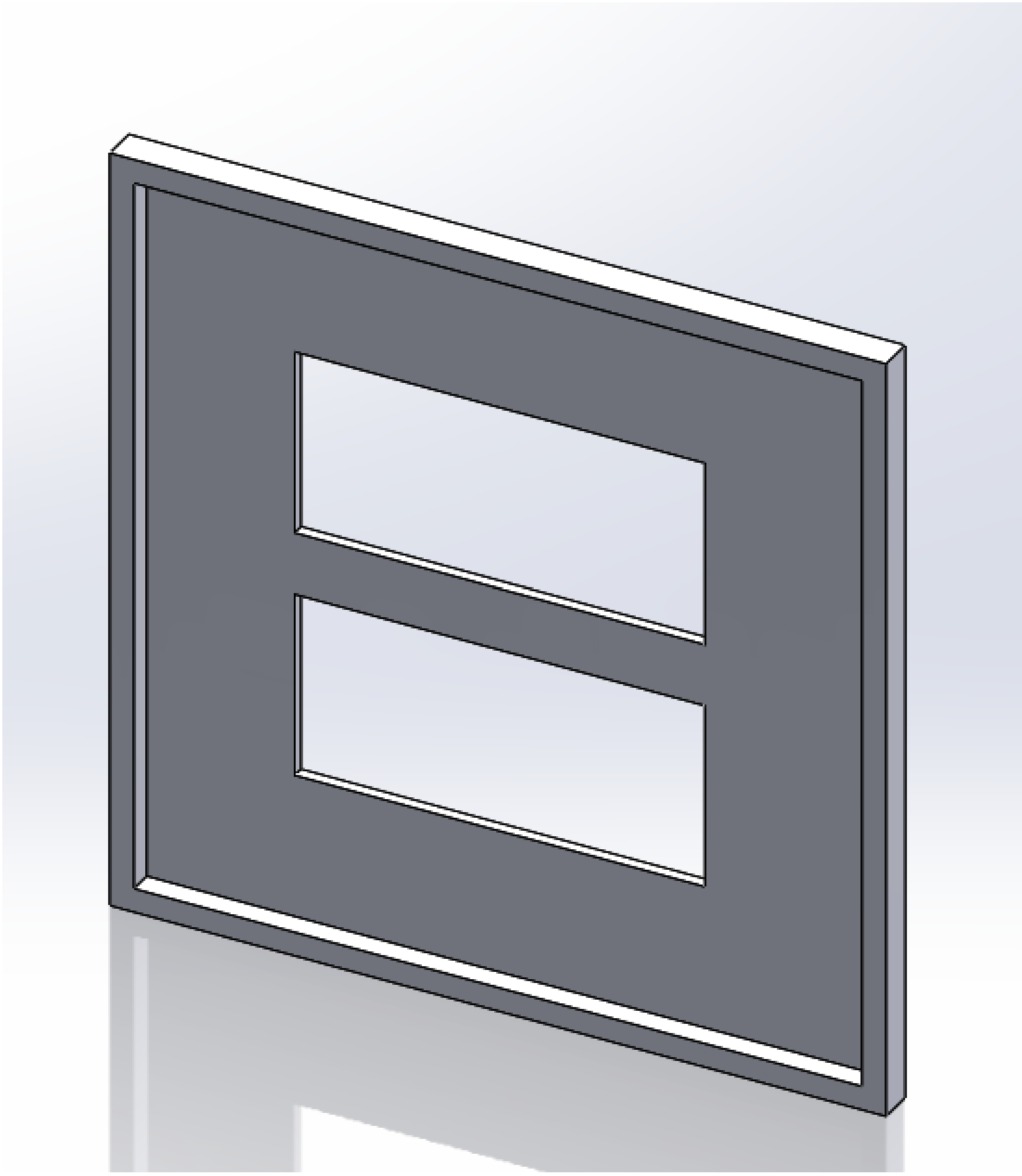

Figure 40 Arduino-LCD Front Casing

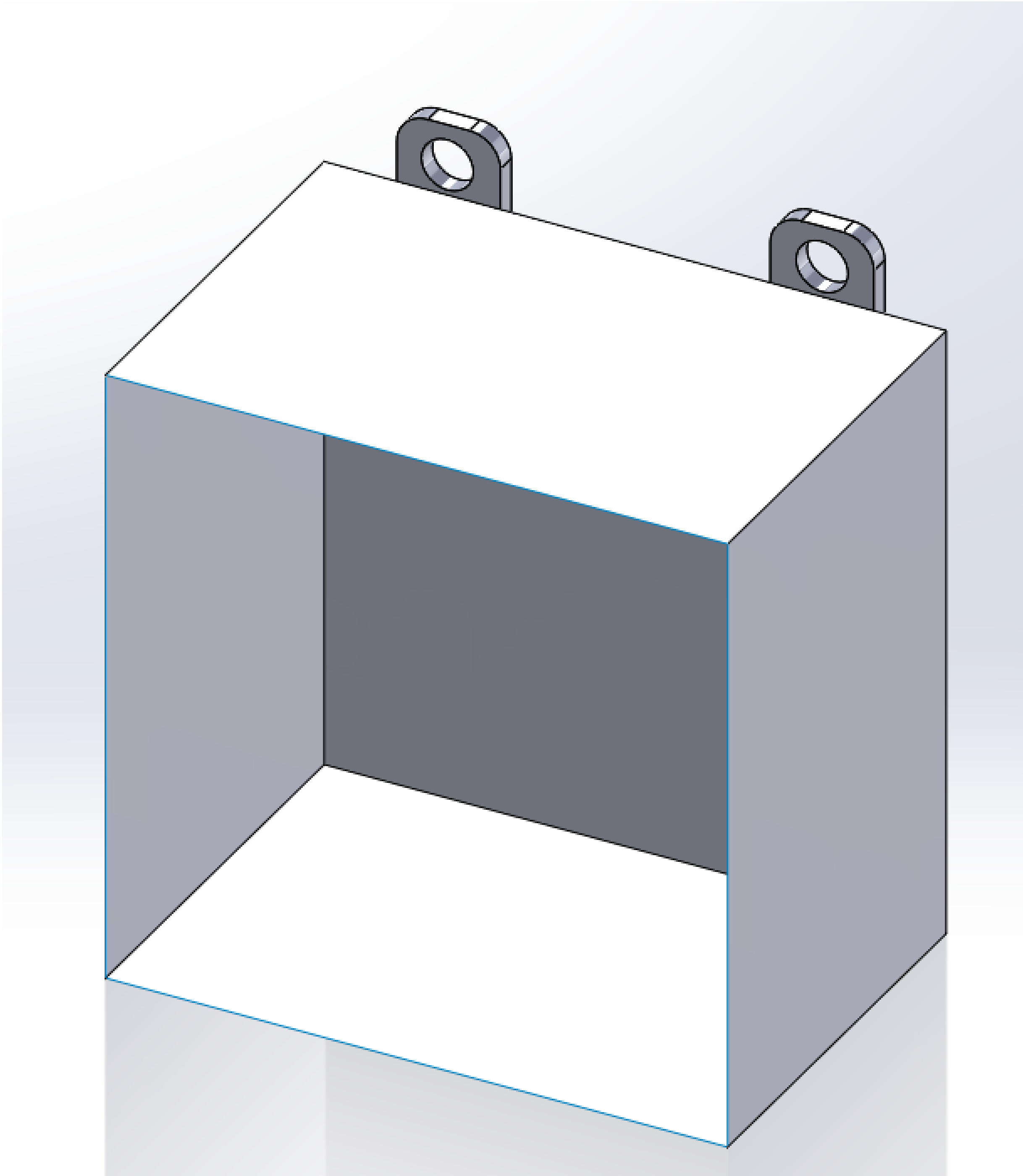

Figure 41 Arduino-LCD Case

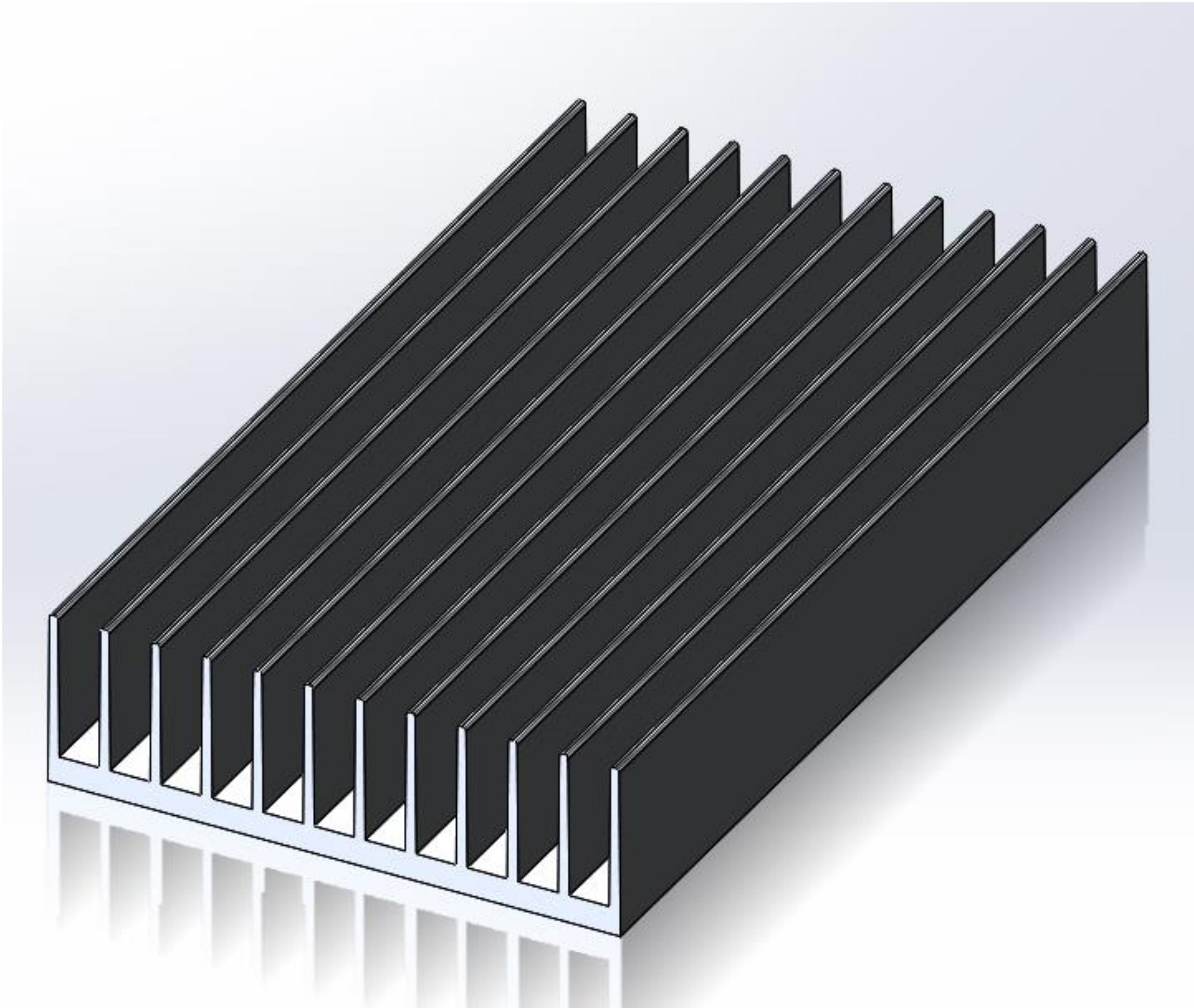

Figure 42 Heat sink for Cooler Space

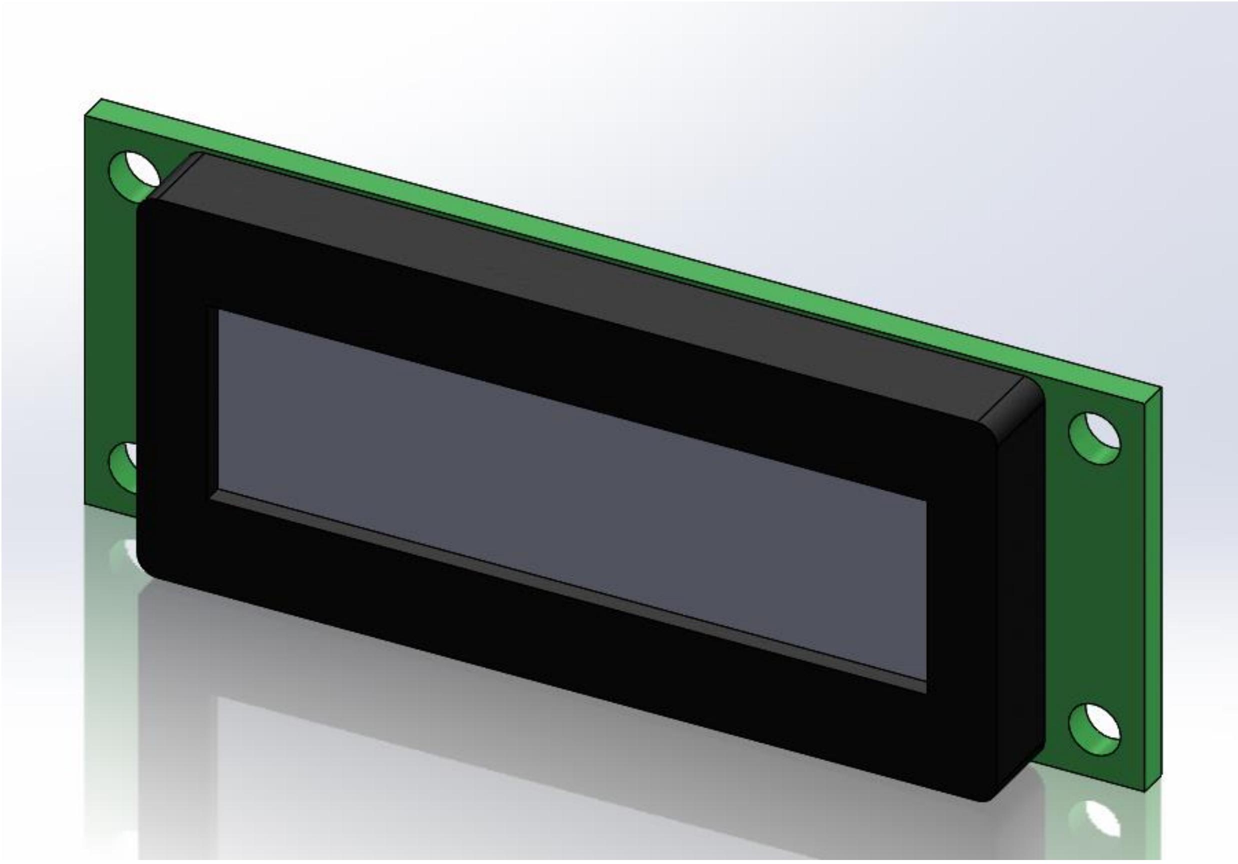

Figure 43 Liquid Crystal Display

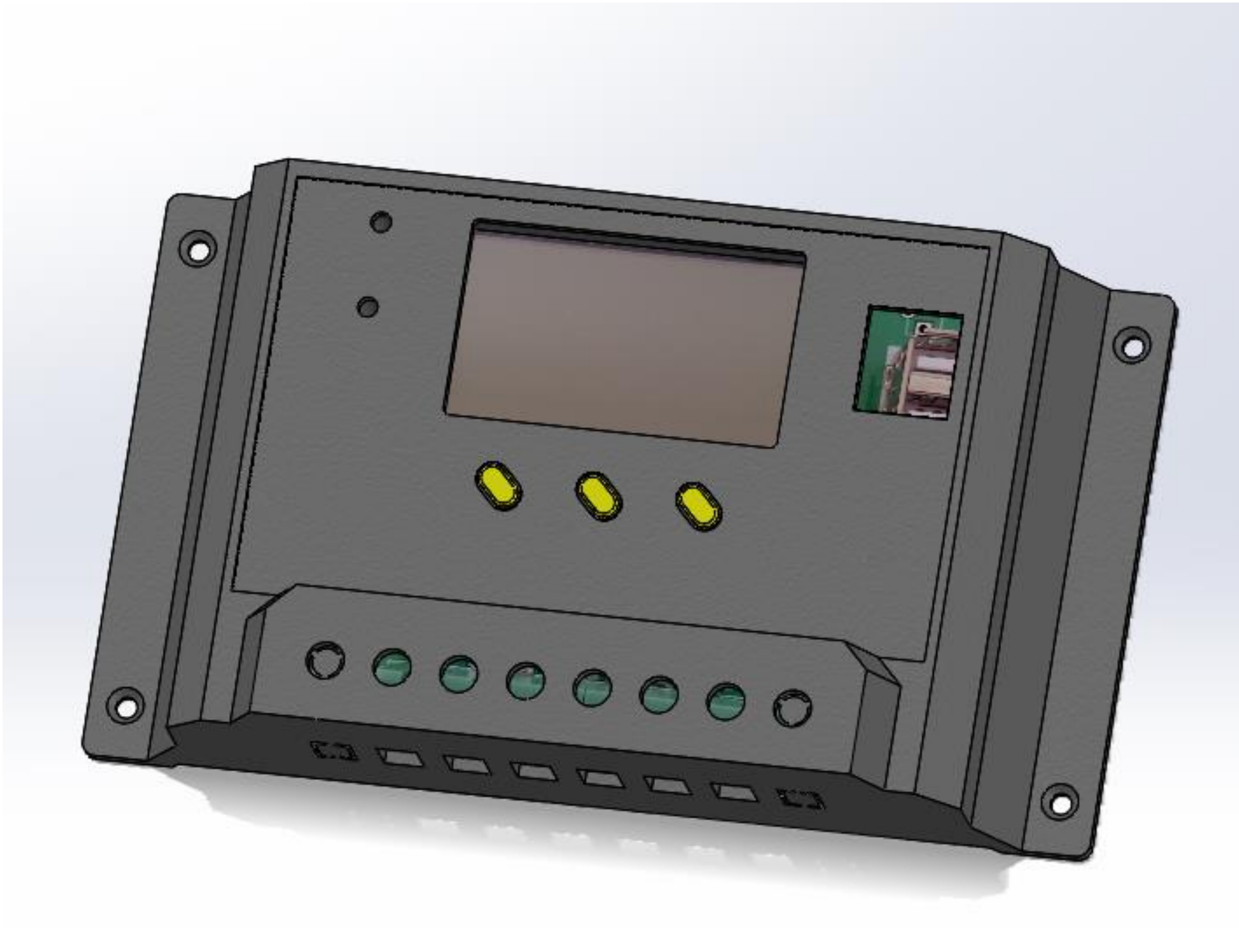

Figure 44 Sixnet PLC controller

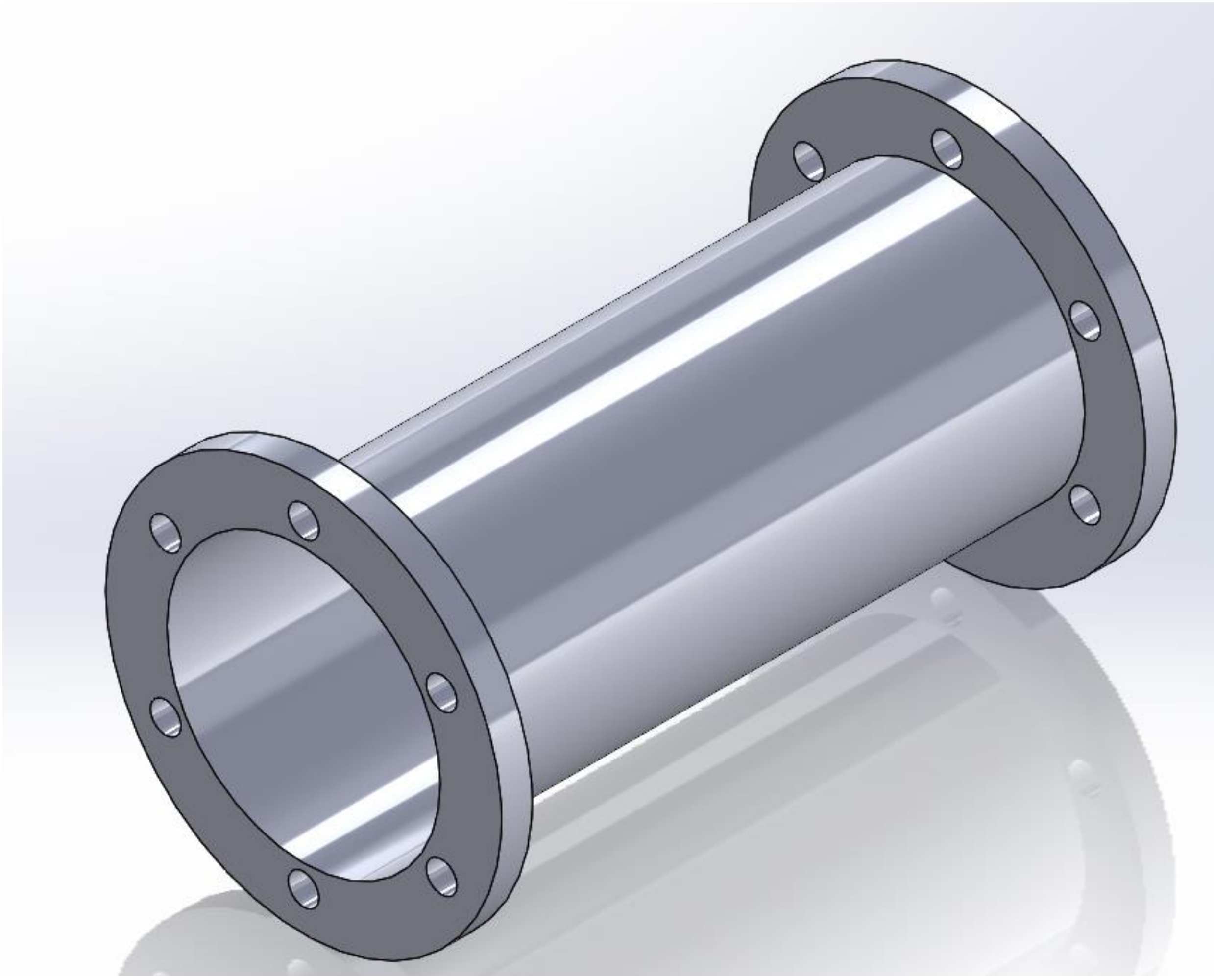

Figure 45 Motor Housing Cylinder

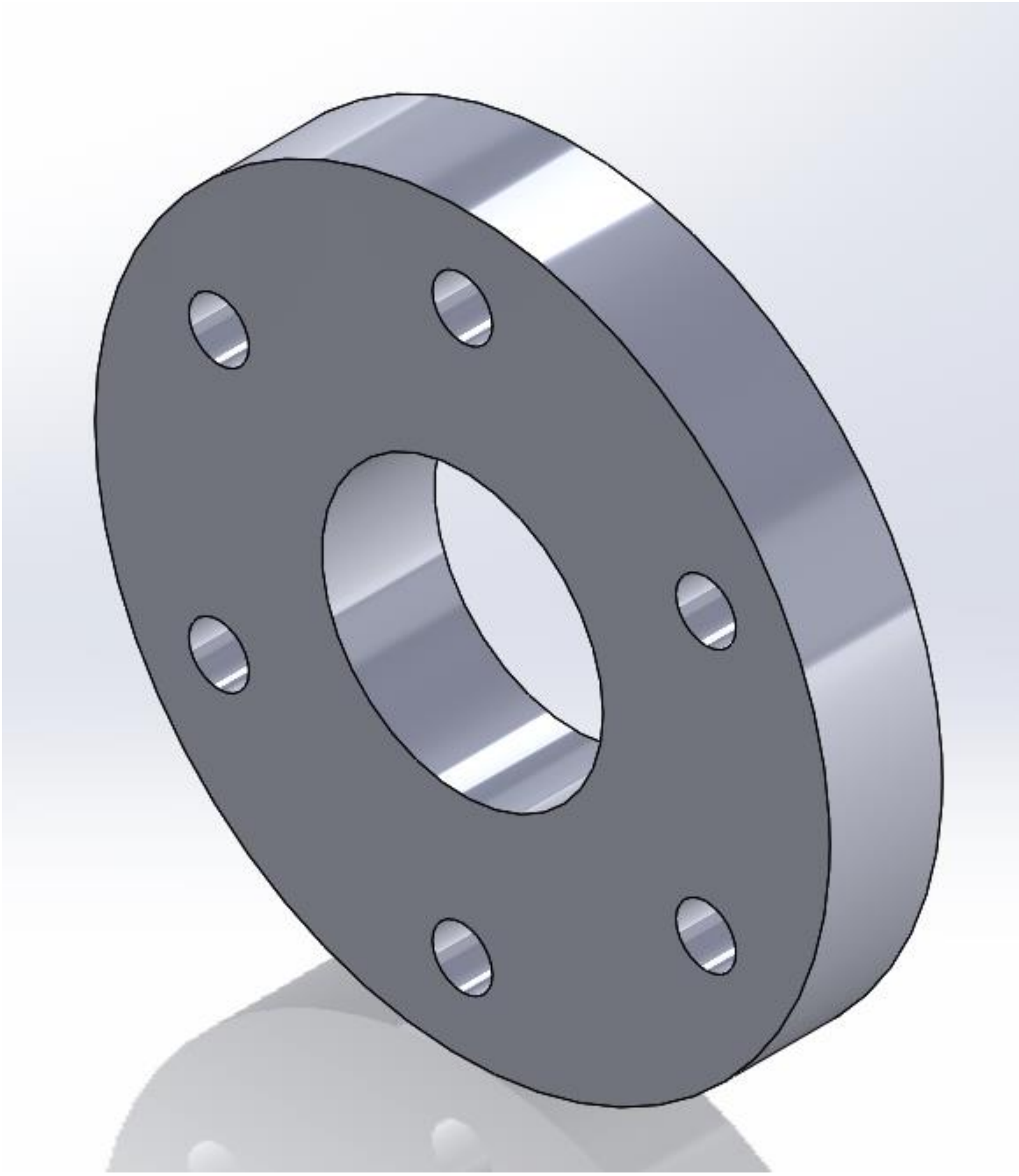

Figure 46 Solenoid Retainer

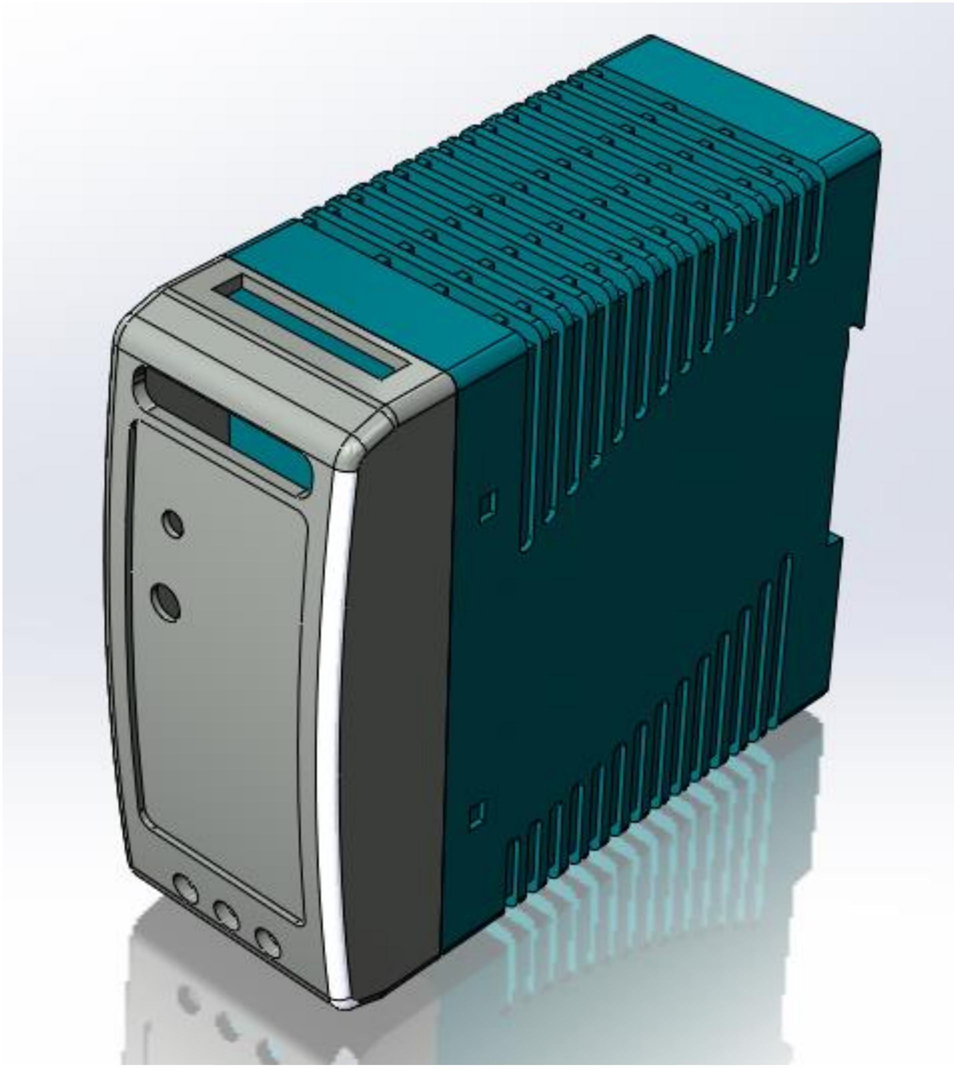

Figure 47 24-volt Power Supply

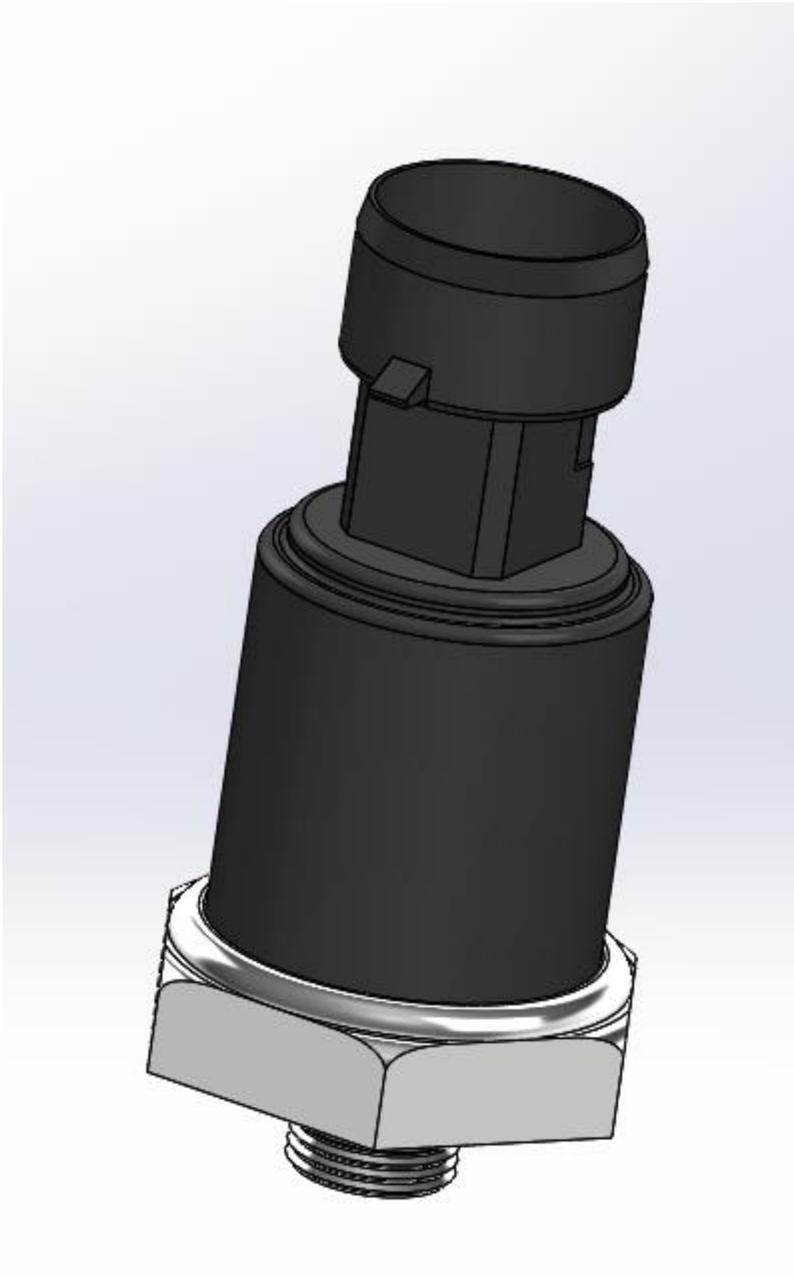

Figure 48 Pressure Transducer