Boundless 2018

Team 09 Project Technical Report to the 2018 Spaceport America Cup

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The 2017-2018 Society for Advanced Rocket Propulsion team at the University of Washington is competing at the Intercollegiate Rocket Engineering Competition's Spaceport America Cup in the 30,000 ft above ground level (AGL) student researched and developed hybrid/liquid category. *Boundless*, the launch vehicle, employs an O-class hybrid motor using paraffin wax and nitrous oxide. For safety, fill and launch operations are conducted remotely and wirelessly. *Boundless* has an aluminum, 3D printed plastic, fiberglass, and carbon fiber airframe structure. For recovery, it employs two parachutes: A 24 in diameter drogue parachute deployed at apogee and a 144 in diameter main parachute deployed at 1,000 ft above ground level (AGL). *Boundless* will carry a 3U CubeSat-standard payload to its descent location. The payload is an exploratory rover vehicle which will survey surroundings and collect data while performing an autonomous maneuver.

Nomenclature

AR	Aspect ratio
a	Speed of sound
C_D	Coefficient of discharge
c	Mean chord length
G	Shear modulus
G_{ef}	Idealized shear modulus
L	Nose cone length
P	Pressure
t	Thickness
R	Nose cone base radius
V_f	Flutter velocity
V_s	Swept flutter velocity
x	Vertical nose cone position
y	Nose cone radius at position x
Λ	Sweep angle
λ	Tip chord length to root chord length ratio
Υ	Volume fraction

I. Introduction

The Society for Advanced Rocket Propulsion (SARP) at the University of Washington is a student-run rocket engineering club with over 100 members who have dedicated themselves to launch an O-class hybrid sounding rocket and scientific payload. The team consists of undergraduates and graduates as well as a faculty adviser, Dr. Carl Knowlen. SARP aims to develop the engineering knowledge and skills of its members in order to prepare them for a lifetime of learning. Each member is given the opportunity to explore and participate in the design, manufacturing, and testing of the rocket. The experience of SARP is rich in hands-on opportunities, from manufacturing in the on-campus machine shops to static hot-fire motor tests. Since 2012, the team has dedicated itself to improving upon the design of previous

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years and inspiring others to be boundless. SARP also serves as a senior capstone project in the Department of Aeronautics and Astronautics. SARP is supported by the Department of Aeronautics and Astronautics, family and friends, and industry sponsors.

SARP is led by the Chief Engineer, a technical program lead whose main role is to oversee integration of all subteams; a Project Manager, who oversees logistical and organizational aspects of the team; five subteam leads, and a Safety Officer. The team is organized into four technical subteams, with the addition of a Business team this year. The technical subteams include Structures, Avionics, Recovery, and Propulsion. The four technical subteam leads are responsible for overseeing every step of the technical projects, from design to integration, as well as the management of their members. This year the team opened its first member application in order to improve member experience and team organization. This effort has increased member retention, with SARP maintaining over twice the number of members as last year.

Through the addition of the Business team, SARP has increased its sponsorship, improved social media presence, streamlined budgeting and purchasing, and increased outreach activities. This year the SARP team participated in five outreach events for K-12 and college freshman students.

II. System Architecture Overview

Boundless is a hybrid sounding rocket carrying a scientific payload. The vehicle has an 8 in outer diameter and is 14 ft 2 in long. It weighs 178 lbs wet and 132 lbs dry. *Boundless* is expected to reach an altitude of 30,000 ft AGL. The rocket's motor is O-class, utilizing a paraffin wax fuel with additives and a liquid nitrous oxide oxidizer. This year's rocket features a carbon fiber body with an exposed aluminum oxidizer tank and glass fiber sections where signal transmission is necessary. The rocket has swept fins manufactured from high density foam and carbon fiber, and a tail cone made of glass fiber.

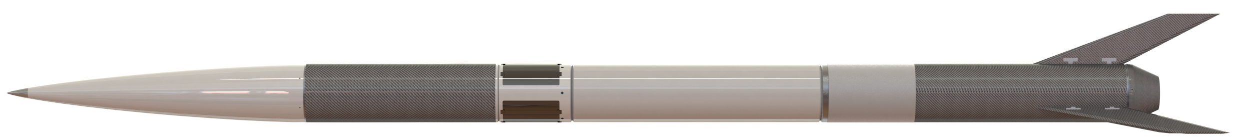

Figure 1. External view of vehicle assembly.

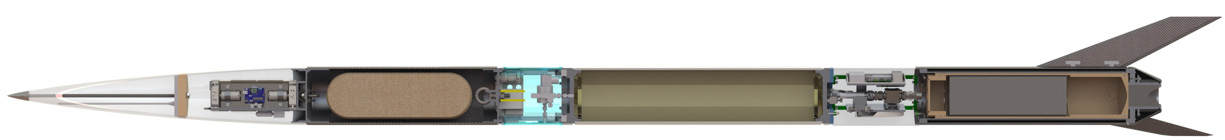

Figure 2. Cross-sectional view of vehicle assembly.

The rocket has ten main sections: Nose cone, payload coupler, upper body tube, recovery coupler, oxidizer tank, actuated valve bay, injector bulkhead, combustion chamber, nozzle, and tail cone. Important features to note are the location of the payload inside of the nosecone, the parachutes housed inside the upper body tube, the recovery electronics bay and oxidizer vent valves in the recovery coupler, and the nozzle protruding from the combustion chamber and shrouded by the tail cone.

II.I. Propulsion Subsystem

The propulsion systems of *Boundless* include the hybrid rocket motor and the remote filling system. In the motor, 36 lbs of liquid nitrous oxide and 12 lbs of solid paraffin wax are burned in 10 seconds to generate a peak of 1200 lbs of thrust and 9200 lb-s of total impulse. The resulting specific impulse is 191 seconds. From fore to aft, the primary sections of the motor in flight configuration are the oxidizer tank, actuated valve bay, and combustion chamber. These primary sections can be seen in Fig. 3.

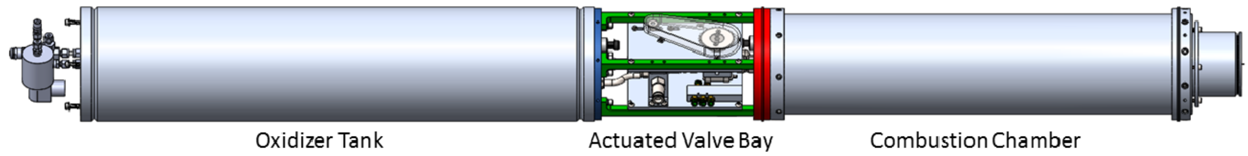

Figure 3. *Boundless* hybrid motor primary sections.

A. Motor Model

A theoretical motor performance model was developed in MATLAB to assist the design of the hybrid motor. A multi-phase thermodynamic model of the oxidizer tank emptying process was created using data from the National Institute of Standards and Technology (NIST) Thermophysical Properties of Fluid Systems and anchored with previous years' test data. This model was integrated into a full combustion simulation model, with inputs for fuel grain properties, oxidizer load, injector/nozzle/chamber dimensions, and initial conditions. A steady-state combustion solution was found for each oxidizer to fuel ratio and chamber pressure using Gibb's energy minimization with NASA's Chemical Equilibrium with Applications software, and properties of the resulting reaction were interpolated for each time step of the model. The simulation ends when either the oxidizer tank is depleted of nitrous oxide, or when all fuel is consumed. The thrust and pressure results are saved and referenced against previous years' test data. The model reasonably predicts total impulse and peak thrust when compared to test data, but it should be noted that assumptions of instant chamber pressurization, 100% combustion efficiency, and purely liquid nitrous oxide flow introduce error to the model. This model was used in conjunction with trajectory models to determine the motor parameters needed to achieve thrust and impulse requirements. During cold flow testing, the model was used to verify mass flow characteristics of the new injector design. For hot fire testing and launch, this model will continue to be used to fine-tune the propellant load to precisely reach the target apogee of 30,000 ft AGL.

B. Oxidizer Tank

The oxidizer tank is a 6061-T6 aluminum tube with machined and welded 6061-T6 aluminum bulkheads. A cross-sectional view of the oxidizer tank is shown in Fig. 4. The tube has an 8 in outer diameter, which is flush with the rocket's outer surface. A 0.25 in wall thickness was chosen because of material availability and for a minimum safety factor of 2.68 at the operating pressure of 1000 psi, expected under maximum flight-load conditions (max thrust). 6061-T6 aluminum was chosen as a structural material for its specific strength, oxidizer contact safety, and weldability.

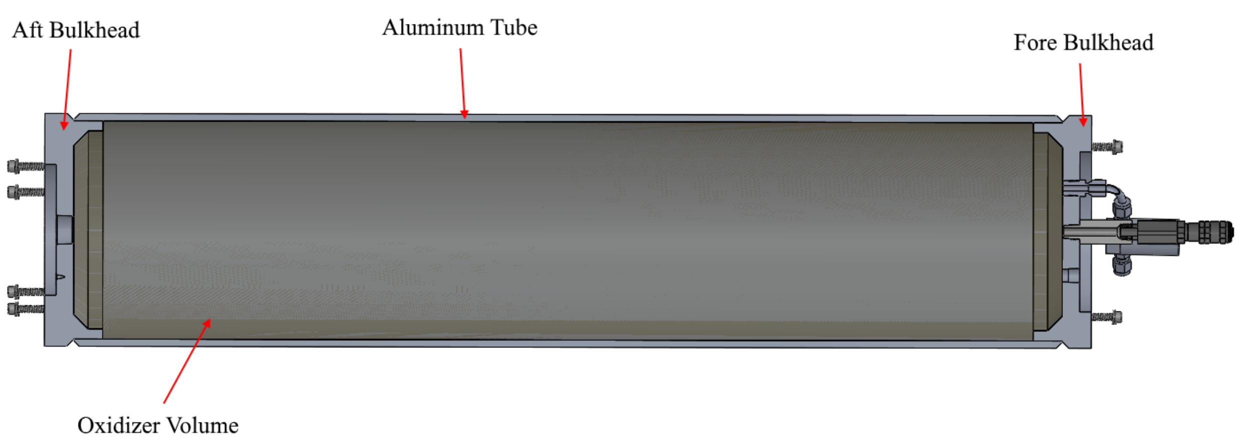

Figure 4. Cross-sectional view of oxidizer tank.

The bulkheads were machined flat instead of elliptical to make attaching the tank with the recovery bay and actuated valve bay simpler and lighter. The bulkhead wall thickness and weld geometry were tested and verified using finite element analysis (FEA) in Femap. Maximum bulkhead von Mises stress converged at 22.2 ksi, giving a safety factor of 2.02. The mesh used for analysis can be seen in Fig. 5, and the resultant von Mises stress distribution can be seen in Fig. 6. The welds were made in the University of Washington Physics instrument machine shop, and heat treated back to T6 temper at Pacific Metallurgical. The tank was hydro-statically pressurized up to 1500 psi for 30 minutes in order to verify integrity of the bulkheads and welds. The mounting screws are all steel 1/4”-20 bolts and the holes are tapped for steel threaded inserts to keep the threads intact during multiple dis-assemblies and re-assemblies. Two additional 1/4” NPT tapped holes were added to the fore bulkhead in case the threads on the other holes were damaged. The extra holes are plugged with brass fittings to prevent leakage.

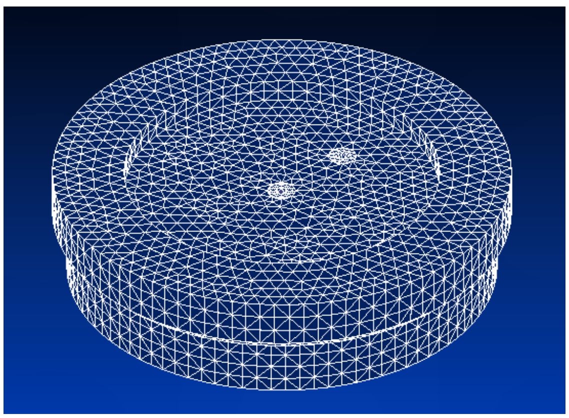

Figure 5. Oxidizer tank bulkhead mesh.

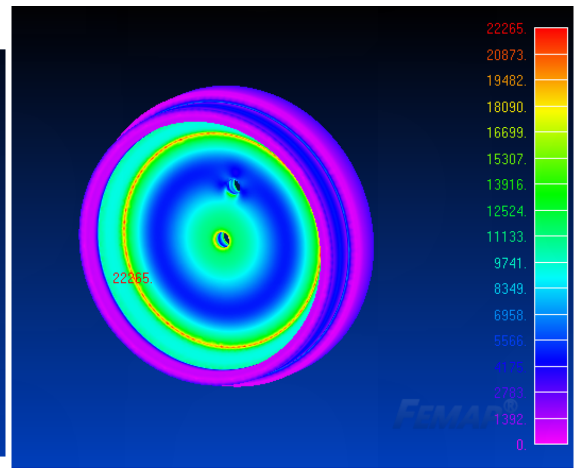

Figure 6. Bulkhead von Mises stress distribution for 1000 psi load.

C. Combustion Chamber and Nozzle

The combustion chamber houses the thermal protection system, ignition system, and fuel grain. It interfaces with the injector bulkhead to allow the oxidizer to be injected into the fuel grain and with the nozzle on the other end to produce the required thrust for the rocket. A cutout of the combustion chamber is shown in Fig. 7.

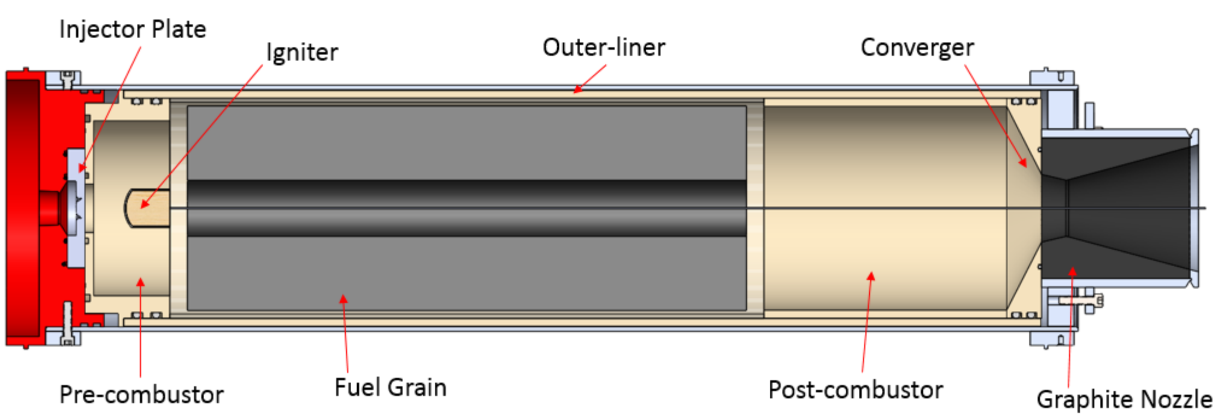

Figure 7. Cross-sectional view of combustion chamber.

The combustion chamber tube is a 7 in outer diameter tube to allow space for the fin can to be the final 8 in outer diameter of the rocket. With a wall thickness of 0.125 in and material of aluminum 6061-T6, the factor of safety for the peak expected internal pressure of 500 psi is calculated to be 2.9. The two outer retaining rings act as the hard points for the combustion chamber where everything is bolted onto. The upper retaining ring attaches the chamber to the injector bulkhead. The lower ring attaches the nozzle assembly to the rest of the chamber. These rings are also the attachment points for the fin can and tail cone.

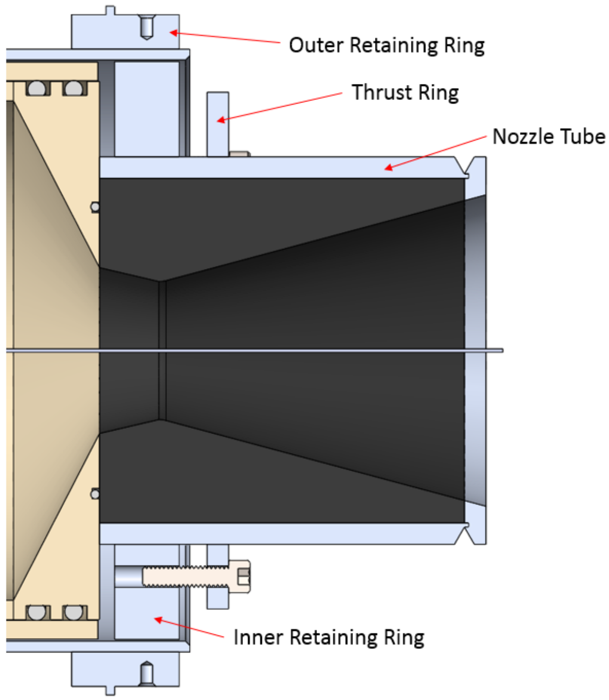

Figure 8. Cross-sectional view of nozzle assembly.

A cutout of the nozzle assembly is shown above in Fig. 8. The nozzle is made of graphite due to the material's ability to withstand high temperatures, allowing the nozzle to be used multiple times. The nozzle is conical, with the diverging section angled at 15 deg for ease of manufacturing and its widely used geometry. Because the geometry of the converging section of the nozzle has minimal impact on the overall performance of the nozzle, it is designed to have a minimal amount of graphite for manufacturing safety; it is instead primarily comprised of linen phenolic, an ablative material. The area ratio of the nozzle is 5.1 so that the nozzle is ideally expanded at ground level at the launch site. This gives the most efficient thrust at the start of the burn and prevents the nozzle flow from becoming over-expanded.

The nozzle is housed inside an aluminum tube, and the end of the tube acts as the exit plane for the divergent section of the nozzle. The tube also has a welded thrust ring, so that the whole nozzle assembly can be bolted axially to the internal components of the combustion chamber. The thrust ring is welded on for faster manufacturing and placed specifically to have enough space for a tail cone. When the nozzle assembly is tightened, it compresses the rest of the internal components in the combustion chamber, solving any issues in tolerances in the length of the thermal protection system or fuel grain.

D. Actuated Valve

The actuated ball valve bay, shown in Fig.9, separates the oxidizer tank from the combustion chamber. This coupler is an important integration point and includes the hardware necessary for starting the rocket, acquiring both oxidizer pressure and chamber pressure data during flight, and housing the low-powered transmitter used for recovery of the rocket.

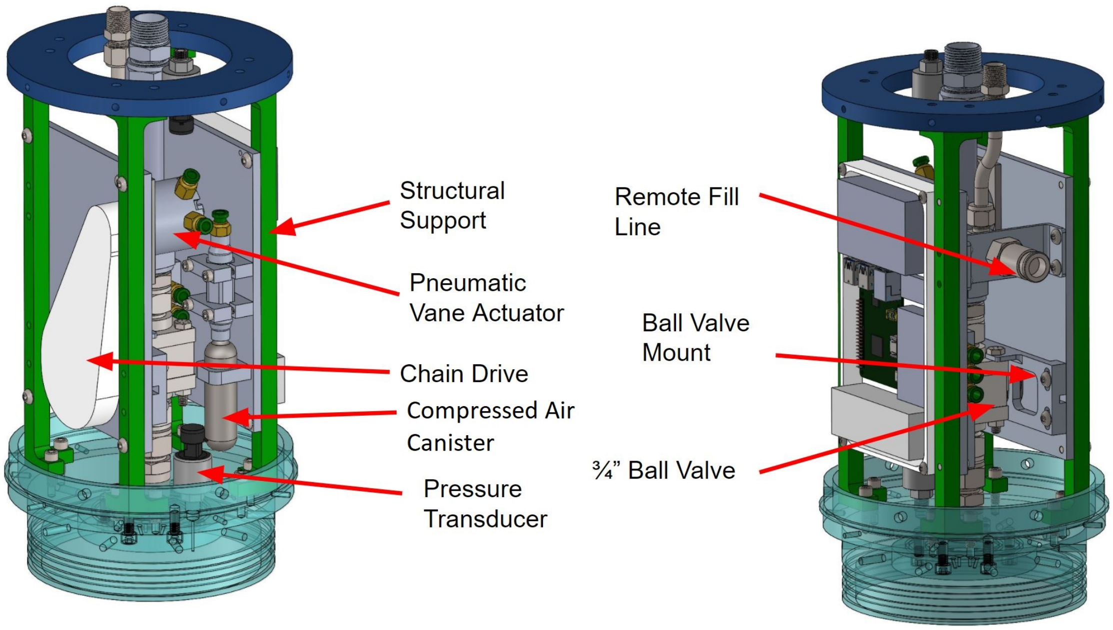

Figure 9. Actuated ball valve assembly.

The primary purpose of this coupler is to port oxidizer into the combustion chamber. This is achieved by using a chain drive linked to a pneumatic vane actuator with a 3:1 gear ratio to turn a 90 degree ball valve. A chain drive was chosen over a geared system for its flexibility in assembly. The pneumatics are powered by a 7.05 in^3 compressed air canister, connected to a five-port two-position solenoid. The solenoid is in turn controlled by an onboard Raspberry Pi (Rpi) and Arduino, which both require identical received signals to activate the ball valve. This adds redundancy to the system to avoid inadvertent openings due to erroneous signals. The air supply only has the capability to open the valve, removing the possibility of the valve being closed after it is actuated.

The ball valve orifice and adjacent tubing have a diameter of 3/4 in to maximize mass flow to the injector bulkhead. The compressed air supplied to the vane actuator at 110 psi provides 36 in-lbs of torque. The ball valve requires 68 in-lbs to open, and with a 3:1 gear ratio, the vane actuator supplies a total of 108 in-lbs of torque. This allows the valve to be opened in under a quarter second.

For the four structural supports, aluminum 6061-T6 was used for its strength-to-weight advantages. Analysis was conducted in Ansys 18.1 for compression loading, and linear buckling of the system. These were conducted solely with the upper and lower bulkheads (without internal components), representing the system at its weakest state. In these worst-case scenarios, the factor of safeties are 12.7 and 10.7, respectively. This system was validated in full-scale testing, where it supported over 1400 lbs.

E. Fuel Grain

The fuel grain cylinder sits within the combustion chamber. The main compound used for the fuel is paraffin wax, specifically hurricane wax. Its high regression rate provides the motor the necessary thrust with a simple grain geometry at the cost of structural instability during combustion. Solving these structural issues was considered a more straightforward task than solving the advanced geometries and low regression rates inherent with arylonitrile butadiene styrene (ABS) and hydroxyl-terminated polybutadiene (HTPB) based fuels. Additionally, hurricane wax has a higher melting temperature than standard paraffin wax (160° F vs 130° F), which allows the wax to absorb more heat before vaporizing and prevents it from melting in the heat of the sun.

In order to solve the structural instability problems mentioned above, a few additives meant to increase stability were selected for sub-scale testing. The additives tested include stearic acid, vybar 103, carbon black and 30 micron aluminum powder in various mass percentage amounts. The most structurally stable combination was found to be 89% paraffin wax, 4% stearic acid, 2% vybar, and 5% aluminum powder.

The fuel grain liner which sits between the pre-combustor and post-combustor ablative liners was chosen to be manufactured from acrylic for its high ignition temperature of 1040° F, its low density of 1.18 g/cm^3, and its high compressive yield strength of 16 ksi. The liner was selected to have a thickness of 0.25 in, well above what is needed for the expected maximum pressure of 500 psi and also accounting for any unexpected burning or melting of the acrylic.

To create each fuel grain, a high heat-resistant silica fabric is first attached to the inside of the acrylic via a high strength plastic binder. This allows the paraffin to be suspended inside the fuel grain liner, as it does not bond to the acrylic as well as the silica fabric. Next, the wax and additives are melted and poured into the liner with temporary end caps attached. The fuel grains are then "spin cast," which involves rapidly spinning the fuel grain along its longitudinal axis while the fuel cools. This method evens out the cooling and minimizes cracks and bubbles formed during the cooling process. If the port is too large, another pour can be performed; if the port is too small, it can be drilled out to size with a lathe. After manufacturing, the fuel grain quality is verified using an x-ray to locate any cracks, bubbles, or abnormalities that may yield inadequate performance of the grain. An image of the port of a completed fuel grain can be seen in Fig. 10.

Figure 10. Top view of finished fuel grain.

F. Oxidizer Injector

Impinging doublet injector ports are utilized to increase atomization of liquid oxidizer flow into the combustion chamber. Interchangeable injector plates allow for easy testing and replacement of varying port configurations, as pictured in the cross-section shown in Fig. 11.

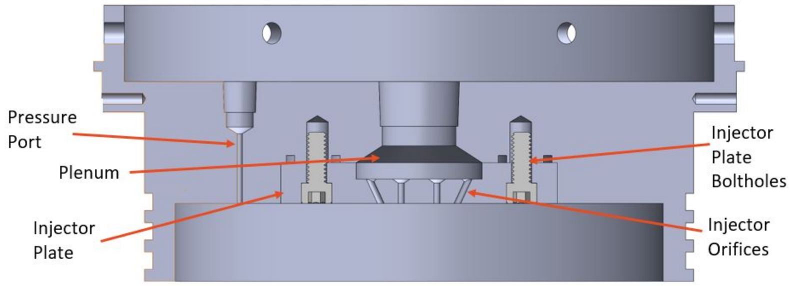

Figure 11. Cross-sectional view of injection bulkhead with injector plate.

Three types of injector plates were designed: non-impinging showerhead, impinging axial-angled doublets, and impinging angled-angled doublets. The showerhead provided a control case against which the visual breakup of the injected fluid core was compared. The axial-angled and angled-angled configurations refer to the inner-outer ports in each doublet. As seen in Fig. 12, high speed imaging revealed clear differences in each configuration. The angled-angled injector produces the most atomized spray, facilitating more efficient combustion.

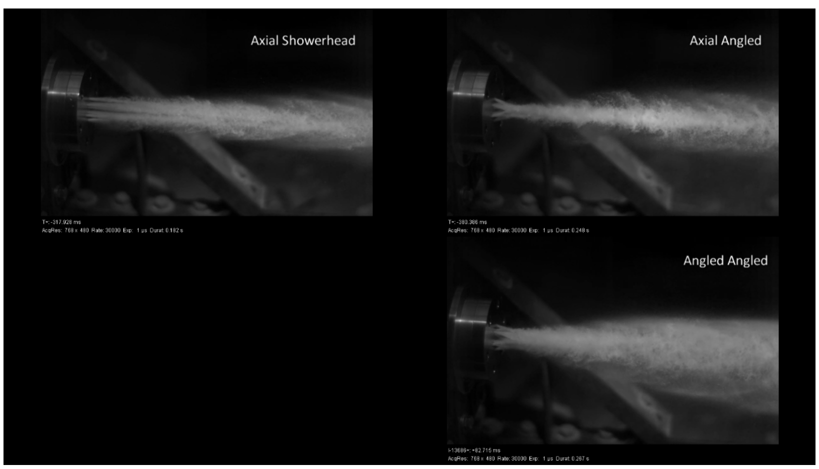

Figure 12. High speed imaging of water cold flows to visualize different injector doublet configurations.

The injector mass flow rate was calculated with data gathered from testing. Cold flow and hot fire back-pressure curves allowed mass flow rate curves to be generated using the incompressible orifice flow equation. These curves were integrated over the liquid portion of the test to ascertain the mass discharged, as seen in Fig. 13 and Fig. 14. This result was compared to the measured propellant fill weight to determine the coefficient of discharge, C_D. Initially, liquid CO_2 cold flows demonstrated lower mass flow and C_D values than expected, interpreted as an effective C_D accounting for flow losses particularly due to two-phase flow. Subsequent hot fire tests with liquid N_2O confirmed the low effective C_D. To compensate for reduced mass flow, the injector ports were increased in diameter. The following cold flow and hot fire performed with a sufficiently consistent effective C_D and validated injector mass flow. Fig. 13 and Fig. 14 show the resulting mass flow rate curves. 95% of the mass is assumed to be discharged during the liquid phase, and the gaseous pressure trail-off phase in red is ignored.

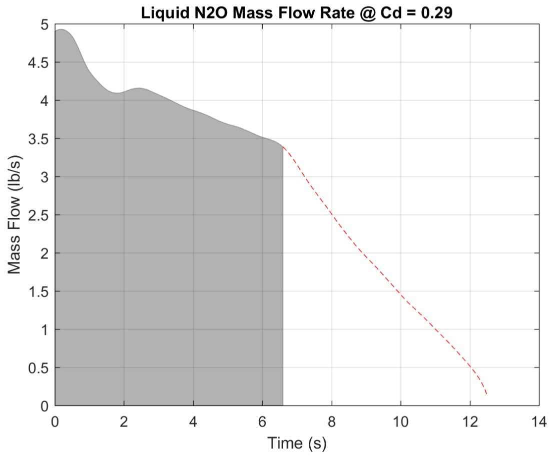

Figure 13. Mass flow rate of liquid N_2O cold flow.

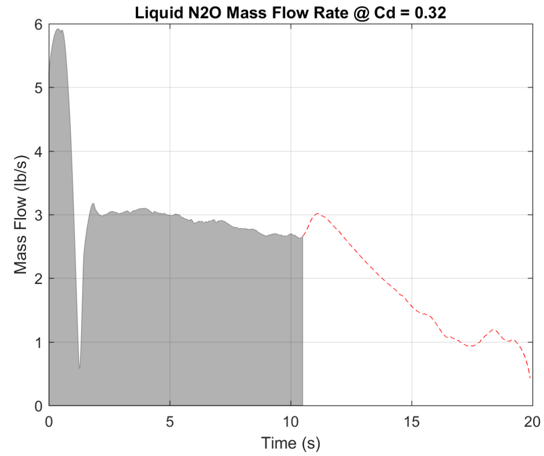

Figure 14. Mass flow rate of liquid N_2O hot fire.

G. Thermal Protection System

The thermal protection system (TPS) consists of two sections of ablative liner, a pre-combustor section, and the converging portion of the nozzle, as labeled in Fig. 7 and reproduced in more detailed renders below in Fig. 15 and Fig. 16.

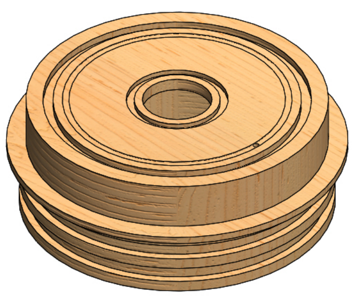

Figure 15. External view of pre-combustor.

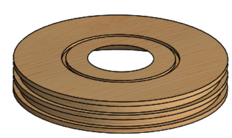

Figure 16. External view of nozzle converging section.

The primary purpose of the TPS is to shield the aluminum combustion chamber tube and nozzle components from the high temperature and pressure gas flow, reaching 3000 K and 500 psi during peak thrust. Linen phenolic is a composite material formed from layers of fine weave linen fabric impregnated with phenolic resin, which is then heated and cured. This material was selected due to its ease of machining, proven ablative properties, and consistency of performance. The TPS also ensures effective sealing of the combustion chamber to limit gas paths and potential failure of the combustion chamber.

Using a tensile strength of 11 ksi the outer liner has been designed to a factor of safety of 2.0 using the von Mises failure criterion. This calculation is made with the assumption that the outer liner takes the entire pressure load. In practice, this is a shared loading with the combustion chamber wall.

To investigate ablative heat management, samples of the linen phenolic were subjected to a 10 second burn from a propane torch, simulating the combustion chamber heat environment. Changes in thickness were observed to be negligible, as they were on the order of hundredths of inches, with an average mass loss of a 0.35 g (below a thousandth of a pound) for 4 in^2 samples with 0.1 in thickness. Therefore, the 0.215 in thick outer liner was determined to be the required thickness to ensure that ablation does not compromise the outer liner structure. The post-combustor tube serves as a secondary layer of ablative heat shielding downstream from the fuel grain.

The pre-combustor and nozzle converging sections are, respectively, the inlet and outlet of the combustion chamber. They both interface with the injector plate and nozzle assembly. These interfaces are susceptible to leakages of high temperature combustion gases, the risk of which has been mitigated with two radial O-rings on each component as well as axial sealing O-rings. The grooves for the O-rings have been designed for a compression factor of 20% for the radial direction and 30% for the pre-combustor axial grooves. The slightly higher compression for these O-rings in particular is due to failures in previous years of the regions adjacent to the pre-combustor component, requiring a tighter seal.

H. Ignition System

The primary purpose of the ignition system is to provide sufficient heat energy in order to achieve motor ignition. The igniter is comprised of a 3D-printed polylactic acid (PLA) shell filled with rocket candy, a solid propellant composed of a 2:1 mass mixture ratio of potassium nitrate and sucrose. The nominal igniter mass is 35 g. Before the remote fill procedure begins, the igniter is inserted into the pre-burner in a "lollipop" fashion as shown in Fig. 17. Fig. 18 shows the pre-burner, which is a cardboard cylindrical tube coated with rocket candy that is placed within the pre-combustor to provide extra propellant to aid the ignition process and assist with combustion stability. This pre-burner contains 70 g of propellant. Both the cardboard tube and the polylactic acid (PLA) shell disintegrate during ignition, preventing possible debris from clogging the fuel grain.

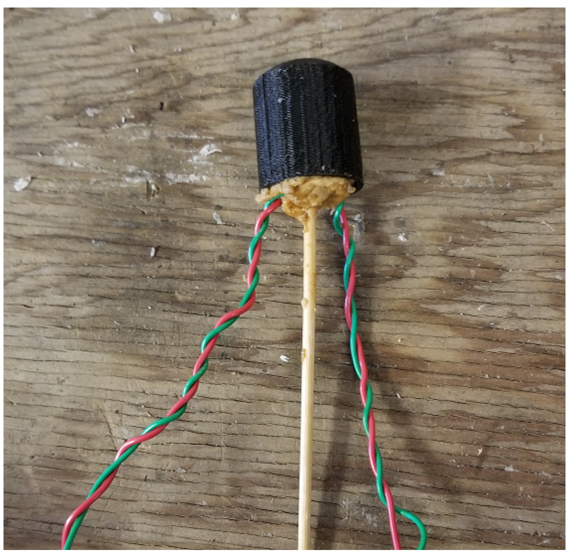

Figure 17. Assembled igniter.

Figure 18. Assembled pre-burner.

In order to achieve ignition, each igniter contains two individual pairs of wires connected by nichrome wire that are soldered onto the leads of one side. These wires are then attached to the main ignition wire connected to the ignition box. The triggering of the ignition box just before injection sends current through the nichrome wires, causing them to heat up and ignite the igniter and surrounding pre-burner. In each igniter, there are two wire pairs for redundancy. Before and after insertion into the chamber, the resistance of the igniter wire pairs is measured and recorded.

I. Remote Fill System

The modular plumbing stand is designed to be flexible and applicable to all testing sequences: sub-scale fuel tests, injector tests, cold flow tests, static hot-fire tests, and flight tests. The remote fill system is operated using a Swagelok system with five pneumatic ball valves and an onboard solenoid vent valve to control the flow of fluids into and out of the oxidizer tank. Pneumatic ball valves were selected for their reliability and high flow rates. As seen in the piping and instrumentation diagram (P&ID) in Appendix F, there is one valve for each available gas, one valve to allow flow into and out of the oxidizer tank, and another valve for venting. For ease of use, all of the gas cylinders are connected to the fill stand using 1/4 in stainless steel flexible hose. A CAD model of the fill stand and close up of the plumbing layup can be seen in Fig. 19 and 20 respectively.

Safety is paramount in the design of this system. Nitrous oxide has the potential to combust in the presence of hydrocarbons. For safety, all parts are made with nitrous oxide-compatible materials such as stainless steel 304 or 316, brass, Buna-N, or Fluorocarbon FKM. All plumbing lines have a diameter of 0.25 in whenever possible to prevent flame propagation through the lines, as the critical diameter for nitrous oxide is 0.27 in. Each leg of the fill stand has a check valve to prevent contamination and mixing in the event of unexpected back flow. There are five manual vent valves to prevent any isolated high pressure areas up to 1000 psi. A 15 micron pore size filter valve exists downstream of the main fill valve to prevent any particulates from flowing into the oxidizer tank.

The oxidizer tank is fitted with a spring relief valve (set to release at 1300 psi) and a venting solenoid valve. The venting solenoid valve releases nitrous oxide vapor through the top of the tank, allowing more liquid to flow into the tank.

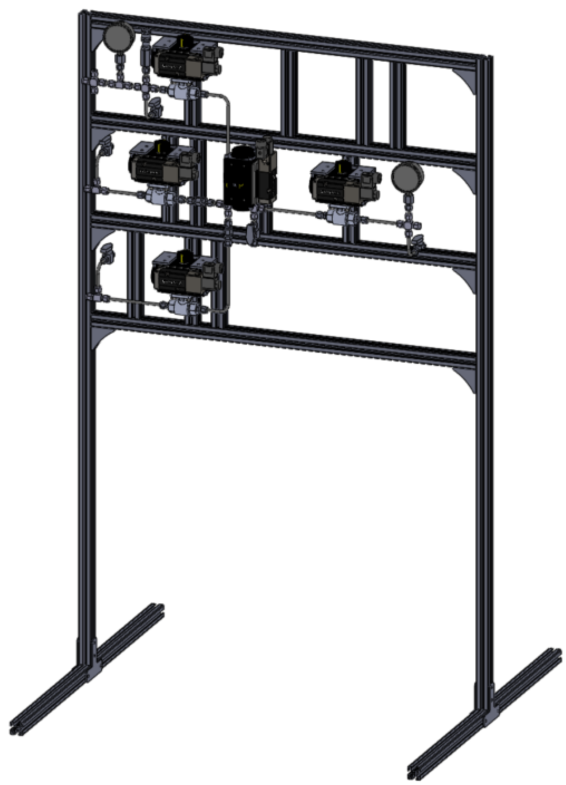

Figure 19. External view of assembled fill stand.

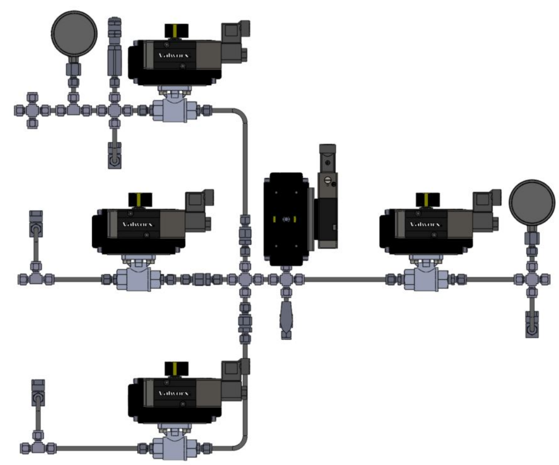

Figure 20. Close-up of plumbing setup

J. Propellant Umbilical

The propellant umbilical safely delivers propellant and other gases from the remote fill stand to the oxidizer tank. Propellant and other gases flow through a 0.25 in flexible hose connected at one end to the remote fill stand to the female portion of a 0.375 in Swagelok Dual End Shutoff (DESO) quick-connect at the other. The female end connects to a male Swagelok quick-connect stem plumbed into the oxidizer tank, located in the actuated valve bay. The DESO ensures that when the proplleant is still contained when the quick connect and stem are separated and both the line and oxidizer tank are pressurized.

Upon completion of the fill procedure, the propellant umbilical is disconnected via the remote fill system controller. A solenoid valve is triggered, and compressed air actuates a pancake pneumatic cylinder. The force produced by the cylinder is transferred through linear rods coupled to a retaining ring that compresses the female Swagelok quick-connect, releasing it from the rocket. The force required to compress the quick connect is 8 lbs, and the maximum force output of the pneumatic cylinder is 80 lbs. Pneumatics were chosen over other linear actuation solutions because it supports a rapid and robust propellant umbilical disconnect mechanism. The mechanism's enclosure is 3D printed ABS for ease of manufacturing, and it exceeds necessary strength requirements for attachment when loaded with 40 lbs longitudinally in compression. The enclosure features a transparent poly-carbonate cover, allowing visibility of the inner workings of the mechanism and sealing the otherwise open enclosure from dust and debris. An image of the assembled propellant umbilical can be seen in Fig. 21.

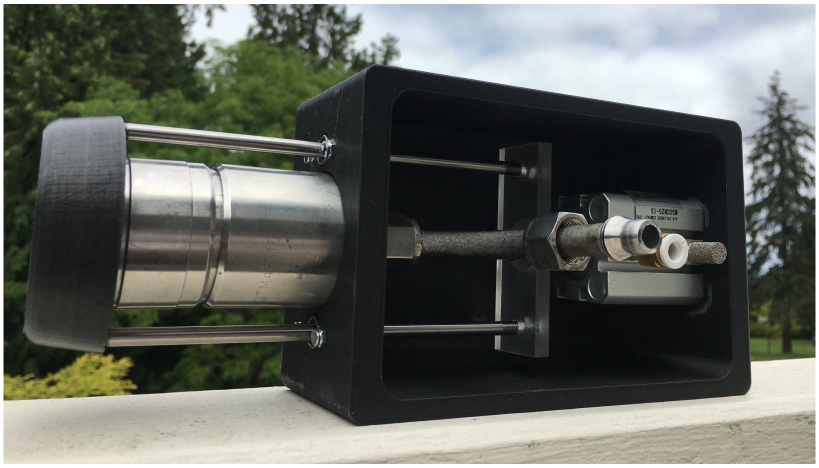

Figure 21. External view of propellant umbilical assembly.

The propellant umbilical disconnect mechanism is supported by an 8020 aluminum extrusion that is affixed to the launch rail. The mechanism is attached to the extrusion using a linear slide in addition to two hinges, giving the mechanism three degrees of freedom in order to ensure successful attachment and disconnection without binding.

K. Remote Fill and Launch Control

The propulsion system contains four RPis and an Arduino to control the remote fill and launch procedures. The Onboard RPi and Arduino are located on the rocket in the actuated valve bay. Two others, the Igniter RPi and Fill RPi, are stationed at the launch rail. Lastly, the Command RPi is located at ground control. A router exists at the launch rail, connecting the Onboard RPi, Fill RPi, and Igniter RPi. The network is then extended to ground control via a wi-fi bridge, allowing the Command RPi to communicate with the others. The control boxes and onboard electronics are shown in Fig. 22 to 25.

Figure 22. Assembled Command box.

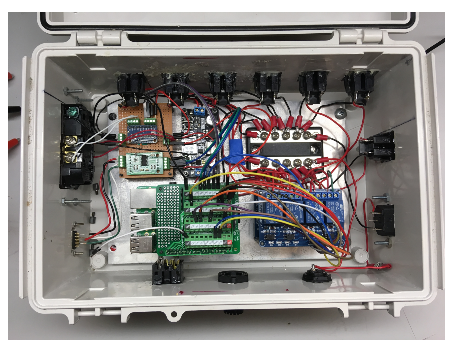

Figure 23. Assembled Fill box.

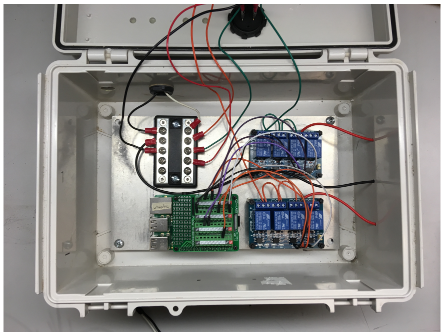

Figure 24. Assembled Igniter box.

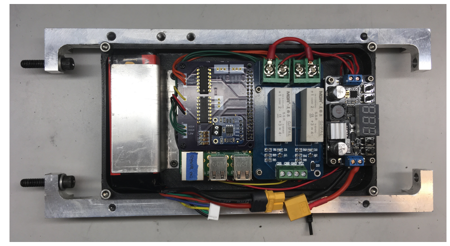

Figure 25. Assembled Onboard electronics.

Fill procedures are primarily reliant on the Fill RPi. The input/output pins on the Fill RPi are connected to relays. When sent an active-low signal, the relays allow each fill component to be powered. To assist with filling, the script displays pressures from the oxidizer tank and fill stand as well as the weight of the rocket. This data is recorded into a local file. The Fill RPi also handles the disconnect procedure, actuating the disconnection of the propellant umbilical.

The launch procedure utilizes the Igniter RPi, the Onboard RPi, as well as the Arduino. To launch, the igniters are lit, and the actuated valve opens after a 2 second delay, allowing oxidizer to flow into the combustion chamber. To initiate the sequence, the Command RPi sends the Onboard RPi a "FIRE" signal. Immediately, the Onboard RPi will light the igniters via the Igniter RPi. Next, a coded signal is sent to the neighboring Arduino, opening one of two solid state relays. The Arduino then sends a signal back to the Onboard RPi. Upon receiving the signal, the RPi will open the final relay, opening the actuated valve. The Onboard RPi manages the igniters and actuated valve independently of the Command RPi. Upon network failure, the Onboard RPi will fail to both light the igniters or open the actuated valve. Given an "ABORT" signal, the Onboard RPi will dump the oxidizer tank through the actuated valve.

II.II. Aero-Structures Subsystems

The aero-structures subsystem consists of all structural components of the rocket forward of the propulsion system, as well as all aerodynamic surfaces on the rocket. This includes the nose cone, body tubes, couplers, and fins.

A. Nose Cone

The primary focus of the nose cone design was to reliably manufacture a high-quality nose cone out of glass fibers, the most common material used for model rocket nose cones. The nose cone has a base outer diameter of 8 in and a height of 40 in, with a 2 in long cylinder on the bottom to attach the payload coupler with shear pins. A 10 oz weave fiberglass roll was used with a room-temperature cure epoxy resin that can be post-cured in an oven at 130 °F for 12-14 hours. The design utilized a 3D-printed male mold and a wooden jig to create the fiberglass mold that was then used to create the final product (Fig. 26).

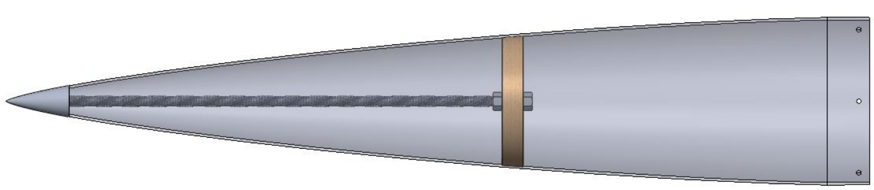

Figure 26. Cross-sectional view of nose cone.

A tangent ogive curve is the most common nose cone shape used in sounding rocketry for its combination of simplicity and effectiveness. The von Kármán curve is constructed from an equation that is mathematically derived to minimize drag. The radius y at a given vertical position x is determined with Eq. 1:

$$y = \frac{R}{\sqrt{\pi}}\sqrt{\theta - \frac{sin(2\theta)}{2}} \tag{1}$$

where R is the radius at the base of the nose cone and the angle θ is defined by Eq. 2:

$$\theta = \arccos 1 - \frac{2x}{L} \tag{2}$$

where L is the total length of the nose cone.

To determine nosecone geometry, RASaero was used to approximate the drag of each shape. With all other rocket specifications the same, it was found that the two cone shapes were nearly identical until the supersonic region, at which point the von Kármán produced slightly less drag than the tangent ogive (Fig. 27).

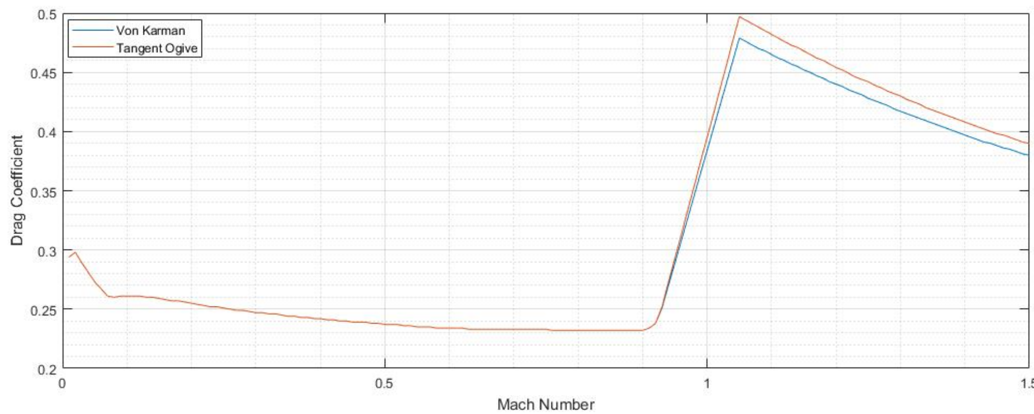

Figure 27. Drag vs. Mach number for von Kármán and tangent ogive .

For the fiberglass body, a female mold was created and used, mitigating external imperfections. The 3 in aluminum tip, attached at the top of the fiberglass body with epoxy, was machined on a CNC lathe. An all-thread rod is screwed into the tip and extends down through the cone. The all-thread has a wooden disk at the end that is pressed against the inside of the cone with a rubber gasket, creating a sealed chamber for the avionics equipment. The payload is tethered to the other end of the all-thread rod.

B. Payload Coupler

The payload coupler provides housing for the payload deployment system and a hard point for parachute deployment. A standoff on the forward face of the coupler mounts the payload cage and provides a volume for the winding of the connection tether. The aft portion of the payload coupler, Fig. 28, is meant to maximize the pressurization of the upper body tube in order to reliably deploy the parachutes.

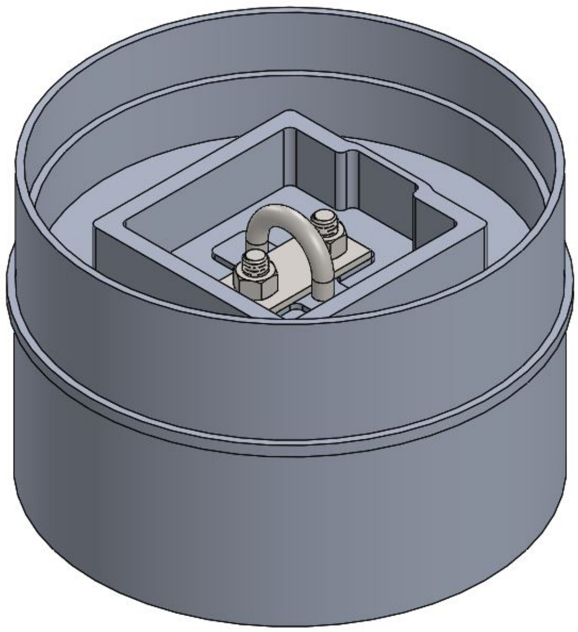

Figure 28. External view of payload coupler.

The coupler must conform to the outer shape of the rocket, so the 8 in diameter was the first constraint of the coupler design. Further constraints came from IREC regulations, which suggested that all coupled and separable components be equipped with sleeves to facilitate clean decoupling while keeping appropriate stiffness during flight. Finally, the remainder of the design was guided by the need to integrate adjacent systems effectively.

The coupling sleeve to join the upper body tube and coupler is 3 in long and forms the primary seal of the pressurized body tube by means of two distinct wrappings of Teflon pipe tape, an agent that creates a resilient seal but does not cause any binding during separation or interference on integration. The nose cone sleeve is 2 in long and has a single wrapping of Teflon pipe tape. Both sleeves are joined to the bulkhead via a non-structural corner weld and sealed with an epoxy agent. This joint occurs twice, once between the inner wall of the sleeve and the lower face of the bulkhead's round-over for the upper body tube coupler, and again between the upper lip of the bulkhead and the inner wall of the sleeve.

While providing a position for the weld, the main purpose of the round-over is to increase the performance of the recovery pressurization compared to a square edge alone. The addition of this feature also increases the strength of the coupler when subjected to the weight of the payload during flight. The payload is incorporated with the upper face of the coupler via a 1 in tall, four-sided standoff which holds the payload cage in place. This stand is designed to fit the cross-sectional area of the payload cage and provides a housing for the tethers and tether hardware that attaches the cage to the coupler.

Analysis for the payload coupler was focused on the failure of the payload bulkhead in three different modes of flight. The first was the loading caused by the weight of the payload coupler, assumed to be 12 lb, at the maximum acceleration of 10 g. According to the FEA of this case, the maximum von Mises stress is 1.264 ksi, resulting in a factor of safety of 1.64 over yield. In the next stage, the drogue chute deploys with a line connected to the aft U-bolt, assumed to be 250 lb. With a max von Mises stress of 24.098 ksi, this loading case has a factor of safety of 1.66 over yield. Furthermore, the FEA model associated with this case, shown in Fig. 29, can be observed to have the highest stress around the holes for the U-bolt, as demonstrated with the close-up view of the holes in Fig. 30. Having the U-bolt through these holes will increase the parts' ability to resist stress at these points. The final case that was considered was the deployment of the payload by separation of the nose cone. This load was assumed to be 50 lb and resulted in a max von Mises stress of 5.267 ksi and a factor of safety of 7.59.

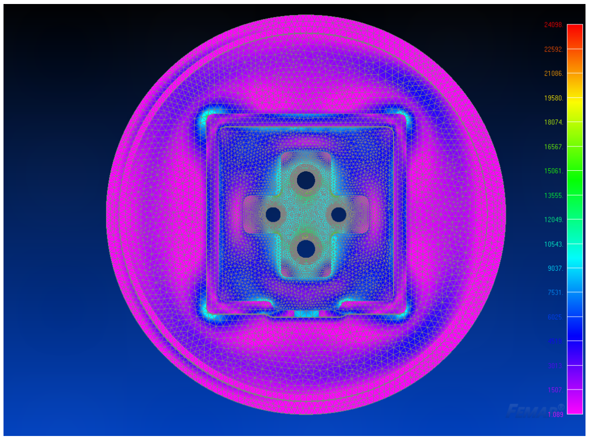

Figure 29. Von Mises stress distribution on payload coupler due to parachute load.

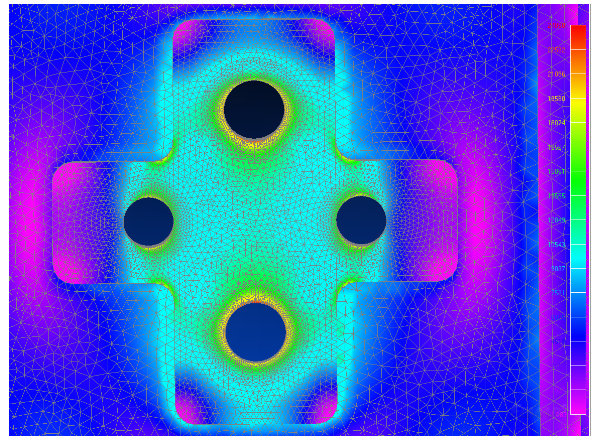

Figure 30. Close up of U-bolt attachment for parachute attachment to payload coupler.

C. Recovery Coupler

The recovery coupler joins the oxidizer tank to the upper body tube. The recovery coupler's purpose is to act as a mounting point for the recovery system hardware and an access point for recovery system arming. The components were constructed to an 8 in outer diameter, and the cage was fixed to a 0.25 in thickness. The coupler was constructed from 6061-T6 aluminum. The main focus was to optimize usable space and accessibility while minimizing the weight. This was done by reducing the height of the cage and removing non-structural metal from the cage. The coupler was given three doors which allows for easy access to the components in the coupler and minimizing the weight of the coupler. The doors, along with its latches, were 3D-printed with PLA plastic. The bulkhead was welded to the top of the cage. The component can be seen in Fig. 31.

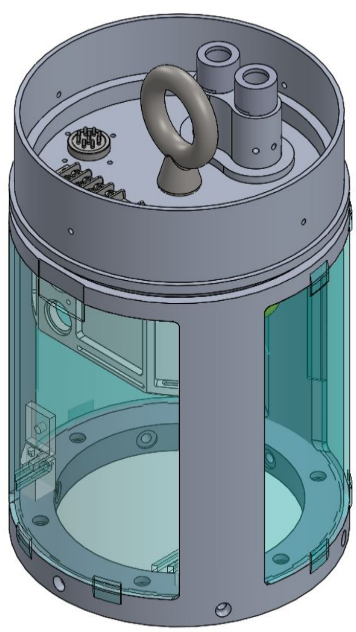

Figure 31. External view of recovery coupler.

Buckling Analysis

A conservative model was chosen to see whether the structure would fail due to buckling. For the recovery coupler model, only the outside shell was used, as the three struts are the main members that would fail in buckling. The assumption that all three struts would take the 500 lbf was used.

The yield strength of 6061-T6 aluminum is tabulated at 40,000 psi. The max von Mises stress calculated under this analysis was calculated at 8523 psi. This conservative analysis gives a factor of safety of 4.70.

Tension Analysis

The top bulkhead, sleeve, washer, and nut were tested for tension analysis so that the stress distribution at this hard point could be observed. It was assumed that the bottom edge of the nut was subject to a 2500 lbf according to calculated parachute loads.

The max von Mises stress calculated under this analysis was approximately 27000 psi. This gives a factor of safety of 1.48 for a conservative analysis of the aluminum parts. The stress analysis that was performed was linear, and does not represent the snatch load of parachute deployment that will occur during the recovery sequence. The results of the FEA analysis are shown in Fig. 32 and 33.

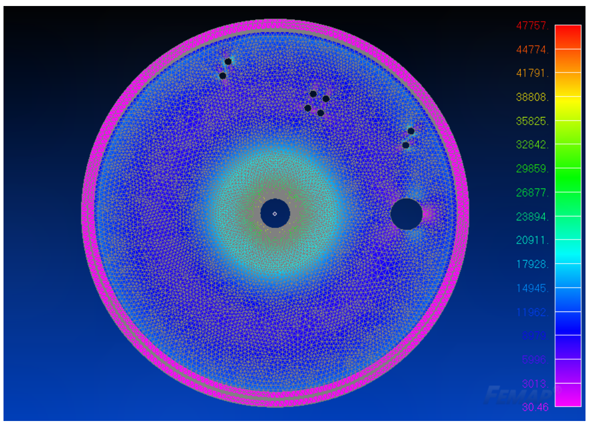

Figure 32. Von Mises stress distribution on recovery coupler due to parachute loading.

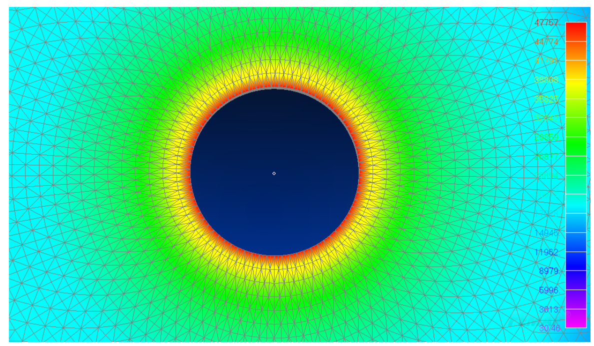

Figure 33. Close up of eye-bolt attachment for parachute attachment to recovery coupler.

D. Upper Body Tube

The main objective for the upper body tube was to create a carbon fiber tube with an 8 in outer diameter that could withstand the loads imparted on it during flight.

Carbon fiber reinforced plastics were chosen for the upper body tube due to their low density and high stiffness. A Toray Composites T800H unidirectional pre-impregnated (prepreg) carbon fiber was used to manufacture the airframe body tubes (see Appendix A for material data sheet). This prepreg carbon fiber was chosen because of its variable cure temperature, allowing for flexibility in the manufacturing method. In order to create structurally sound body tubes, a stack pattern returning quasi-isotropic material properties was chosen. The stack pattern calculated using Classic Laminate Theory was $[0, 90, 0, +45, -45]s$. This pattern allows the tube to handle loads in both the axial and hoop directions, along with torsional loading. The tubes are made to have an 8 in outer diameter to match the outer mold of the rocket.

Finite Element Analysis

To facilitate detailed analysis of stress concentration under various loads, a Finite Element model of the body tube was made using FEMAP. The model was tested under several loads, including an axial load applied to the rim of the tube, an axial load applied through the bolt holes of the tube, and an internal pressure. These load cases model the acceleration forces during flight as well as the pressure loading during deployment of the recovery system. Several meshes of the tube were generated and tested under the axial loading until the resulting maximum failure index had converged to within 1%.

The load case resulting in the largest failure index was the axial loading when applied through only the bolts. The stress concentration occurred at the bolt holes, with a peak value of 0.208 or a factor of safety of 4.8. Contours of the stress concentration are shown in Fig. 34 and Fig. 35.

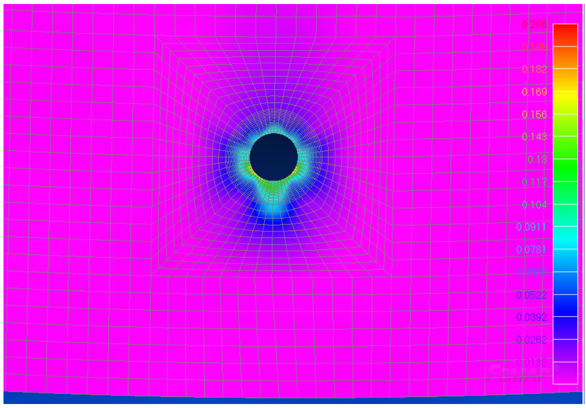

Figure 34. Stress concentration contour of upper body tube top holes.

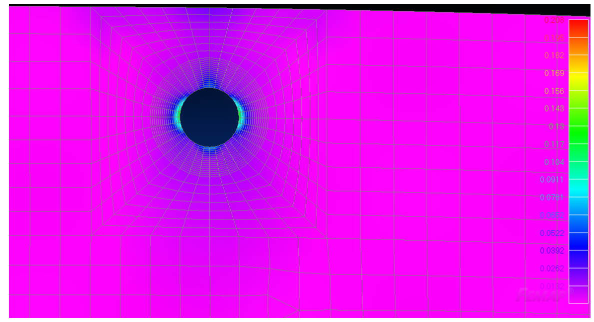

Figure 35. Stress concentration contour of upper body tube bottom holes.

E. Fins

The fins feature an innovative design to allow for optimal alignment and streamlined manufacturing as well as adequate stability and overall performance. This is achieved via a new two-stage manufacturing process consisting of a mechanical interface assembly to ensure proper alignment combined with standard carbon fiber layup and curing techniques.

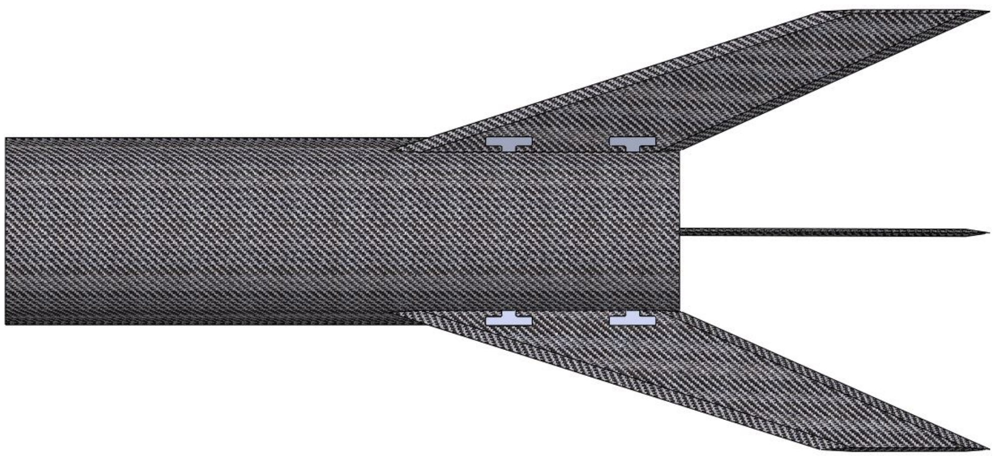

Figure 36. External view of fins.

In this design, a foam core was cut to the desired fin geometry, shown in Fig. 36, and was overlaid with carbon fiber. Prior to curing, machined aluminum inserts were set into the foam using epoxy. Both the fins and a separate carbon fiber tube, the fin can, were cured individually. The cured fins were then bolted radially through the fin can to ensure proper alignment. Carbon fiber was laid over the full assembly to permanently hold the aligned fins in place. Structural fairings were also added to the fin roots during this process to aid in flutter reduction.

A portion of the structural analysis has been devoted to studying the expected aeroelastic flutter and its effects on the fins. The fin design this year intended to reduce the possibility of failure by first substantiating a boundary point for the flutter as a relation to velocity. This relation is defined as:

$$V_f = a\sqrt{\frac{G}{\frac{1.337AR^3P(\lambda+1)}{2(AR+2)(t/c)^3}}} \tag{3}$$

where a is speed of sound, G is the shear modulus of the material, λ is the ratio of chord length from tip to root, c is the mean chord length, AR is aspect ratio, t is thickness, and P is pressure. For swept fins, the results of Eq. 3 must be adjusted for any non-zero angle using the relation in Eq. 4:

$$V_s = \frac{V}{cos\Lambda} \tag{4}$$

which correlates to the example shown in Fig. 37 of a swept wing profile.

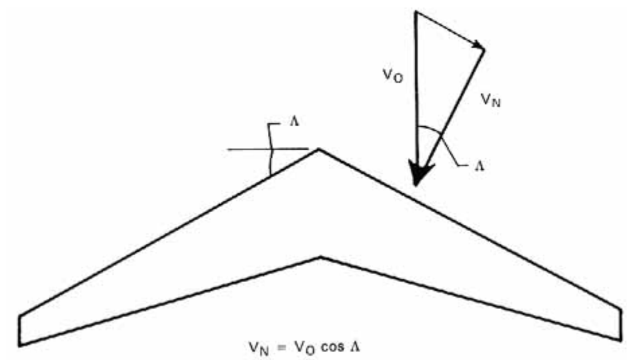

Figure 37. Effective velocity over swept wing of angle Λ

It is important to note that the relation in Eq. 3 is for isotropic material cases, which is not the case for the current design. As such, this relation was used for simplified fin geometry comparisons as more steps were taken to find an applicable relation for orthotropic materials. To modify the velocity boundary relation, the material needed to be idealized as isotropic, effectively changing its shear modulus. The following sourced relation shows that

$$G_{ef} = \frac{G_a G_b}{\Upsilon_a G_b + \Upsilon_b G_a} \tag{5}$$

where G_{ef} is the idealized shear modulus, and G and Υ are the respective shear modulus and volume fraction of each material. This relation provided a more accurate expectation of the flutter limit.

Computational Analysis

In order to simulate the conditions experienced by the rocket during its launch and ascent, RASAero II and Open Rocket were used. Both programs were chosen for having accurate results of $\pm 3.38\%$ and $\pm 10\%$ between simulation and experimental data. To begin, the atmospheric conditions of the launch site, Las Cruces, New Mexico, were input using previously recorded weather data for the competition dates of June 19 - 23. The engine's motor file was determined based on the rocket's anticipated impulse and burn duration. When setting the launch rail for the rocket, a height of 28 feet was used with an offset angle of 5° from normal.

For the initial fin design, the dimensions of a low, swept shape were used to establish a foundation to work from. Important factors that were focused on maintaining a static margin of 1.5 and 3 calibers throughout the rocket's flight as well as maximizing the max apogee distance. After initial launch simulations were ran, the rocket's height, velocity, stability, and drag over time were recorded and plotted. The fin's sweep distance, sweep angle, root and tip chord length, and span were incrementally changed while ensuring each iteration's data was saved. By following trends of increases in height and stability, three varying fin designs were created, as seen in Table 1. Based on this analysis, Fin 1 was chosen for *Boundless*.

Table 1. Fin dimensions used in trade study.

Fin	Root Chord (inches)	Tip Chord (inches)	Span (inches)	Sweep (inches)
1	12.54	7.254	8.750	18.49
2	11.88	2.229	9.788	21.94
3	13.60	3.863	9.063	20.45

Once all of the parameters for the rocket were inputted, simulations were conducted for each of the three fins. The main variables of concern from the data outputted were altitude, stability, drag, and velocity over time. However, it was clear that between RASAero and Open Rocket, there was a distinct difference between the results produced. This was particularly noticeable when comparing the Mach number against the stability of the rocket. In Fig. 38 to 40, the RASAero plot does not show the same sharp decrease in stability at burnout as Open Rocket does. The program also shows that the stability only changes a negligible amount even after achieving apogee. Despite having a reported accuracy of $\pm 3.38\%$ from experimental testing, RASAero appears to have over simplified the results in comparison to Open Rocket and ignored the larger fluctuations in data before, at, and after burnout.

The plots displayed trends that helped determine the fin geometry that would be most efficient. Altitude was plotted from the data of both programs, shown in Fig. 38 to Fig. 40), with Open Rocket displaying max apogee heights of 32,917 ft, 33,286 ft, and 33,155 ft, for fin geometries 1, 2, and 3, respectively. RASAero had values that were several thousand feet greater at 39512 ft, 39965 ft, and 39,615 ft. This altitude difference can be attributed to different methods of calculation as well as the fact that RASAero does not provide the same accessibility to add or remove weights. However, the common trend among the three plots demonstrated how the apogees do not vary significantly from the average of 33,119 ft. for Open Rocket and 39,697 ft. for RASAero. It is also noted that the maximum altitudes are all reached in approximately 46 seconds for Open Rocket and approximately 51 seconds for RASAero. After analyzing and comparing the data from above, fin geometry 1 was chosen for having the best combination of maximum altitude and consistent stability.

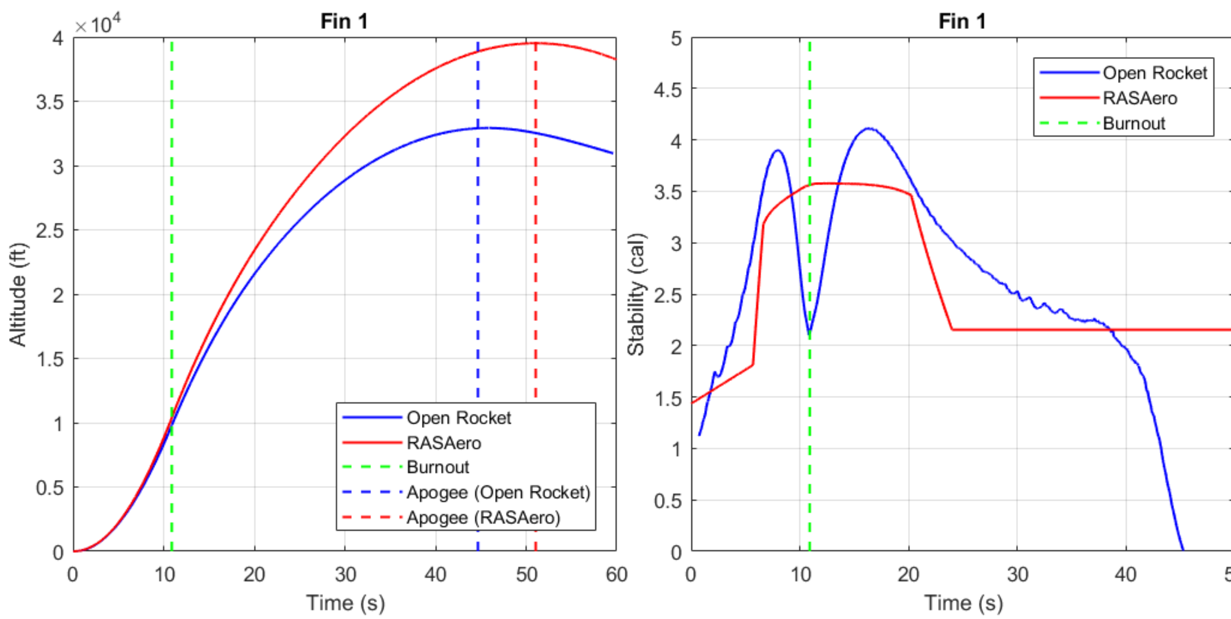

Figure 38. Altitude and stability vs. time for Fin 1.

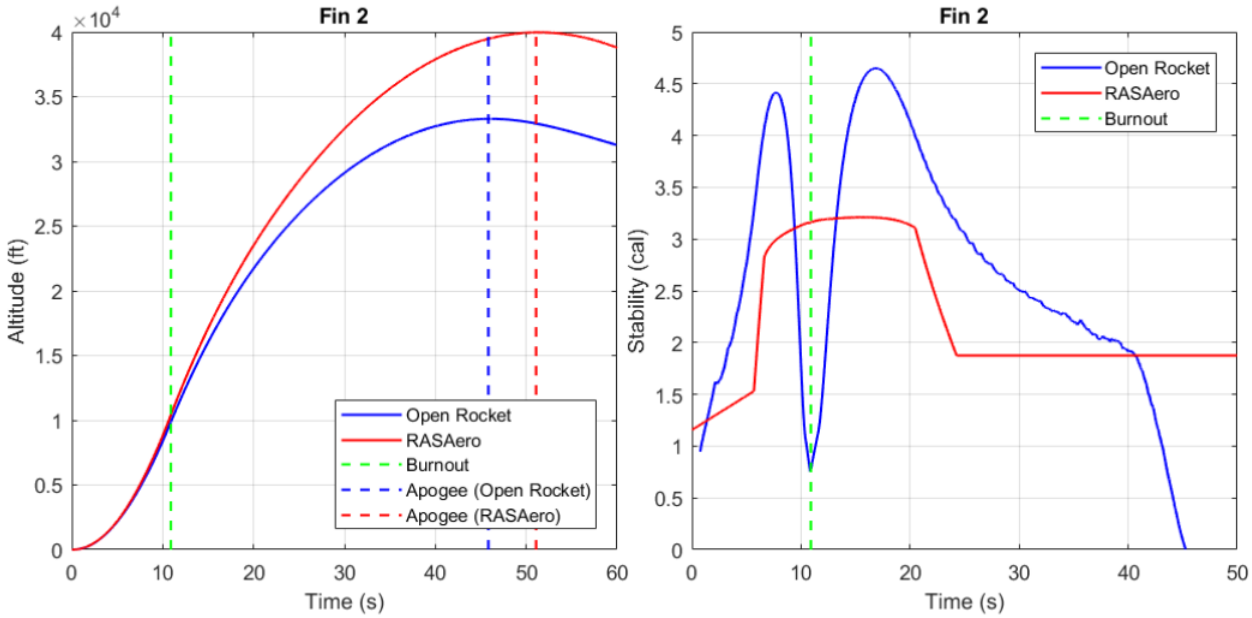

Figure 39. Altitude and stability vs. time for Fin 2.

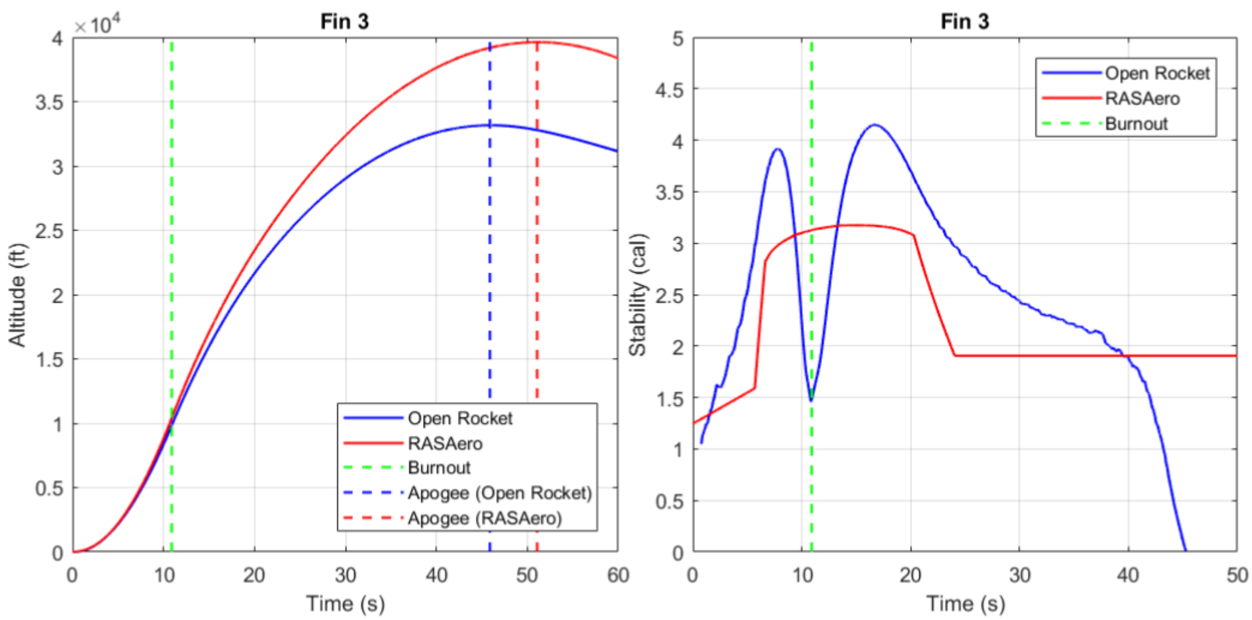

Figure 40. Altitude and stability vs. time for Fin 3.

Once the three static hot-fire tests were completed, thrust curves were acquired and used for the analysis of Fin 1. The manufacturing phase for the rocket was also completed and allowed all of the individual components to be weighed and measured. From these dimensions, a more accurate model of the rocket was inputted into OpenRocket for analysis. The calculated and weighed mass values, 176 lbs and 173 lbs respectively, as well as the calculated and measured center of gravity values, 105 inches and 103 inches from the tip respectively, were within an acceptable percent error of under 5%.

Stability caliber is used as a guideline for flight expectations, defined as the approximate distance, measured in body widths, between the center of pressure and center of gravity. The stability caliber has been determined using

OpenRocket and independent calculations to be at or above the specified 1.5, within the required range for stable flight.

From the second test fire, an apogee of 27,063 ft was outputted along with a stability range of 0.5 to 3.6 calibers. For the third and final test fire, the maximum altitude was determined to be 32,133 ft with a similar stability range to the previous results of 0.5 to 3.5 calibers. These can be seen in Fig. 41.

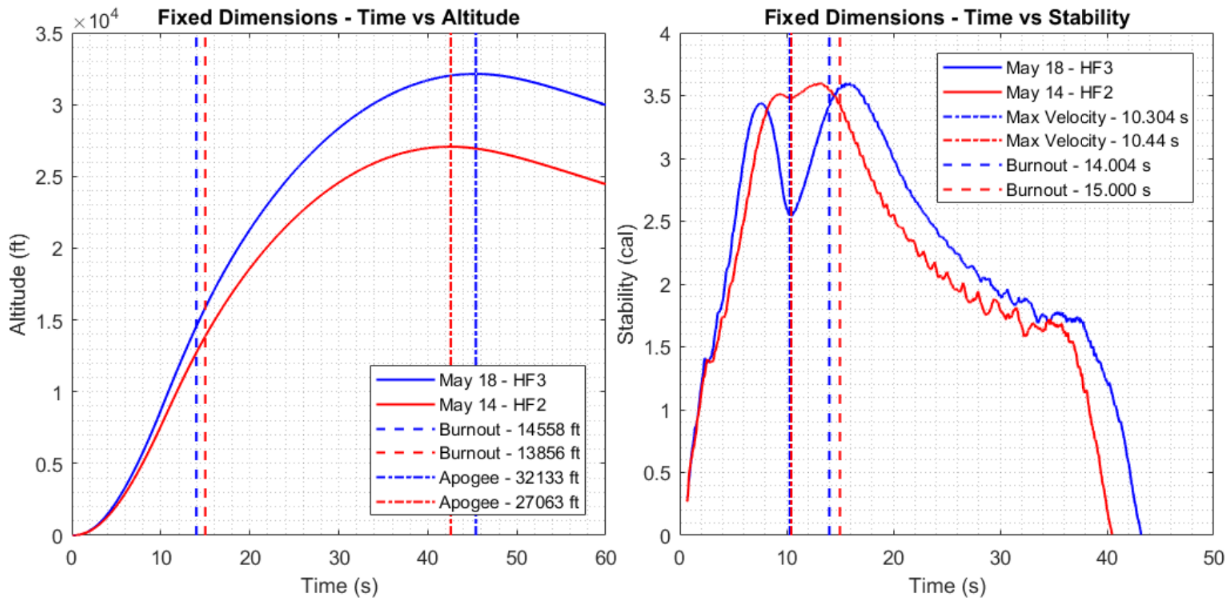

Figure 41. Altitude and stability vs. time for Fin 1 using hot fire test data.

F. Tail Cone

The tail cone was introduced to reduce drag during coast and increase the apogee altitude. The design depicted in Fig. 42 was decided upon because it tapers the outer diameter of the rocket from 8 inches to that of the rocket's nozzle, while effectively covering the nozzle so as not to leave it exposed on the aft section of the rocket. To determine the effectiveness of the tail cone, flight simulations of the rocket both with and without the tail cone were run in Open Rocket to determine the altitude of the rocket as a function of Mach number. The altitude plot is shown in Fig. 43.

Figure 42. External view of tail cone.

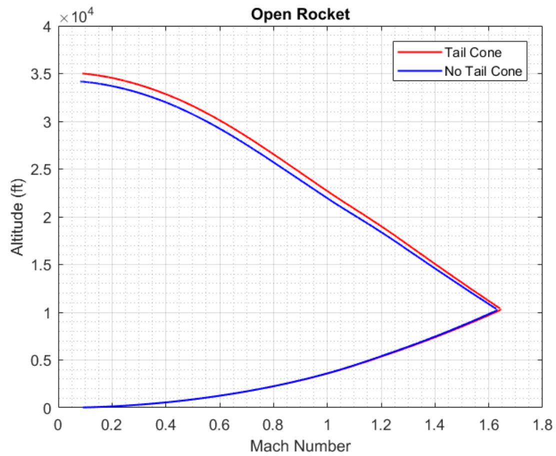

Figure 43. Altitude vs Mach number for tail cone configurations.

It can be seen from the altitude plot that the use of a tail cone increases the maximum achieved altitude by approximately 1,000 ft.

II.III. Recovery Subsystems

The recovery system includes the rocket's parachutes and all components that facilitate their deployment, as well as the tracking systems that will locate the vehicle. This includes the altimeters and wiring, the CO_2 nose cone ejection mechanism, the main parachute release mechanism, the parachute rigging, and the avionics suites.

A. Parachutes

The rocket has two parachutes: a 24 in. diameter drogue and a 144 in diameter main. Both parachutes were sewn by students and have toroidal geometries with an estimated drag coefficient of 2.2. Using 132 lb for the dry weight of the rocket, the descent rate under drogue is calculated to be 128 ft/s and the descent rate under main is calculated to be 21.4 ft/s. A picture of the main parachute during inflation testing can be seen in Fig. 44.

Figure 44. Inflation testing of main parachute.

The parachutes were sewn from 1.1 oz. calendared ripstop nylon and heavy duty sewing thread. The fabric patterns for the panels are in Appendix F. All seams were doubled over to produce a reinforced and non-fraying seam. The shroud lines are continuous lengths of 1.8 mm Dyneema running from one side of the parachute to the other, and loop through the primary recovery rigging, making the two inseparable short of severing Dyneema. The shroud lines are each rated to 500 lb of force.

Using Parks College Parachute Research Group's tool, OSCALC, the main parachute's opening shock force without reefing would be 2000 lb. To lessen this force, a student-machined aluminum reefing ring is placed on the main parachute's shroud lines. Additionally, taped and threaded Z-folds are added to the primary recovery ropes. All parts of the rocket that take the full opening force of the main parachute are designed for a 2000 lb load. This includes the rigging lines and the recovery coupler. Similarly, the opening shock of the drogue parachute was calculated to be 300 lb. The parachute stage separator was brought to failure at 3.75 times that load during an Instron strength test.

B. Parachute Stage Separator

The parachute stage separator (PSS) is a mechanical subsystem that releases the main parachute when main deployment is triggered by the altimeters. It releases a 2.5 ft line under tension. Its design is based off the three ring release, which skydivers use to cut a fouled parachute before deploying an emergency chute. The three rings interlock together to provide mechanical advantage, meaning that two strands of heavy duty sewing thread can hold the full tension of drogue parachute deployment. For redundancy, a single continuous loop composed of eight passes of thread run through a hole in the nylon webbing and through two electrically isolated coils of nichrome wire. When the altimeters send current through the nichrome wire, heating them, the thread is severed. Only one thread must sever to release the smallest ring. This allows tension to pull the small ring through the middle ring, which may then pull through the large ring, fully separating the PSS. This mechanism can be seen in Fig. 45.

The nichrome wires are connected to 22 American Wire Gauge (AWG) leads with ring crimp connectors. The leads are run through the inside of the tubular nylon webbing connecting the PSS to the hard point. They emerge from the webbing through a small hole and connect to the terminal blocks. The nichrome wire itself is shielded from accidental damage or electrical conduction with a 3D printed ABS housing (Fig. 46), which is then sewn to the webbing.

Figure 45. External view of PSS. (nichrome wires not visible)

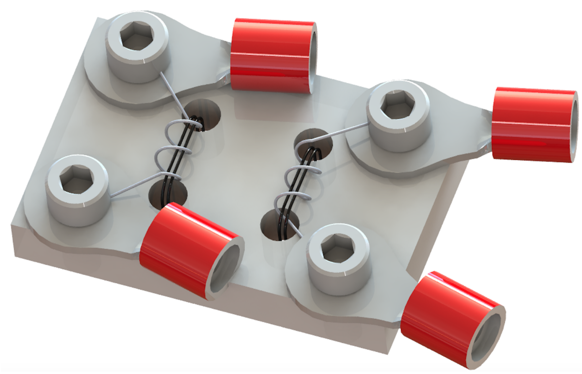

Figure 46. Close-up of wires box under PSS, showing nichrome-wrapped thread

The PSS is packed into the upper body tube above the main parachute bag and below the drogue parachute. One end is tethered to the point labeled "PSS" in Fig.47 and the other end is the webbing tethered to the hard point on the recovery coupler bulkhead. When the drogue parachute is deployed, it lifts to just above the upper edge of the upper body tube. When the main parachute is deployed, most of the PSS remains tethered directly to the hard point, while the largest ring remains tied to the main line as it pulls away.

The PSS is electrically redundant. If either of the nichrome wires receives current, the system will deploy. The two nichrome wires are wired separately to the two altimeters. The PSS has been test-deployed multiple times under 130 lb of tension, which simulates the weight of the rocket falling at constant velocity under drogue.

C. Rigging

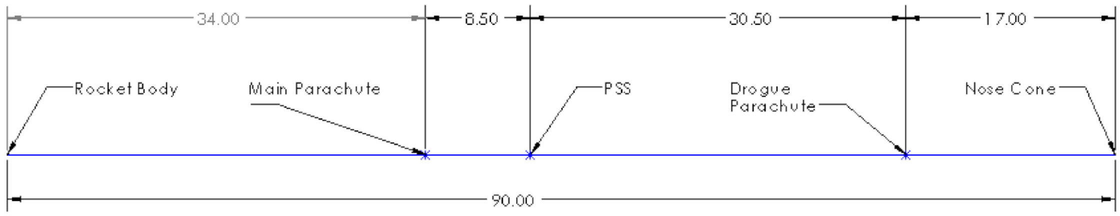

Figure 47. Parachute system rigging (dimensions in ft)

The rigging for the parachutes consists of one 90 ft. length of 3/16" AmSteel Blue rope. Loops are tied in this line at various points to attach to hardware, as diagrammed in Fig. 47. When the nose cone is ejected by the CO_2 mechanism, the drogue parachute pulls all of the length of the rigging line above the PSS taut and out of the rocket. When the PSS releases the direct connection from the the middle of the rigging line to the hard point, the drogue parachute pulls the main parachute out of its bag and the upper body tube, allowing it to deploy.

To organize the lines, prevent fouling, and absorb some of the opening shock loads from parachute deployment, the 34 ft length, the 8.5 ft length, and half the 30.5 ft length of the rigging line were bundled into Z-folds. Most Z-folds use masking tape, while several on each line use nylon thread. This tape/thread breaks under the initial shock load during drogue or main deployment, reducing the peak shock load transmitted to the rest of the rocket.

A fireproof bag for the main parachute and the 34 ft length of rope was sewn from Nomex. It helps organize the upper body tube, prevents fouling, and protects the main from the ejection gasses of the CO_2 mechanism. The bag itself is tied to the hard point so that it does not leave the upper body tube during main parachute deployment.

To prevent zippering, bumpers were constructed to affix to the parachute harnesses where they contact the upper edge of the upper body tube. The bumpers are composed of layers of closed-cell foam and thick fabric, which help absorb and spread impact forces between the rope and the body tube upon parachute deployment.

D. CO_2 Ejection Mechanism

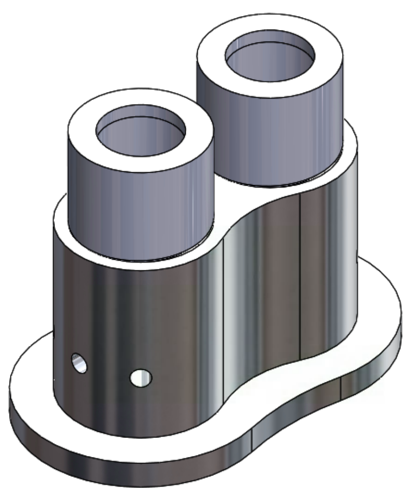

Figure 48. External view of CO_2 ejection mechanism.

The CO_2 ejection mechanism, shown in Fig. 48, is a student researched and designed pyrotechnic subsystem that punctures two 45 g CO_2 canisters. It is triggered at apogee, and the carbon dioxide provides enough pressure to shear through the nylon bolts holding the payload coupler on. This ejection of the payload coupler deploys the drogue parachute, which is packed at the top of the upper body tube. The payload coupler is at this point still tied to the rocket, as shown in Fig. 47.

The CO_2 ejection mechanism is mounted to the top recovery coupler bulkhead, with the two canisters protruding through the bulkhead and into the recovery coupler itself. When the altimeters send current to the igniters, the black powder charge is detonated. This sends the plunger into the CO_2 canister at high speed. The diaphragm on the canister is ruptured, and the CO_2 escapes out the side holes, flooding the upper body tube.

The CO_2 ejection mechanism is electrically and physically redundant. While there are two CO_2 cylinders, testing has shown that one is enough to successfully deploy. Furthermore, each black powder charge has two igniters, with one coming from each of the two altimeters. If one igniter were to fail, that charge would still detonate. If one altimeter were to fail, both charges would still be detonated.

Because the CO_2 subsystem relies on briefly using the upper body tube as a pressure vessel, precautions must be taken to seal it. On the bulkhead, custom rubber gaskets seal the holes for the eye bolt and the CO_2 ejection mechanism. The main electrical connector through the bulkhead was epoxied in place. The welded seam in the upper skirt of the recovery coupler was sealed. Thread tape was applied to the bolts fastening the upper body tube to the recovery coupler. Thread tape was also applied to the bottom edge of the payload coupler. This sealing effort was proven effective, as the CO_2 ejection mechanism successfully ejected the payload coupler using only one CO_2 canister during ground testing.

E. Recovery Electrical System

All recovery events are controlled via two off-the-shelf Featherweight Raven altimeters, which are entirely independent and redundant. They are programmed identically. Launch is detected via accelerometer. One apogee channel is programmed to fire when barometric pressure begins increasing, while the other is programmed to fire when velocity detected by accelerometer becomes negative. Both of the main channels are programmed to fire when the barometric pressure is increasing, altitude is less than 1,500 ft AGL, and velocity is less than 400 ft/s. Because the apogee leads are wired in parallel, if any of the four apogee channels between the two altimeters fires, both CO_2 canisters will be punctured simultaneously.

The wiring between the altimeters and the components they control is shown in Appendix F. The altimeters are powered by three 9V batteries, with two of them wired in parallel. For each battery, the positive lead is broken by a key switch, then connected to both the 10-pin military connector and to the positive terminal on the altimeter. Similarly, the four channels on the altimeter are connected to the military connector. Finally, the negative lead on the battery is connected directly to the negative terminal on the altimeter.

Figure 49. Installed recovery components in recovery coupler. (arming switches visible)

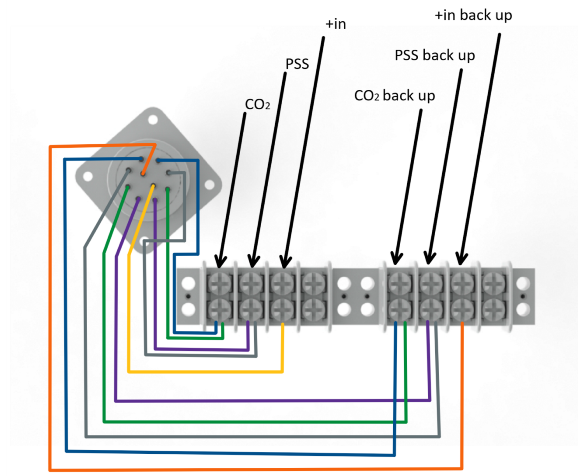

Figure 50. Recovery bulkhead wiring diagram

The 10-pin military connector is a removable, airtight electrical connection between the altimeters below the recovery coupler bulkhead and the recovery components above it. Fig. 50 shows how the top of the recovery coupler bulkhead is wired. Upon installation, the leads from the CO_2 igniters and from the PSS are connected to the screw terminals. The upper half of the military connector and the wires running from it to the terminal blocks are permanently installed. All connections to the military connector on both sides were soldered. All connections to the terminal blocks from the military connector use ring crimp connectors. All singleton wires to recovery components (e.g. a PSS negative lead) were wrapped at least 180 degrees clockwise around the correct screw before the screw was tightened down securely. When multiple leads are fed into the same screw terminal, ring connectors were used.

F. Avionics

The Avionics system includes a diagnostic sensor suite with telemetry capabilities, an automated packet reporting system (APRS), as well as redundant emergency transmitter beacons. The diagnostics sensor suite collects altitude, orientation, GPS data, acceleration, and speed. These data points are both saved to an local SD card and transmitted to command. This suite exists in the recovery coupler, neighboring the Raven altimeters. The APRS, located in the nosecone, transmits in the 70 cm band. The APRS data will be received at the ground station using a hand held radio containing a built-in terminal node controller, allowing APRS packets to be decoded without depending on local towers. Lastly, two low powered beacons will be placed on the rocket; one in the nosecone, and one in the actuated valve bay.

II.IV. Payload Subsystems

The 2018 SARP payload is an autonomous exploratory vehicle. The rover's mission is to characterize the surrounding climate of the New Mexico desert upon landing. For this reason, the rover will be collecting pressure, temperature, air quality, and humidity data. The deployment scheme of the rover mimics the parachute deployment of the Recovery team. After the rocket has deployed the main parachute, the CO_2 system within the nosecone will separate the nosecone from the payload coupler at 1,500 ft from ground level, freeing the rover. The rover will then be suspended and tethered to the nosecone and coupler. Once the rocket has landed, the rover will exit its enclosure and perform its mission.

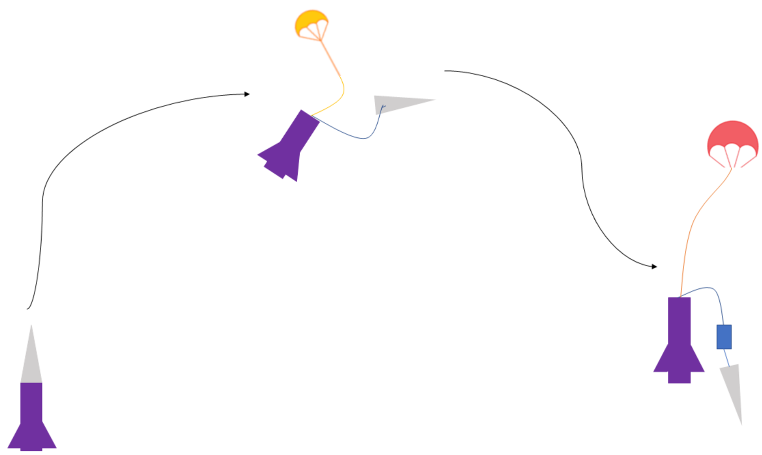

Figure 51. Payload deployment scheme.

A. CubeSat Rover Enclosure

The rover will be housed in the nosecone within its enclosure shown in Fig. 52. The cage meets a 3U CubeSat standard. To be able to support the expected loading of the ejection, the cage was built out of the following materials: aluminum plates, aluminum spring hinges, eye bolts, and wooden side doors. The main structural components that will take the tensile loading once the payload is deployed are the aluminum walls of the cage. The spring hinges will act in compression on the wooden doors to open. The three wooden doors will be held together by a single aluminum pin.

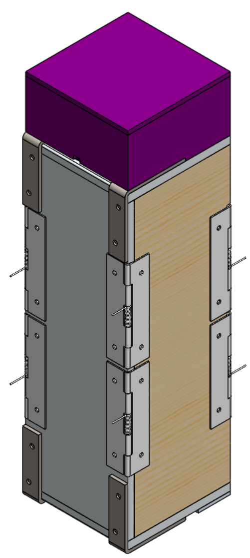

Figure 52. External view of rover enclosure.

The cage described above will open once the rocket lands, using a servo arm and hinged wall panels. The servo is attached to the single pin that holds the wooden doors together. This pin will be pulled out when the servo arm rotates. The servo attached to the arm will be controlled by an Arduino. The outer dimensions of the cage will be confined to the 3U standard of approximately 12 in X 4 in x 4 in. The rover will fit inside this cage with an outer diameter of 3.6 inches and length of 11.5 inches.

To ensure the strength of the cage would be sufficient to withstand the expected deployment load, FEA was conducted to determine the expected stresses with pressure loading. An expected pressure loading from deployment of 12 psi was assumed. Fig. 53 shows the von Mises resultant stress concentration. As shown in the figure, the higher stress concentrations are located near the L-brackets at the top and bottom of the cage. It was determined that the cage would withstand the expecting loading and launch.

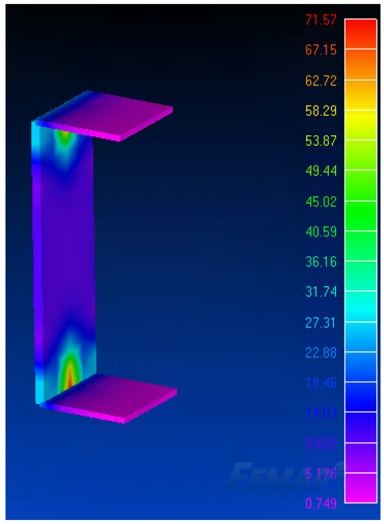

Figure 53. Von Mises stress distribution for payload coupler under deployment pressure load.

B. Rover Vehicle

The 2018 payload is an autonomous exploratory vehicle. The goal of making the rover autonomous is to demonstrate and explore the use of control theory in autonomous vehicles, an emerging technology in many fields. The rover therefore has a predetermined maneuver to perform upon landing that will take it up to 500 m in distance from the rocket. During this time, the rover will be collecting and storing data to an onboard Micro SD card.

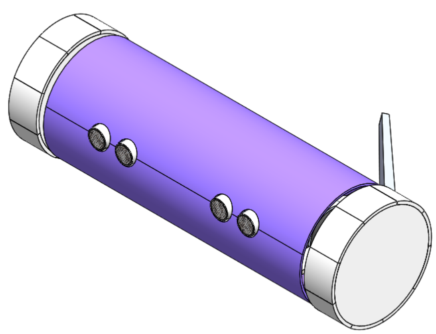

Figure 54. External view of rover.

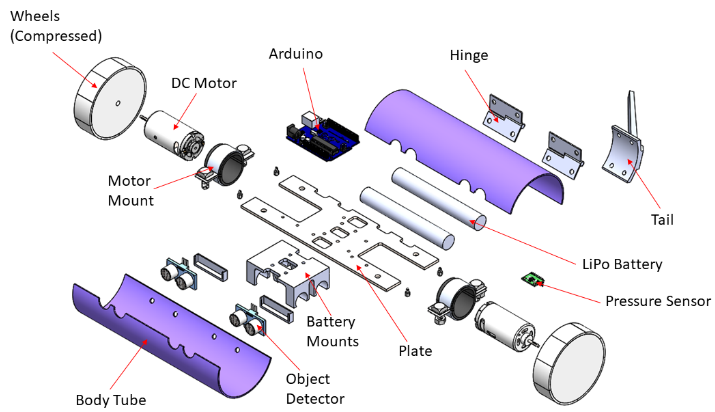

Figure 55. Exploded view of rover internals.

An Arduino Uno was used because of its availability, price, and large online database. Arduino also has a wide variety of sensors, which were used to assist in the rover control. The main component of the rover control was an Ultrasonic Distance Sensor (UDS). The UDS was used to detect obstacles in the path of the rover. If an object is detected, the rover will follow a path to avoid the obstacle before returning to its objective path.

The rover will be collecting its data using an Adafruit BME680 sensor. This data will be stored on board as well as transmitted back to ground control. In order to receive data from the rover in real time, the recovery bay avionics suite is used to assist in data transmission. The recovery bay avionics suite will record and send the rocket's GPS location during flight. Once the rocket has landed, the rover will take advantage of the telemetry infrastructure located in the suite, sending data across the launch site to ground control. The data transmission plan is shown in Fig. 56. The rover will use an Adafruit RFM96W LoRa Radio Transceiver Breakout (433 MHz) to send data back to the rocket. The antenna is a simple thin wire. In addition to this, an onboard SD card will be used to store this data in case of failed data transmission.

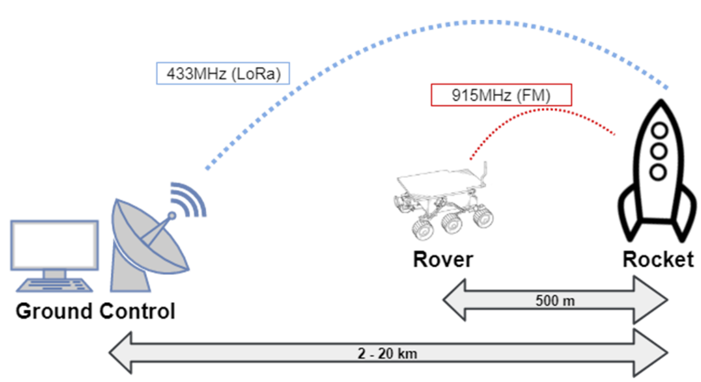

Figure 56. Payload data transmission schematic.

To accommodate the necessary electronics, the diameter of the rover body should be as large as possible. Trade studies were performed to develop a wheel that would increase the clearance of the body off the ground, thereby increasing the allowable diameter of the rover body. The chosen wheel is a spring-actuated wheel; it will be compressed when packaged into the payload cage, and upon deployment, will expand as seen in Fig. 57. The wheel hub and wheel pads were 3D printed with PLA.

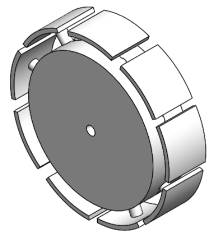

Figure 57. External view of expanded rover wheel.

III. Mission Concept of Operations Overview

A flow-chart of the SARP Mission Concept of Operations for *Boundless* can be seen in Fig. 58.

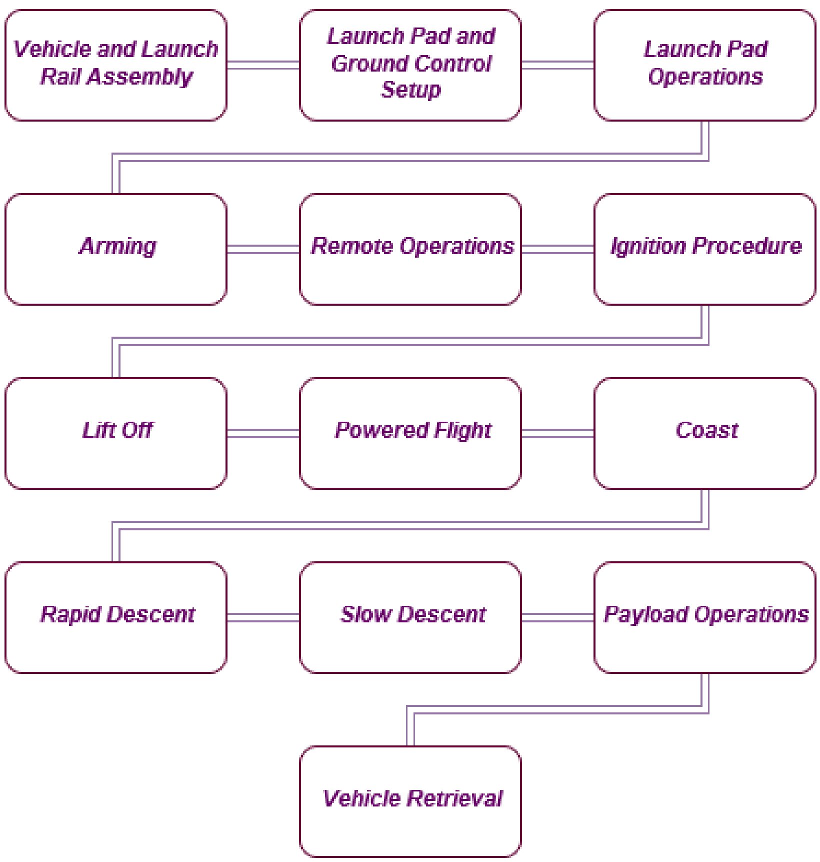

Figure 58. Mission operations flow chart.

Phase	Transitions and Nominal Operations
	All batteries are determined to be fully charged.

Vehicle and Launch Rail Assembly	Assembly and integration of all rocket subsystems are completed. Launch rail is fully assembled. All rocket subsystems are in place. Transmission of APRS packets is confirmed.
	Launch rail and vehicle fully assembled.
Launch Pad and Ground Control Setup	Antennas are raised, connected, and powered. Router and access point are connected and powered. Launch pad and command computers are powered. Fill stand is erected and all valves are connected to fill box. Initial fill stand checks are completed.
	Rocket is brought to the launch pad to be put on the rail.
Launch Pad Operations	Systems tested to ensure nominal behavior. This includes telemetry connections verification, final valve checks, leak checks, ignition/injection system checks, and network connection confirmation. Propellant umbilical is connected to the vehicle for the final time.
	Non-critical personnel have evacuated the launch pad.
Arming	Systems are armed. These include the recovery system, payload, avionics, and ignition box. Avionics transmissions are confirmed.
	All personnel have evacuated from the launch pad.
Remote Operations	Motor is loaded with propellant remotely from ground control to nominal pressure and mass. Connection between command box and on board computers are confirmed periodically throughout fill.
	Propellant umbilical is detached from the motor.
Ignition Procedure	Given permission from Ignition Team and Range Safety, the team is T-10 seconds to lift-off. Countdown begins. At T-2 seconds, a FIRE signal is sent to the igniter. At T-0 seconds, the main valve opens and oxidizer injection occurs.
	Countdown ends.
Lift Off	Vehicle begins rising off the launch rail. Wired connections between the ground and the rocket disconnect. Actuated valve remains completely open, allowing full mass flow.
	Vehicle leaves the rail.
Powered Flight	Actuated valve remains fully open. Rocket remains structurally stable. The rocket motor continues to burn until resources are depleted.
	Motor loses thrust.
Coast	The rocket reaches apogee. Altimeters fire the CO_2 ejection mechanism.
	Payload coupler and attached nosecone are deployed.
Rapid Descent	The drogue parachute inflates after leaving the upper body tube. Tension from the drogue breaks the Z-folds in the upper section of the rigging line before pulling taut against the PSS and recovery coupler bulkhead. The rocket falls under drogue at a terminal velocity of 126 ft/s.
	Vehicle falls to 1500 ft. AGL.
Slow Descent	PSS deploys, allowing the drogue parachute to pull the main parachute out of the upper body tube. Main parachute inflates while breaking Z-folds in the lower half of the rigging line. Rocket's terminal velocity decreases to 20.1 ft/s. The payload deploys out of the nosecone and remains tethered to between the payload coupler and nosecone.

	Rocket touches the ground.
Payload Operations	Rover cage opens and rover deploys. Rover performs its mission routine.
	Completion of rover mission.
Vehicle Retrieval	Personnel moves out into the field to locate and retrieve the rocket. APRS continues to transmit packets at 0.2 Hz.
	Rocket is retrieved to base.

IV. Conclusions and Lessons Learned

This year, SARP saw a growth in membership, implemented higher-quality design and testing procedures, and built a robust review process. Throughout the year, however, the team encountered both administrative and technical challenges that it is now prepared to face in future years. SARP introduced a number of new administrative procedures this year. These included a member application cycle, internal design reviews, an unveiling event, and a formal leadership application process. Many of these changes were made to better manage a growing team. Though these procedures have been immensely helpful, they have introduced their own set of challenges. The introduction of new design reviews cluttered the overall timeline, while manufacturing and ordering mishaps set us back further than planned. Greater effort at the start of the next year will be put into creating a conservative timeline and the procedures needed to maintain it.

In contrast to previous years, where the new leadership had been selected near the time of competition, the team selected leadership for the 2019 SARP team in early Spring quarter to facilitate a better trasnfer of knowledge. Applicants were required to submit their resumes and a short essay. The current leadership team held formal interviews, simulating an industry interview environment. The early transition allowed the new leadership to not only shadow this year's leadership to gain a tangible understanding of their designated roles, but also encouraged the incoming leads to take on greater responsibility in preparation for next year. Thorough documentation and frequent design reviews has allowed junior members to retain an understanding of the processes implemented by this year's team. With an incoming leadership team that is more informed about their roles, SARP is confident that this knowledge will carry through the successive team.

Technical knowledge of several new systems increased throughout the year. The remote filling and operation systems used for static tests and launches have allowed for a safer and more streamlined filling procedure. Improvements in ignition control systems have prevented cold flows during testing, a common failure mode in past years. Emphasis on validating each individual subsystem before full-scale tests has resulted in individually reliable systems and more streamlined integration. Additionally, personnel have been assigned specific tasks during testing and launching, reducing the potential for error in launch procedures. In the future, this focus on testing and validating individual systems will continue in order to identify failure modes in advance of larger tests.

There have also been several lessons learned over the course of the year. Certain designs, such as the the structural couplers and combustion chamber, are engineered to conservative factors of safety due to uncertainty of in-flight loading, particularly during the main parachute deployment and the internal combustion pressure. More robust modeling and testing earlier in the design process will help to reduce this uncertainty and allow for weight savings. Additionally, the weights of the components were not accurately recorded throughout the year. This reduced the accuracy of theoretical flight modeling until the full rocket could be integrated. Better documentation of the actual weights during manufacturing will allow for more responsive modeling of the rocket's performance.

These improved procedures, combined with increased technical knowledge, have allowed SARP to develop increasingly sophisticated rockets that are safer and more reliable than each previous iteration. By building on setbacks and lessons from this year, SARP will continue its process of innovation and improvement.

V. Acknowledgements

Boundless would not be a reality without the financial support of our generous sponsors and donors. SARP's corporate sponsors include Appian Construction; Blue Origin; Digipen Institute of Technology; Systima Technologies, Inc.; Microsoft; 3DConnexion; Toray Industries, Inc.; Charter Construction; Misumi; SOLIDWORKS; and King Hydroseeding, Inc. Our donors include The Kim Family, Larry Shatos, Thomas Ortman, Queenie Chu, The Thomas Hodge Foundation, Naomi Stokes, Michael Kawaguchi, Ramesh Manne, Sarah Douglass, Janet Nahpi, John and RaDawn Smythe, and Steven Moy.

In addition to the support of SARP's faculty advisor, Professor Carl Knowlen, SARP received technical advising support from many individuals These include University of Washington Professors Raymond Golingo, Jim Hermanson, Justin Little, Kristi Morgansen, John Sahr, Uri Shumlak, and Anthony Waas. Additional support was received from UW staff, including Stanley Choi, Ed Connery, Wanda Frederick, Eliot George, Michelle Hickner, Pam McGrath, Eamon McQuaide, Steve Pearson, Nancy-Lou Polk, Reginald Rocamora, Bob Scott, Fiona Spencer, and Dzung Tran.

Appendix A: System Weights, Measures, and Performance Data

Spaceport America Cup

Intercollegiate Rocket Engineering Competition

Entry Form & Progress Update

Color Key | SRAD = Student Researched and Designed | v18.1

Must be completed accurately at all time. These fields mostly pertain to team identifying information and the highest-level technical information.

Should always be completed "to the team's best knowledge" , but is expected to vary with increasing accuracy / fidelity throughout the project.

May not be known until later in the project but should be completed ASAP, and must be completed accurately in the final progress report.

Date Submitted: 5/24/2018

Team ID: 9

* You will receive your Team ID after you submit your 1st project entry form.

Country: USA

State or Province: Washington

State or Province is for US and Canada

Team Information

Rocket/Project Name:	Boundless
Student Organization Name	Society for Advanced Rocket Propulsion
College or University Name:	University of Washington - Seattle
Preferred Informal Name:	SARP
Organization Type:	Club/Group
Project Start Date	9/27/2017
Category:	30k – SRAD – Hybrid/Liquid & Other

Projects are not limited on how many years they take

Member	Name	Email	Phone
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Alt. Student Lead	Tyler McIrvin	tsmcirvin@gmail.com	15093060332
Faculty Advisor	Carl Knowlen	knowlen@aa.washington.edu	12065437159
Alt. Faculty Adviser			

For Mailing Awards:

Payable To:	Aeronautics & Astronautics ATTN: SARP
Address Line 1:	University of Washington
Address Line 2:	Box 352400
Address Line 3:	Seattle, WA 98195-2400
Address Line 4:	
Address Line 5:	

Demographic Data

This is all members working with your project including those not attending the event. This will help ESRA and Spaceport America promote the event and get more sponsorships and grants to help the teams and improve the event.

Number of team members

High School	0	Male	107
Undergrad	129	Female	24
Masters	2	Veterans	1
PhD	0	NAR or Tripoli	0

Just a reminder the you are not required to have a NAR, Tripoli member on your team. If your country has an equivelant organization to NAR or Tripoli, you can cant them in the NAR or Tripoli box. CAR from Canada is an example.

STEM Outreach Events

SARP participates in the University of Washington Engineering Discovery Days. This is a two day event hosted by the College of Engineering that promotes K-12 exposure to engineering. SARP hosts a booth where the team brings rocket parts for students to interact with and talk to K-12 students about sounding rockets. SARP also visited a local elementary school to talk about rocketry. The most recent event SARP attended was a TedxUW event where team members spoke to attendees about SARP.

Rocket Information

Overall rocket parameters:

	Measurement	Additional Comments (Optional)
Airframe Length (inches):	170	
Airframe Diameter (inches):	8	
Fin-span (inches):	6.81	
Vehicle weight (pounds):	121.2	
Propellent weight (pounds):	48	
Payload weight (pounds):	8.8	
Liftoff weight (pounds):	178	
Number of stages:	1	
Strap-on Booster Cluster:	No	
Propulsion Type:	Hybrid	Paraffin/Nitrous Oxide
Propulsion Manufacturer:	Student-built	
Kinetic Energy Dart:	No	

Propulsion Systems: (Stage: Manufacturer, Motor, Letter Class, Total Impulse)

1st Stage: SRAD Hybrid, 12 pounds of paraffin wax fuel and 36 pounds of nitrous oxide, O Class, 40,960 Ns

Total Impulse of all Motors: 40,960 (Ns)

Predicted Flight Data and Analysis

The following stats should be calculated using rocket trajectory software or by hand.

Pro Tip: Reference the Barrowman Equations, know what they are, and know how to use them.

	Measurement	Additional Comments (Optional)
Launch Rail:	Team-Provided	
Rail Length (feet):	36	27 feet from top launch lug to top of rail.
Liftoff Thrust-Weight Ratio:	6.9	
Launch Rail Departure Velocity (feet/second):	116.9	100.1 ft/s when the top launch lug has cleared the rail.
Minimum Static Margin During Boost:	1.5	*Between rail departure and burnout
Maximum Acceleration (G):	6.9	
Maximum Velocity (feet/second):	1544.9	
Target Apogee (feet AGL):	30K	
Predicted Apogee (feet AGL):	26800	OpenRocket

Payload Information

Payload Description:

This year’s payload will be an exploratory autonomous rover. As of today, the payload is still functional. The payload will be housed in the nose cone within a cage conforming to the 3U CubeSat form factor. Using a combination of IMU’s (sensing the shock of the main parachute tether) and timers with an Arduino, the forces the payload feels will be tracked. At 1,000 ft when the main parachute deploys, the conditions in the Arduino code shall be true.This will then initiate the pressurization of the nosecone, which will detach the nosecone from the coupler. The pressurization scheme uses a CO_2 cannister that is punctured using a puncture disk and black powder charge, like the recovery system deployment. The payload cage will be tethered between the nose cone and coupler with two tethers such that it is suspended once it has been deployed. After release the payload in its cage will be suspended between the coupler and the nose cone via the tethers mentioned above. The payload will continue its decent with the rocket, maintaining the same decent speed as the rocket. The rover will be deployed out of its cage once the rocket has safely landed using the same tracking of acceleration and flight time data. The cage will unravel to allow the rover freedom to move. The payload will then perform a maneuver while collecting atmospheric data (i.e. pressure, temperature, gas composition) and send that data back to the rocket's antenna aboard the flight data suite which will then be transmitted to ground station. The rover will be a two-axis rover with a hollow round body which houses all the electronics and batteries. The wheels will be deployed after landing to increase the clearance above the ground while still conforming to the CubeSat standard during launch. To deploy, the wheels use a simple spring mechanism to expand out once free of the cage. All electronic parts are COTS. The rover is controlled with an Arduino Uno controller. The rover utilizes ultrasonic sensors, an accelerometer,an LoRa transceiver, and a pressure/temperature/humidity sensor to complete its mission. Tests will be performed for the deployment and data collection.

Recovery Information

The entire rocket and all its components are recovered together under a dual-deployment parachute system. The drogue parachute is a SRAD 24-inch toroidal parachute. The main parachute is a SRAD 144-inch toroidal parachute. Both parachutes have been manufactured. Verification of the parachutes included tying them to a vehicle at a nearby beach and flying them in strong winds of up to 30 mph.

All recovery events are triggered by two independent COTS Featherweight Raven altimeters. The Ravens use accelerometers to detect launch, and barometers to detect altitude. The two altimeters are entirely redundant. No event relies on only one altimeter. When a firing condition has been met (e.g. apogee) the Ravens ground current across the appropriate pins.

At apogee (detected by barometric pressure and nominally 30,000 ft AGL), the Ravens send current through electric matches in a pyrotechnic CO_2 release system. This system is SRAD, with its design based off the Peregrine Raptor. A black powder charge pushes a plunger to puncture a 40-gram CO_2 canister. The nose cone of the rocket is fastened with four nylon shear pins. When the upper body tube pressurizes with CO_2, the tethered nose cone ejects and the drogue parachute beneath it is deployed. There are two redundant electric matches per CO_2 canister, and two redundant CO_2 canisters. One CO_2 canister alone is enough to eject the nose cone and deploy the drogue parachute. The CO_2 system has been detonation tested and it has performed successfully at least once. More tests are planned. If it fails further validation, the SRAD system can be swapped out for the COTS Peregrine Raptor.

At 1000 ft AGL (detected by barometric pressure), the Ravens send current through nichrome wire in the Parachute Stage Separator. The estimated descent rate under drogue is 122 ft/s. The Parachute Stage Separator is an SRAD part based on a three-ring release, a system commonly used in skydiving for cutting a fouled chute. When the drogue parachute deploys, the load path is through the Parachute Stage Separator to the recovery bulkhead. When current is sent, nichrome wire cuts a retaining thread, and the Parachute Stage Separator releases that load path. The drogue parachute is free to pull the main parachute out of its bag and out of the upper body tube. This is how the main parachute deploys. The estimated descent rate under main is 20.5 ft/s.

Planned Tests

* Please keep brief

Date	Type	Description	Status	Comments
2/26/18	Ground	Injector test - cold flow	Successful	rent injector port geometries. Expected mass f
4/27/18	Ground	Static test of hybrid motor.	Minor Issues	Tare test with self-pressurized N2O
5/11/18	Ground	Static test of hybrid motor.	Successful	Configuration test with back pressurized N2O
5/18/18	Ground	Static test of hybrid motor.	Successful	Configuration test with back pressurized N2O
5/17/18	Ground	Recovery deployment test.	Successful	ful deployment of parachute with one CO2 car
5/24/18	Ground	Recovery deployment test.	Minor Issues	CO2 cannisters. One piston bound to the casir
5/28/18	Ground	Payload deployment tets.	TBD	Test rover deployment from enclosure.
5/29/18	Ground	Payload deployment tets.	TBD	egrated rover with nosecone and deploy with
5/30/18	Ground	Recovery deployment test.	TBD	ting of full system with redundant CO2 cannist
6/1/18	Ground	Recovery deployment test.	TBD	ting of full system with redundant CO2 cannist
6/2/18	Ground	Recovery deployment test.	TBD	ting of full system with redundant CO2 cannist

Any other pertinent information:

Please help us to help you, by filling this box out as completely as possible. The more information we have the better we can help you.
(Tip: [Alt] + [Enter] for new line)

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Appendix B: System Test Reports

Recovery System Full Tests

Purpose: The entire recovery system must be validated to ensure that the rocket will return safely to the ground. Redundancy of the recovery system must be proven.

Test Design: The recovery system was tested under flight integration conditions; all rocket components from the recovery coupler to the payload coupler were installed in flight configuration. The entire assembly was set at an angle on grass to ensure the safety of the components. The simulation altimeter was not in flight configuration. It was unscrewed from its mounting because it must be vertical to run a simulated flight. By connecting a computer to the simulation altimeter, a flight was simulated, triggering the various recovery systems. After drogue deployment, drogue parachute tension was simulated by pulling on the drogue parachute by hand.

Figure 59. The recovery full system test apparatus before and during drogue deployment

Safety Concerns: The CO_2 ejection system is an energetic system. Extreme care must be taken at all times while assembling the recovery system. All personnel must wear safety glasses and closed-toed shoes throughout the test. All personnel must stand back from the recovery system until after drogue deployment. Bystanders must be warned that the test is ongoing and dangerous.

Test Summaries:

May 17, 2018: The system was set up with only one CO_2 canister armed. This was to prove that the two canisters are redundant. Both drogue and main parachutes deployed successfully and without incident.

May 24, 2018: The system was set up with both CO_2 canisters armed. However, one of the two canisters failed to puncture due to a binding issue. The drogue parachute still deployed. The PSS also deployed, but the main parachute line fouled. The CO_2 system needed minor machining for a better fit, and greater care should be taken in packing the parachute lines. Z-folds are a necessity even for ground testing.

Future Plans: At least three more full recovery system tests are planned between May 25 and June 9, 2018. These tests will assess modifications to the system and ensure reliability. However, as of the successful test on May 17 the recovery system was fully validated.

Propulsion System Cold Flow

Purpose: The oxidizer tank of the SARP hybrid sounding rocket was loaded with nitrous oxide propellant remotely with the equipment to be used in the launch configuration to validate fill and actuation systems.

Test Design: The nitrous oxide propellant is loaded into the oxidizer tank using a remote fill system. The fill control box, located at the launch control site, controls the pneumatic ball valves to remotely fill and a solenoid valve to vent nitrous oxide from the rocket. A diagram of the remote fill system is on the next page. The nominal operating pressures.

Testing: The oxidizer tank was statically mounted and loaded with nitrous oxide via the remote fill system. The system was unloaded with a cold flow test where the propellant flowed through the injection system.

Safety Concerns: The primary safety concerns during cold flow testing are pressure vessel failure and oxygen displacement. Both of these are mitigated by conducting filling and testing remotely in a underground bunker after personnel have been evacuated.

Results: Shown below is the oxidizer tank pressure during coldflow testing.

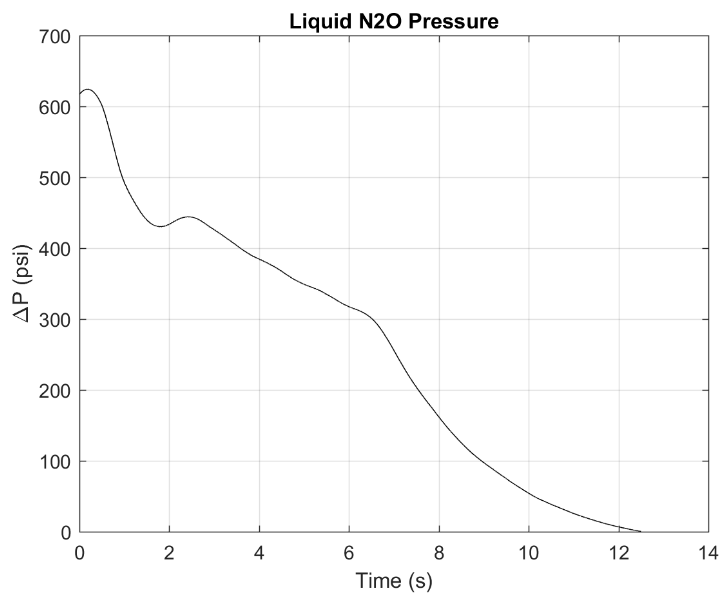
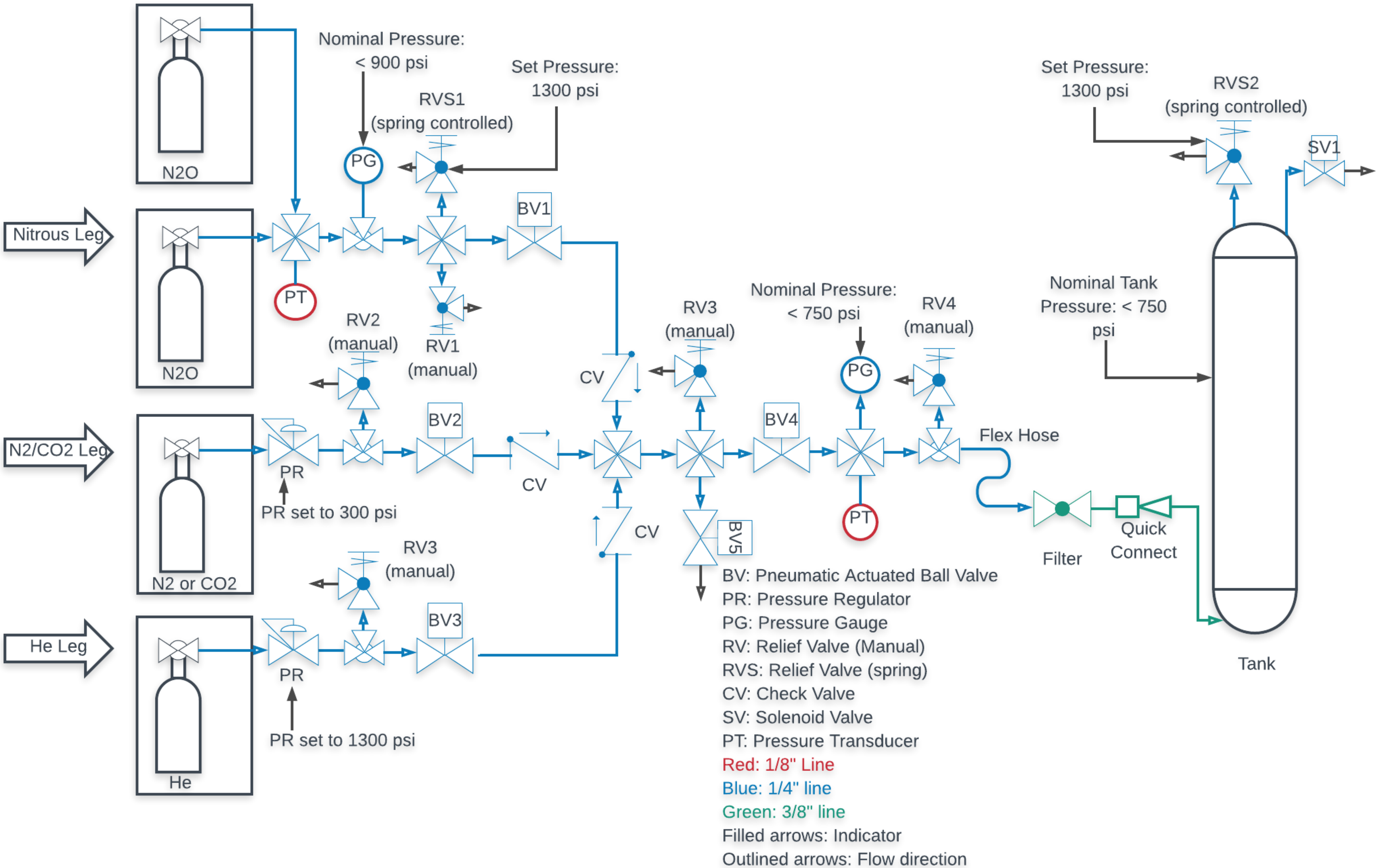


Figure 60. Oxidizer tank pressure during cold flow



N2O
N2O
N2 or CO2
He
Nitrous Leg
N2/CO2 Leg
He Leg
Nominal Pressure:
< 900 psi
PG
PT
RVS1
(spring controlled)
Set Pressure:
1300 psi
BV1
RV1
(manual)
RV2
(manual)
PR
PR set to 300 psi
BV2
CV
RV3
(manual)
PR
PR set to 1300 psi
BV3
CV
CV
RV3
(manual)
BV5
Nominal Pressure:
< 750 psi
BV4
PG
PT
RV4
(manual)
Flex Hose
Filter
Quick
Connect
Nominal Tank
Pressure: < 750
psi
Set Pressure:
1300 psi
RVS2
(spring controlled)
SV1
Tank
BV: Pneumatic Actuated Ball Valve
PR: Pressure Regulator
PG: Pressure Gauge
RV: Relief Valve (Manual)
RVS: Relief Valve (spring)
CV: Check Valve
SV: Solenoid Valve
PT: Pressure Transducer
Red: 1/8" Line
Blue: 1/4" line
Green: 3/8" line
Filled arrows: Indicator
Outlined arrows: Flow direction

Propulsion System Static Hot-Fire Tests

Purpose: The oxidizer tank of the SARP hybrid sounding rocket was loaded with nitrous oxide propellant remotely with the equipment to be used in the launch configuration to validate fill and actuation systems.

Test Design: The SARP hybrid rocket motor is a student researched and developed (SRAD) rocket motor. It consists of an oxidizer tank pressure vessel, actuated injection valve system, and a combustion chamber. The hybrid rocket motor uses 12 lb of paraffin-based fuel and 36 lb of nitrous oxide as propellants. The motor is designed to produce a peak thrust of 1200 lb and a total impulse of 9200 lb-s with a burn time of 12 seconds.

Test: The propulsion system was mounted to a static thrust stand (Fig. 61 below). The loading of the oxidizer and ignition was performed remotely. The hot fire test was performed with all personnel at least 150 feet away behind a protective berm.

Safety Concerns: The primary safety concerns during hot-fire testing are due to over pressurization of the combustion chamber or failure of the oxidizer tank. Both of these risks are mitigate by having all personnel behind the protective berm and out of visual sight of the rocket before oxidizer loading begins. In addition, only essential personnel are present for the ingniter arming and opening of the gas bottles.

Figure 61. Static thrust stand during a hot-fire

Results: The resultant thrust curve of the second hot-fire is shown below. In addition the results of all full-scale hot-fires are summarized below.

Date	Oxidizer Fill Mass (lb)	Peak Thrust (lb)	Burn Time (s)	Impulse (lb-s)	Notes
4/27/2018	28	900	15	4500	TPS failure & blowout
5/11/2018	34	1200	9.5	9200	Valve not fully open
5/18/2018	37	1200	9.5	10500	Nominal

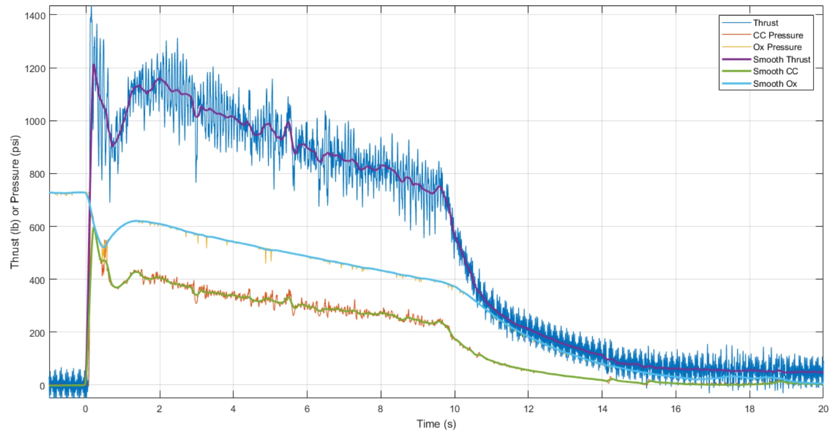


Figure 62. Data collected during the static fire

Pressure Vessel Validation

Purpose: The oxidizer tank and combustion chamber of the SARP hybrid sounding rocket must be proof tested to ensure the structural integrity of the chamber.

Test Design: The oxidizer tank is designed to an operating pressure of 1000 psi, while the combustion chamber is designed to a combustion pressure of 500 psi. Both were tested hydrostatically to 1.5 times their respective operating pressures for over two times the max load duration.

Safety Concerns: The primary safety concern during this testing is a pressure failure. This risk is mitigated by pressurizing and depressurizing each vessel in an underground bunker after all personnel have been evacuated.

Results: Both chambers held the required pressures without showing any signs of yielding. This validates the design factors of safety.

Avionics Subsystem Tests

Purpose: The lifespan and range of the avionics tracking system must be tested to ensure the utmost reliability for launching the rocket to ensure a safe and successful recovery.

Design: The vehicle's avionics tracking system contains redundant tracking solutions for all individual separable parts of the rocket. For primary long-range tracking, held within the nosecone, there is a long range APRS based transmitter capable of transmitting GPS coordinates, altitude, and heading. In addition, a short range "avalanche beacon" style transmitter is also placed inside the nosecone to ensure ease of discovery once the rocket has landed. This transmits at a much lower power to not create any addition interference. Finally, inside the actuated valve bay located in the body tube of the rocket, an additional short range "avalanche beacon" will be installed, in the event the nosecone and body are to separate during main parachute deployment. Ground station contains a hand held radio, utilizing a Yagi style antenna for better reception capability. This radio contains all the necessary software for decoding and logging any data received for future processing.

Range Testing: Range testing of the APRS beacon was conducted under optimal and sub-optimal conditions to determine the max transmission range feasible by the current hardware setup. Optimal conditions included line of sight and full charged batteries which would simulate the best-case scenario for in field tracking. Sub-optimal conditions remove the line of sight aspect to simulate more realistic topography conditions as well as removal of the Yagi style antenna with replacement of the integrated ¼ wavelength hand held antenna. With the APRS beacon transmitting at 5 second intervals, 3 sets of 10 data points were recorded and logged to test for proper data decoding. The amount of data decoded was recorded and then the range was extended until the ratio of decoded to corrupt data met with design specification. The tables and pictures below show the average of different range tests of optimal and sub-optimal conditions utilizing both styles of antennas.

Lifespan Testing: Lifespan/battery Testing was conducted under normal load conditions with all transmitters transmitting at frequencies and power ratings precisely to that when installed in the rocket itself. Each system contains a different capacity lithium polymer battery and therefore will last different amounts of time. The transmitters were plugged in and once transmission had begun, time was recorded until the integrated low voltage shutoff (3.2V) ceased operation. The table below shows the lifetime of each device.

Results: Both the range and lifespan testing demonstrate successful operation. As predicted, under optimal circumstances the APRS has a much farther range than under sub-optimal conditions. All tracking systems function for the desired amount of time.

Test 1: Sub-Optimal	Integrated Hand Held Antenna	Directional Yagi Antenna
1 mile	9 of 10	10 of 10
2 miles	7 of 10	9 of 10
Signal Strength	Moderate	Good

Test 2: Optimal	Integrated Hand Held Antenna	Directional Yagi Antenna
4 miles	5 of 10	8 of 10
5 miles	4 of 10	7 of 10
Signal Strength	Poor	Good

Device	Duration
Long Range APRS Beacon	46 Hours
Close Range Avalanche Beacon	52 Hours

Appendix C: Hazard Analysis

The primary hazardous material that this project deals with is nitrous oxide. The following documentation provides procedure and hazard analysis for handling this propellant.

1. Propulsion System Cleanliness

Before any propulsion system use, the system components are cleaned. This is achieved by using Vertrel MCA, an eco-friendly cleaning solution designed specifically to remove grease and particulates from a system. For non-accessible areas of the oxidizer system, the Vertrel MCA will be flushed through by using pressurized nitrogen. This is done by opening one port on the top of the oxidizer tank and manually pouring the Vertrel MCA into the tank. The port is closed and the tank is rotated to allow the liquid to touch all areas of the inside of the tank. Nitrogen is hooked up to the tank and the bottom port is opened allowing the Vertrel MCA to be purged from the system. For easily accessible sections, Vertrel MCA can be manually wiped using a microfiber cloth, removing all traces of contaminants. All personnel handling the Vertrel MCA are required to wear nitrile solvent-resistant gloves, safety glasses, and respirator masks.

2. Nitrous Oxide Material Compatibility

Materials in contact with N2O:

- Fuel Components - Paraffin wax, Stearic Acid, LDPE, EVA, Carbon black and polycarbonate. All of these are designed to energetically react with the nitrous.
- Actuated Injection: Nozzle: 316 Stainless Steel. Tubing/Fittings: Stainless Steel (304 OR 316). Ball Valve: 316 Stainless Steel Fastener, Ball/Stem, and Body; Fluorocarbon FKM Flange Seal; Reinforced PTFE Seat*.
- Remote Fill: QC: 316 SS, PTFE-coated 300 Series SS, PTFE, Solenoid Valve: FKM, 400 SS, polyimide

The O-Ring materials used are compatible with nitrous oxide. There is also evidence that indicates that there are no compatibility problems between nitrous oxide and stainless steel or aluminum. Nitrous oxide and brass are satisfactorily compatible except when moisture is present at which point there can be corrosion. All metals should be completely cleaned of grease before exposure to nitrous, or there is the risk of violent reaction (particularly with the fittings). PTFE and PEEK are also compatible with nitrous oxide, with no obvious evidence of potential problems.

3. Nitrous Oxide Handling Safety

All nonessential personnel are evacuated to a safe distance before opening the nitrous bottles. Only the initial opening of the bottle is required as a manual task, as the rest of the fill procedure is done remotely. Safety glasses and leather work gloves are required for all personnel working with open nitrous oxide bottles.

Appendix D: Risk Assessment

Hazard	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury After Mitigation
Vehicle and Launch Rail Assembly				
Recovery system deploys during assembly	Prematurely arming recovery system, discharge	Low; entire system would need to short	Grounding the rocket through the load cell	Low
Launch rail becomes vertically unstable, falling and damaging vehicle	Over-tightening of tie-down straps in one direction; ground stakes become unearthed under strap tension	Medium; Three hand-tightened straps and dry, sandy earth to anchor into	Exhibiting care when tightening straps	Low
Launch Pad and Ground Control Setup				
Plumbing lines, fittings, or tanks fails while pressure testing ground equipment	Improper installation of fittings	Low; fill lines, fittings, and bottles are used within specification limits	Limit number of personnel near vehicle during tests; ensure proper PPE is worn; check pressure through transducers and analog sensors before loosening or tightening fittings	Low
Launch Pad Operations				
Igniter system lights igniter while personnel are present at the launch rail	Igniter builds up static electricity	Low; igniter requires significant heat to burn	Ignition system requires three step verification to actuate igniters; several pins have to output high signals for the igniters to light; igniters are shorted until attached to igniter box at the end of this phase	Low
Valves on fill stand fail to open when actuated	Car batteries deplete or valves lose pressurization	Low; batteries and compressed air cylinder are checked prior to vehicle and launch rail assembly phase	Car batteries will be checked and have spares. Remote fill procedures require recording compressed air pressure	Low

Arming				
Shorting of igniter during wiring or insertion leads to ignition failure	Crossed leads or failure of insulation	Low; care is taken during wiring of igniters and continuity is tested often to detect shorts or disconnected wires	After each step of handling the igniter, it is visually inspected and continuity tested	Low
Remote Operations				
Loss of wireless connection to the network	Generator is depleted of gasoline	Medium; antennas require line of sight, generator may be left on during long periods	Network is tested and generator is re-filled prior evacuation of launch pad	Low
Ignition Procedure				
Ignition failure leads to cold flow	Prior short of wire, faulty igniter, electronics failure	Low-Medium; an igniter is tested from the same batch as the flight igniter to validate manufacturing and systems	Validation of ignition systems immediately prior to launch and continuity testing is performed to discover a procedural error	Low
Actuation failure causes no oxidizer to enter the combustion chamber	Chain drive not properly tensioned, electronics failure, loss of pressure in compressed air canister	Low; validation of actuation systems is performed in tandem with ignition test; ignition control will not fire if communication is lost with the actuator; there is a pressure gauge to read pressure and is topped off before personnel evacuation	System is visually inspected before arming and actuation test is performed	Low
Lift Off				
Lack of thrust leads to the rocket being unstable off the rail	Inaccurate weight during filling leads to low oxidizer mass, fuel cracking clogs nozzle and chokes thrust	Low; motor has reliably provided required thrust during each static hot-fire	Fuel grain is x-rayed before launch to inspect for cracking, load cell is calibrated against known weights before fill	Low

Powered Flight				
Over pressurization leads to blow out in combustion chamber	Fuel cracks and clogs the nozzle, thermal protection system fails	Low; thermal protection has had greater than expected performance and durability during static hot-fires	Fuel grain is x-rayed before launch to inspect for cracking, thermal protection system is assembled in advance to avoid inconsistencies	Low
Coast				
Pre-mature deployment of parachutes	Faulty pressure or other altimeter malfunction	Low; the altimeters are off-the-shelf, certified, and reliable in testing.	Care when handling altimeters and ensuring proper programming before launch	Low
Rapid Descent				
Drogue does not deploy fully, resulting in a ballistic trajectory	CO_2 system fails to deploy payload coupler, fouled drogue parachute lines	Low; testing has proven the CO_2 system to be robust and redundant.	Care when sealing upper body tube, CO_2 redundancies, careful line management with Z-folds	Low
Slow Descent				
Main parachute fails to deploy fully and leads to rapid touchdown	Fouled main parachute lines, PSS failure	Medium; main parachute lines have fouled in testing when proper procedures were not followed. The PSS never failed in testing	Extreme care must be taken when packing the parachutes and folding the lines. Z-folds are key	Low
Payload Operations				
Rover is incapacitated and unable to move	Rover breaks due to fall; rover is falls/drives into brush and is unable to break free	Medium; rover falls at 21 ft/s; desert has tall bushes and deep holes	None	Low
Vehicle Retrieval				
APRS no longer transmits	Batteries for the APRS deplete	Low; batteries have been tested to last 47 hours	Batteries are checked prior to assembly; APRS is turned on at last possible moment in assembly	Low

Appendix E: Assembly, Preflight, and Launch Checklists

Table 4. Motor Assembly Checklist

Oxidizer Tank Preparation	
Step	**Action**
1.01	Clean oxidizer tank for nitrous oxide safety
1.02	Install vent valve to side port on fwd bulkhead and orient for integration with recovery coupler
1.03	Install spring relief valve to center port on fwd bulkhead
1.04	Install quick connect tube connector on aft bulkhead
1.05	Install 3/4” NPT to AN adapter on aft bulkhead
1.06	Ensure all connections are sealed

Actuated Valve Assembly	
Step	**Action**
2.01	Attach vane actuator to mounting plate.
2.02	Attach vane actuator and mounting plate to chain drive plate.
2.03	Attach ball valve to ball valve support.
2.04	Attach ball valve to chain drive plate.
2.05	Attach small ten tooth sprocket to vane actuator
2.06	Attach large thirty tooth sprocket to ball valve.
2.07	Attach the chain.
2.08	Tension the chain by sliding the vane actuator and ball valve mount.
2.09	Attach chain drive plate mounting supports
2.10	Attach 3/4” Swagelok to NPT adapter to the injector bulkhead
2.11	Attach 3/4” Swaglok port connector to 3/4” NPT adapter.
2.12	Mount the plate and supports on the right side of the injector if the 1/8 npt hole is in the back of bulkhead. Attach the lower part of the ball valve in the process
2.13	Mount the Swagelok to AN adapter on the top of the ball valve.
2.14	Attach the two supports to the electrical plate
2.15	Attach the solenoid valve to the inside of the plate (side facing ball valve)
2.16	Put two bolts and lock washers into the holes at the top facing each other.
2.17	Attach compressed air cylinder.
2.18	Attach electical tray and install stand-offs.
2.19	Attach supports with electrical plate to injector bulkhead
2.20	Attach voltage regulators at the bottom of the electrical tray. Stack with 5V on the bottom and 12V on top. Connect black wire to negative and red to positive.
2.21	Attach soldered arduino to stand-offs
2.22	Attach solid state relay above the arduino
2.23	Wire yellow wire from arduino to channel one on relay
2.24	Wire red wire from arduino to VCC terminal on relay
2.25	Wire ground from arduino to ground terminal on relay
2.26	Install RPi and attach soldered shield.
2.27	Install 2200mAh Venom battery using battery bracket to tray.

Table 4 continued from previous page

2.28	Install 1/8" flex hose from canister to solenoid in port.
2.29	Install 1/4" flex hose from solenoid out to vane actuator
2.30	Atatch 3/4" steel braided flex hose to ball valve
2.31	Take Assembly and transfer to oxidzer tank mount with ox adapter.
2.32	Slowly tighten bolts and hosing alternating between each
2.33	Tighten the remaining plumbing.
2.34	Ensure all hardware is tightened.
2.35	Install pressure transducers. Both injector bulkhead and ox tank.
2.36	Install quick connect stem to ox tank
2.37	Install quick connect stem support bracket.

Combustion Chamber Assembly	
Step	**Action**
3.01	Grease all O-rings
3.02	Place 360 O-rings radially and face sealing O-rings in pre-combustor
3.03	Set outer-liner against jaws of lathe
3.04	Set pre-combustor on other end of the outer liner
3.05	Push pre-combustor into outer-liner using tailstock of lathe
3.06	Place pre-burneron top of the fuel grain and slide into the outer-liner
3.07	Grease the outside of the post-combustor
3.08	Insert post-combustor into outer-liner using tailstock of a lathe
3.09	Place radial 360 O-rings and face sealing 152 O-ring in converger
3.10	Insert converger into outer-liner using tailstock of lathe
3.11	Slide bulkhead retaining onto fore end of chamber
3.12	Slide whole TPS assembly into combustion chamber w/ converger facing the apt end
3.13	Place the 260 O-rings on injector bulkhead
3.14	Slide chamber over injector bulkhead and bolt on through bulkhead retaining ring
3.15	Slide fin can over combustion chamber
3.16	Insert graphite nozzle into nozzle tube
3.17	Insert inner and outer retaining ring onto aft end of combustion chamber
3.18	Bolt inner retaining ring through outer retaining ring
3.19	Slide nozzle tube inside inner retaining ring
3.20	Bolt nozzle tube onto inner retaining ring
3.21	Tighten bolts on nozzle tube until noticable force is required and ensure nozzle tube is level
3.22	Slide tailcone onto outer retaining ring and bolt on

Table 5. Payload Assembly

	Rover Assembly
Step	**Action**
1.1	Attach PCB to Arduino. Mount unit onto Rover face plate using M3 screws and nuts with standoffs.
1.2	Attach motor to face plate using 3D printed mount and 1/4"-20 bolts and nuts.
1.3	Connect motor to motor controller Motor 1 and 2 screw terminal.

Table 5 continued from previous page

1.4	Attach tail to body tube. Attach hinges to body tube.
1.5	Attach second wheel onto motor and mount wheel to plate as described in 1.2-1.3.
1.6	Adjust position of wheel until wheels are evenly spaced.
1.7	Unplug LiPo battery from charger. Slide LiPo battery into 3D printed holder beneath Rover face plate. Plug in male to female harnesses into battery.
1.8	Plug battery into one motor controller Power + and - screw terminal.
1.9	Test rover functionality.
2.0	Clamp body tube over rover face plate.

	Pyro Housing Assembly
Step	**Action**
2.1	Insert electric match through hole at top of pyro cap. Epoxy wires in, sealing the hole.
2.2	Flip pyro cap over and fill with black powder. Epoxy the pyro cap closed.
2.3	Slide cap into pyro housing cube, making flush with step. Slide plunger in then spring.
2.4	Screw in fitting. Thread in 8g C02 cannister.
2.5	Screw one end of e-match into motor controller 1 screw terminal. Other end to arduino ground.

	Cage Assembly
Step	**Action**
3.1	Connect the top and bottom aluminum base plates (4x4) to the back aluminum (4x11.5) plate using 4 bolts/nuts to create a C shape using (size of bolts).
3.2	Attach the hinges to the back plate. 2 on each side with the screw head on the opposite side of the protruding plates.
3.3	Attach the wood walls. The walls should be flush with back plate. One side of the aluminum plate will have one wooden piece, the other side will have two adjecent pieces.
3.4	Place servo arm in the flat position on the base plate labelled top.
3.5	Wrap strap over cage and align it with the servo arm.
3.6	Using 1/4”-20 bolts, bolt in pyro housing into back of aluminum cage plate.
3.7	Mount and connect electronics into PLA electronics bay. Bolt in top electronics bay using 4 M6-2” bolts and nuts.

	Rover and Cage Integration
Step	**Action**
4.1	Take an elastic band. Wrap around the rover wheel and keep in place with a rubber band.
4.2	Place the rover between the aluminum plates of the cage. Wrap three of the four walls around the rover.
4.3	Cut the rubber band around each wheel. Close final wall.
4.4	Insert pin into slot, closing the box.
4.5	Wrap the thread of the pin taut around the servo arm.

	Rover and Nosecone Assembly
Step	**Action**

Table 5 continued from previous page

5.0	Ensure the avionics package is packed into the nosecone.
5.1	Tether eye-bolt on payload cage to u bolt on payload coupler.
5.2	Carefully store tether in cavity. Place payload cage between struts on protruding base.
5.3	Connect deployment electronics to switch in nosecone. Pull wire through tether and provide 6 feet of slack to prevent pullout.
5.4	Put nosecone on. Make sure the payload is safely cushioned against the internal foam. Put radial nylon pins in.

Table 6. Launch Rail Assembly Procedure

Step	Action
1.1	Set long horizontal stabilizer downrange, short horizontal stabilizer down back
1.2	Use socket, crescent, and x4 silver 1” bolts with nut and washer
1.3	Short segment is the bottom portion, ensure corner with two holes at one end is positioned downrange and that the pins in the truss align with the pins on the triangle base. Truss section with no pins in one end goes on top and the truss section with no holes takes the middle position. Follow these instructions for first truss joint before proceeding to second.
1.4	Insert large pins into the slots on the truss so that the tapered bolt hole faces out from the center
1.5	Add shear pins through the bolt holes, tap with hammer to set if needed but do not use brute force (if needed revert to 2b and ensure the pins and bolt holes properly align). DO NOT PUT PINS IN THE DOWNRANGE BOLT HOLES.
1.6	Lay all rails out and expose the marked faces. The 8’ rail will be collinear with one 20’ rail and parallel to the other. The marked faces together should form the charging American flag when arranged correctly
1.7	Slide 8020 coupling plate down to cover the flag markings such that the close bolts connect the collinear joint and the spaced bolts will lie within the same 20’ rail. Do not tighten the bolts, only slide the piece down the guide
1.8	Add one T-8020 plate to each side of the top of the rails such that the free holes face the single long rail. Do not tighten the bolts, only slide the plates down the guides
1.9	Add load cell from the bottom of the 8020 rails
1.10	Add T-8020 plates to the bottom of the rails in the same manner as 3c. Do not tighten the bolts, only slide the plates down the guides
1.11	Slide the 6 round head bolts down the single long rail and remove the nuts and washers
1.12	Fit the free T-8020 holes to the holes on the truss corners and insert the aluminum spacers parallel to the 8020 rails while also aligning the round head bolts with the downrange shear pin holes. Connect the plates to the truss using the wing nut bolts.
1.13	Tighten the bolts in the all the plates now that the spacers are slid into place

1.14	Slide the angle steel pieces onto the top of the rail and tighten to eliminate flex at top of rail. The flat end will be facing upward after connecting the two rails to each other.
1.15	Slide blast plate into the stand
1.16	Slide connecting tab down the downrange horizontal stabilizer (upper)
1.17	Connect blast plate unistrut to the upper carriages of the rail base
1.18	Connect blast plate to the stabilizer tab

Table 7. Ground Systems Assembly Checklists

	Network Setup at Launch Pad
Step	**Action**
1.1	Attach antenna to PVC pipe
1.2	Attach 50 ft. ethernet cord to the antenna
1.3	Raise antenna and stake down pvc pipe
1.4	Connect other end of 50 ft. ethernet to black adapter in the POE port
1.5	Power the router by plugging wall plug into power strip
1.6	Ensure green lights on the router are on
1.7	Connect an ethernet between antenna adapter and an orange port on the router
1.8	Plug black adapter into power strip
1.9	Power Igniter RPi by plugging into power strip
1.20	Power Fill RPi by plugging into Anker battery

	Network Setup at Command
Step	**Action**
1.1	Attach antenna to PVC pipe
1.2	Attach 50 ft. ethernet cord to the antenna
1.3	Raise antenna and stake down pvc pipe
1.4	Connect other end of 50 ft. ethernet to black adapter in the POE port
1.5	Power access point by plugging wall plug into power strip
1.6	Ensure green lights on the access point are on
1.7	Connect an ethernet between antenna adapter and an orange port on the router
1.8	Plug black adapter into power strip
1.9	Power Command RPi by plugging into Anker battery
1.10	Connect HDMI between monitor and Command Rpi
1.11	Connect USB between monitor and Command RPi

Stand Assembly				
Step #	**Description**	**Details**	**Person**	**Completed**
1.1	Pull out the stand from the truck	Includes the stand and feet		
1.2	Flip the stand over on its back on top of a table	Allows for easy assembly		
1.3	slide the feet over the legs			
1.4	tighten the M6 hex bolts	located along the vertical side posts		
1.5	flip the stand over back onto its feet			
1.6	Attach the appropriate flex hoses to the stand	4 (5ft lengths) hoses connected for each bottle and main QC (20ft length) connect for the rocket		
1.7	Connect the corresponding flex hose to each bottle	Make sure have correct CGA fittings N_2O: 326 He/N_2: 580 CO_2: 320 with additional Teflon fitting Compressed Air: 590		
1.8	Attach the air hose from the stand to compressor/air cylinder			
1.9	Proceed to leak checks	refer to the leak check procedure		

		Personnel		

Leak Check Procedure				
Step #	**Description**	**Details**	**Person**	**Completed**
2.1	Close all Manual Relief Valves and Pneumatic Ball Valves	Leak checking the legs of the stand		
2.2	Open bottle in the N2O line	Replace normal N2O bottle with N2 for safety		
2.3	Close bottle in N2O line			
2.4	Listen for Leaks	use soapy water		
2.5	Open RV1 (N2O)			
2.6	Fix leaks	Refer to Leak Fixing Procedure		
2.7	Continue to repeat steps 1.1 to 1.6 as needed to fix all leaks			
2.8	Repeat steps 1.1 to 1.7 for N2 and back pressure legs	Make sure to swap in N2 or another inert gas for all the legs		
2.9	Close all Manual Relief Valves (RV) and Ball Valves			
2.10	Open N2 bottle	Leak checking downstream of the check valves		
2.11	Open BV2 and BV4 (N2 and post union cross)			
2.12	Listen for Leaks			
2.13	Open RV4			
2.14	Fix leaks			

Leak Fixing Procedure				
Step #	**Description**	**Details**	**Person**	**Completed**
3.1	Disassemble leaky joint			
3.2.1	If at Swagelok fitting try to realign the piping			
3.2.2	If joint is a NPT fitting re-pipe tape the joint			
3.3	Reassemble the joint			
3.3.1	If Swaglok it should hand tighten most of the way smootly then 3/4 turn with wrench to tighten			
3.4	Go back and redo leak detection			

Fill Ox Tank for Static Fire					
Step #	**Description**		**Values**	**Person**	**Completed**
	Valve Controller personel:				
4.1	ENSURE connection of QC (Quick Connect)				
4.2	Close all Manual Relief Valves and Pneumatic Ball Valves				
4.3	Open all bottles (N2O, N2, and He)	N2 pressure regulator set to 300psi, He pressure regulator set to 1300psi			
4.4	Evacuate to the Command Center				
4.5	Double check if test stand is cleared	Verbal communication			
4.6	Open BV2 (N2)	*Initial Purge of system			
4.7	Open BV4	Venting the purge			
4.8	Close BV2 (N2)				
4.9	Open SV1 (rocket)	Open until the PT reads atmospheric pressure			
4.10	Close SV1				
4.11	Close all Valves (BV1, BV2, BV3, BV4, and BV5)				
4.12	Open BV1 (N2O)	Filling of Oxidizer			
4.13	Open BV4 (to the rocket)				
4.14	Open SV1	open when the Ox tank pressure equilibriate			
4.15	Close SV1				
4.16	Repeat steps 2.14-2.15 until complete fill	Fill until the desired 40lb of N2O			
4.17	Close BV4				
4.18	Close BV1				
4.19	Open BV5	Vent remaining N2O			
		*Close All Valves			
4.20	Open BV2 (N2 branch)	Nitrogen purge			
4.21	Close BV2				
4.22	Open BV5				
4.23	Close BV5				
		*Close All Valves			
4.24	Hand off to command	*DO THIS BEFORE HELIUM PRESSURING*			
4.25	Open BV3 (He)	Back Pressuring			
4.26	Open BV4 (to the rocket)	Up to 750psi			
4.27	Close BV3 (He)				
4.28	Close BV4				
4.29	Open BV5				
4.30	Close all Valves (BV1, BV2, BV3, BV4, and BV5)				
4.31	Open BV2 (N2)	getting ready for blow down step			
4.32	Pass over command to ignition	(launch rocket)			
Refer to Blow-Down Procedure if Static Fire					
Post fire/launch					
4.33	Make sure all valves are closed				
4.34	Close all bottles				
4.35	Open RV1, RV2, RV3, and RV4	To vent any residual pressure			

Fill Ox Tank for Launch					
Step #	**Description**		**Pressure Values**	**Person**	**Completed**
	Valve Controller personel:				
4.1	ENSURE connection of Propellent Umbilical				
4.2	Close all Manual Relief Valves and Pneumatic Ball Valves				
4.3	Open all bottles (N2O, N2, and He)	N2 pressure regulator set to 300psi, He pressure regulator set to 1300psi			
4.4	Evacuate to the Command Center				
4.5	Double check if test stand is cleared	Verbal communication			
4.6	Open BV2 (N2)	*Initial Purge of system			
4.7	Open BV4	Venting the purge			
4.8	Close BV2 (N2)				
4.9	Open SV1 (rocket)	Open until the PT reads atmospheric pressure			
4.10	Close SV1				
4.11	Close all Valves (BV1, BV2, BV3, BV4, and BV5)				
4.12	Open BV1 (N2O)	Filling of Oxidizer			
4.13	Open BV4 (to the rocket)				
4.14	Open SV1	open when the Ox tank pressure equilibriate			
4.15	Close SV1				
4.16	Repeat steps 2.14-2.15 until complete fill	Fill until the desired 40lb of N2O			
4.17	Close BV4				
4.18	Close BV1				
4.19	Open BV5	Vent remaining N2O			
		*Close All Valves			
4.20	Open BV2 (N2 branch)	Nitrogen purge			
4.21	Close BV2				
4.22	Open BV5				
4.23	Close BV5				
		*Close All Valves			
4.24	Hand off to command	*DO THIS BEFORE HELIUM PRESSURING*			
4.25	Open BV3 (He)	Back Pressuring			
4.26	Open BV4 (to the rocket)	Up to 750psi			
4.27	Close BV4	DO OPENING AND CLOSING OF BV4 IN SHORT BURSTS DUE TO WATER HAMMERING			
4.28	Close BV3 (He)				
4.29	Open BV5	Venting residual helium on the stand			
4.30	Close all Valves (BV1, BV2, BV3, BV4, and BV5)				
4.31	Disconnect the Propellant Umbilical				
4.32	Open BV4				
4.33	Open BV5	Allows venting of all lines upstream			
4.34	Pass off launch control				
Post fire/launch					
4.35	Make sure all valves are closed				
4.36	Close all bottles				
4.37	Open RV1, RV2, RV3, and RV4	To vent any residual pressure			

Cold Flow				
Step #	**Description**		**Person**	**Completed**
2.1	ENSURE connection of QC (Quick Connect)			
2.2	Close all Manual Relief Valves and Pneumatic Ball Valves			
2.3	Open all bottles (CO2/N2O, and He)	N2 pressure regulator set to 300psi, He pressure regulator set to 1300psi		
2.4	Evacute to the Command Center			
	Double check if test stand is cleared	Verbal communication		
2.5	Open BV2 (CO2)			
2.6	Open BV4	Open to fill rocket with CO2		
2.7	Close BV2 (CO2)			
2.8	Open SV1 (rocket)	Open to optimize the fill		
2.9	Close SV1			
2.10	Close all Valves (BV1, BV2, BV3, BV4, and BV5)			
2.11	Give command to actuated ball valve for control			
Approach the stand				
2.12	Close off all tanks			
2.13	Open manual relief valve	Make sure flow is facing opposite of operator		

Blow Down				
Step #	**Description**		**Person**	**Completed**
3.1	Open BV4	blow down step		
3.2	Close BV2 (N2)			
3.3	Close BV4	Close when flame is put out		
		Final purge before reapproaching the stand		
3.4	Open BV2 (N2)			
3.5	Close BV2 (N2)	Open and close in a pulsing manner		
3.6	Open BV5	Kept open		
3.7	Close BV5	Close when the PT reads atmosphere		

Emergency Full Tank Relief				
This will be done if failure of the actuated ball valve during fill				
Step #	**Description**	**Details**	**Person**	**Completed**
4.1	Close BV1, BV2, and BV3			
4.2	Open BV4, BV5, and SV2	For full tank venting		
4.3	Close BV4, BV5, and SV2	Close when the PT reads atmosphere		

Valve Background		
Name	**Type**	**Default**
BV1	Pneumatic Ball Valve	Close
BV2	Pneumatic Ball Valve	Close
BV3	Pneumatic Ball Valve	Close
BV4	Pneumatic Ball Valve	Close
BV5	Pneumatic Ball Valve	Close
SV1	Solenoid Valve	Close
RV1	Manual Relief Valve	Close
RV2	Manual Relief Valve	Close
RV3	Manual Relief Valve	Close
RV4	Manual Relief Valve	Close

Installing Swagelok Ferrules		
Advice:	**Easiest way is to use a vice as a hard point**	
Step #	**Description**	**Details**
1.1	Make sure the back and front ferrules are installed with the nut	*Be careful with orientation*
1.2	Fully insert tube into fitting	Make sure the tube is resting on inside shoulder
1.3	Rotate the nut finger-tight	Make sure not to overtighten
1.4	Mark the nut at the 6 o'clock position	
1.5	With a wrench tighten the nut one and one quarter turn	Make sure to end at the 9 o'clock position

Table 8. Pre-flight Checklist

Step	Action
1	Complete all vehicle assembly checklists
2	Complete all ground equipment assembly checklists
3	Complete launch rail raising checklist
4	Ensure all personnel wearing proper PPE (eye protection)
5	Attach vent valve electrical connector to recovery coupler
6	Connect propellant umbilical air hose to supply, power to remote fill control
7	Ensure nominal operation of all remote fill valves
8	Line up propellant umbilical arm with launch vehicle on the rail and connect propellant umbilical
9	Ensure nominal actuation of propellant umbilical and arm moving to clear path for vehicle
10	Connect propellant umbilical to the launch vehicle
11	Visually inspect actuated valve bay electrical connections
12	Ensure onboard RPi are communicating with command RPi
13	Connect igniter to igniter cable
14	Measure resistance of igniter to ensure proper connection
15	Secure igniter to ground in a safe location for an ignition test
16	Ensure ignition box is de-energized by hitting cables together and looking for sparks
17	Connect igniter to ignition box
18	Arm ignition box
19	Have fire extinguishers ready
20	Perform igniter and ball valve actuation test
21	Ensure igniter and surrounding area is free of flames
22	Disarm the ignition box and disconnect the igniter cable
23	Set actuated injection valve to final closed position
24	Repressurize onboard air supply
25	Reset the onboard RPi, ensure reconnection to the network
26	Perform pressure check of ox tank, monitor pressure at command
27	Perform propellant umbilical actuation test, ensuring arm moves clear of the vehicle
28	Vent ox tank using onboard vent valve
29	Ensure load cell is operational by hanging weight from the vehicle
30	Connect igniter to ”lolipop” stick
31	Connect igniter to igniter cable
32	Measure and record resistance of igniters
33	Insert igniter into combustion chamber and secure stick to aft end of the motor
34	Measure and confirm no change in resistance of igniters
35	Ensure ignition box is de-energized by hitting cables together and looking for sparks
36	Power recovery bay avionics suite
37	Ensure transmissions from both avionics suites, recovery bay and nosecone
38	Evacuate all non-critical personnel
39	Connect igniter to ignition box
40	Final check of launch controller operation
41	Ensure onboard tracking systems are transmitting

Table 8 continued from previous page

42	Perform final sweep of launch site, prepare to evacuate
43	Open all gas cylinders, record nitrous pressure
44	Arm payload deployment system
45	Arm recovery system with dual key switches and ensure operation
46	Arm ignition box
47	Evacuate launch site

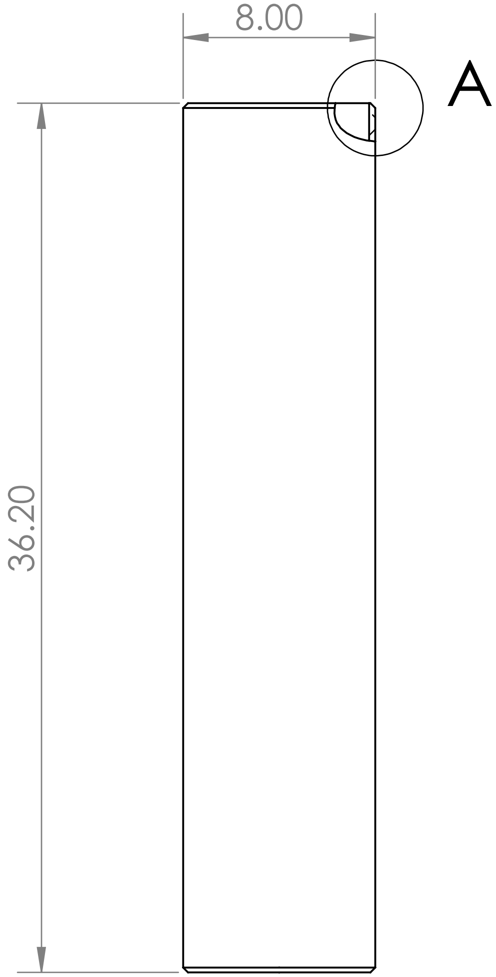
Table 9. Launch Checklist

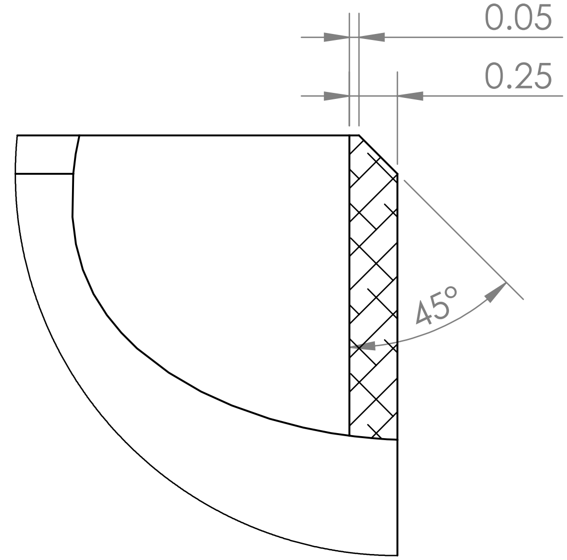
Step	**Action**
1	Verify all personnel are at appropriate distance from launch site
2	Verify communication with onboard controller and ignition control
3	Receive GO from range official
4	Receive GO from propulsion
5	Receive GO from telemetry
6	Receive GO from payload
7	Receive GO from cameras
8	Receive GO from launch control
9	ARM launch control system at T-10
10	Send FIRE signal at T-2
11	Disarm launch controller
12	Visually track and point at vehicle for flight duration
13	Ensure high speed camera remains powered
14	Receive GO from range official to approach launch site
15	Launch site remote fill venting
16	Turn off all controllers
17	Disarm recovery system
18	Proceed with vehicle takedown

Appendix F: Engineering Drawings

Propulsion

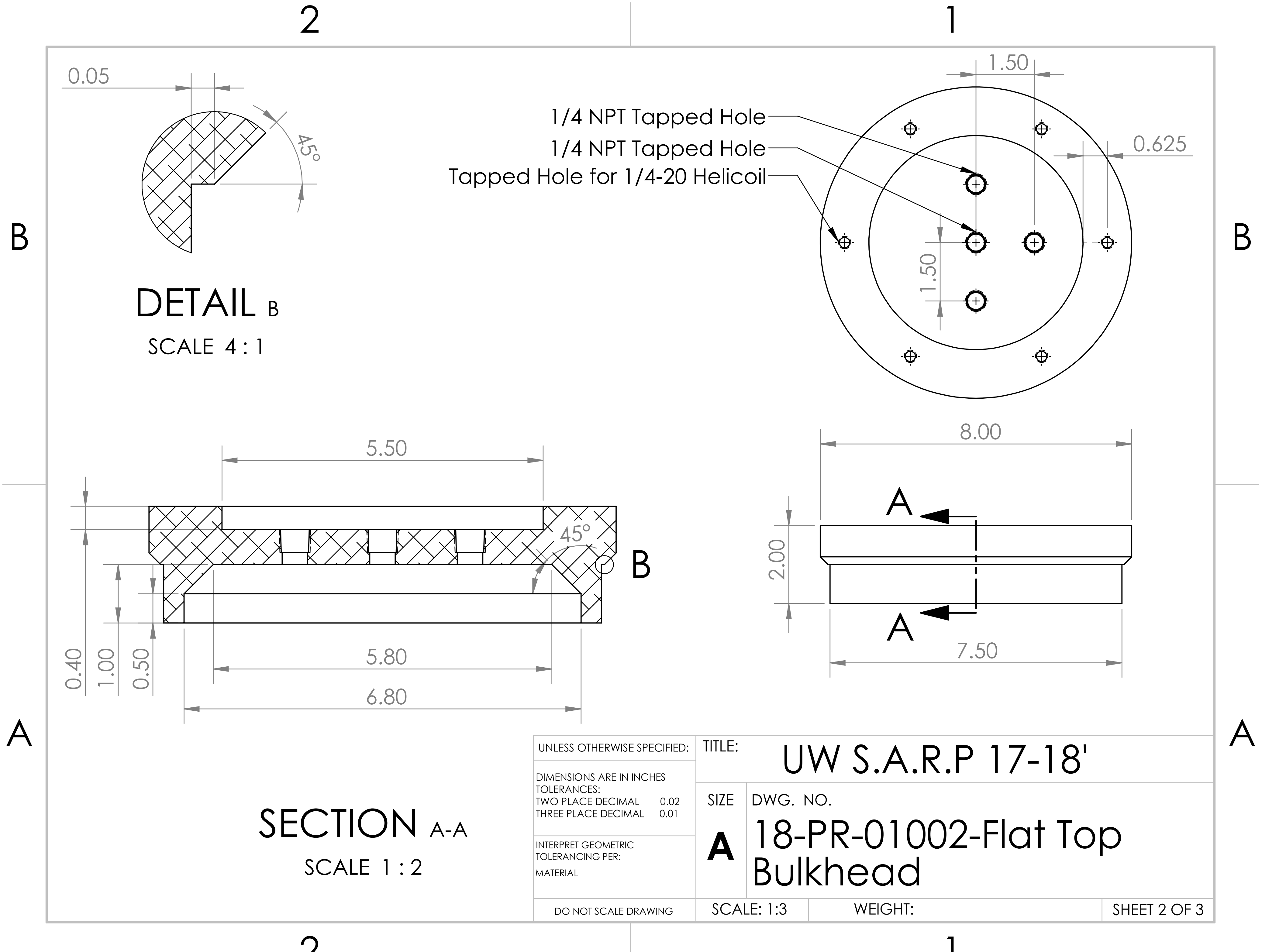
Oxidizer Tank



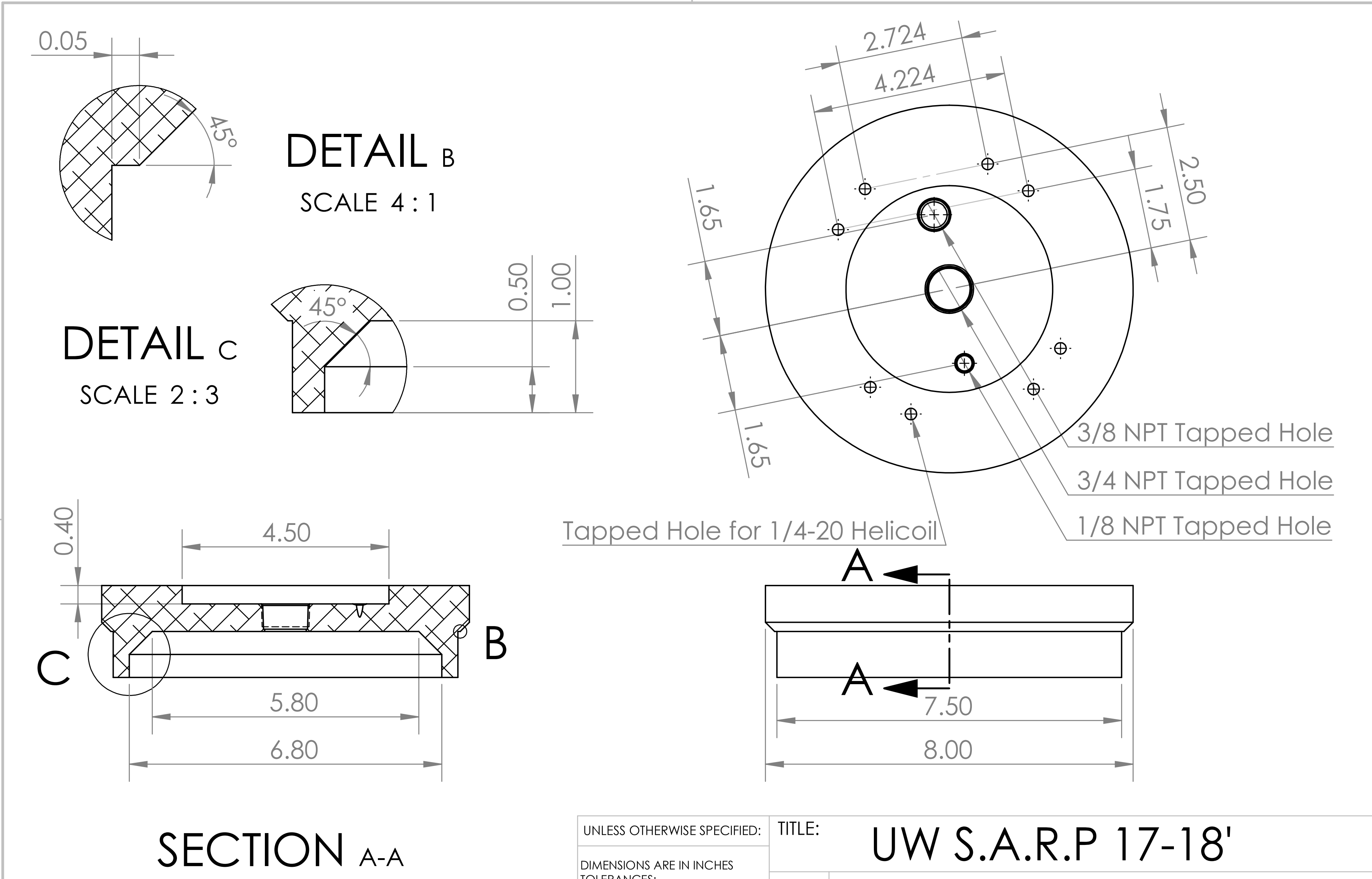


DETAIL A
SCALE 1 : 1

UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL 0.02 THREE PLACE DECIMAL 0.01	SIZE **A**	DWG. NO. 18-PR-01001-Aluminum Tube
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:8	WEIGHT: SHEET 1 OF 3

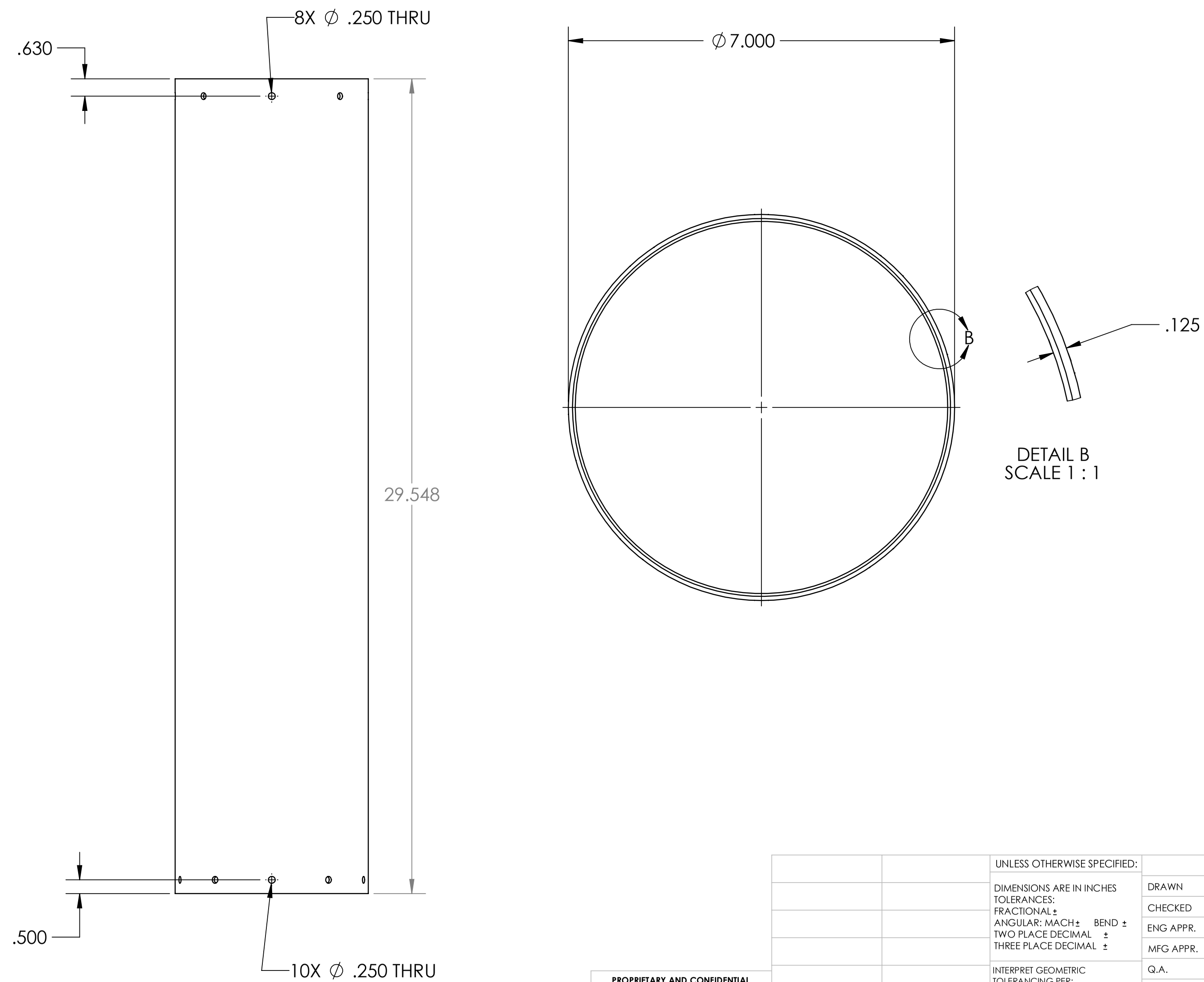


2
1
B
A
0.05
45°
DETAIL B
SCALE 4 : 1
1.50
1/4 NPT Tapped Hole
1/4 NPT Tapped Hole
Tapped Hole for 1/4-20 Helicoil
0.625
1.50
5.50
45°
B
0.40
1.00
0.50
5.80
6.80
SECTION A-A
SCALE 1 : 2
8.00
A
A
2.00
7.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL 0.02
THREE PLACE DECIMAL 0.01
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
DO NOT SCALE DRAWING
TITLE:
UW S.A.R.P 17-18'
SIZE
A
DWG. NO.
18-PR-01002-Flat Top Bulkhead
SCALE: 1:3
WEIGHT:
SHEET 2 OF 3



UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL 0.02 THREE PLACE DECIMAL 0.01	SIZE **A**	DWG. NO. 18-PR-01003-Flat Bottom Bulkhead
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:3	WEIGHT: SHEET 3 OF 3

Combustion Chamber and Nozzle



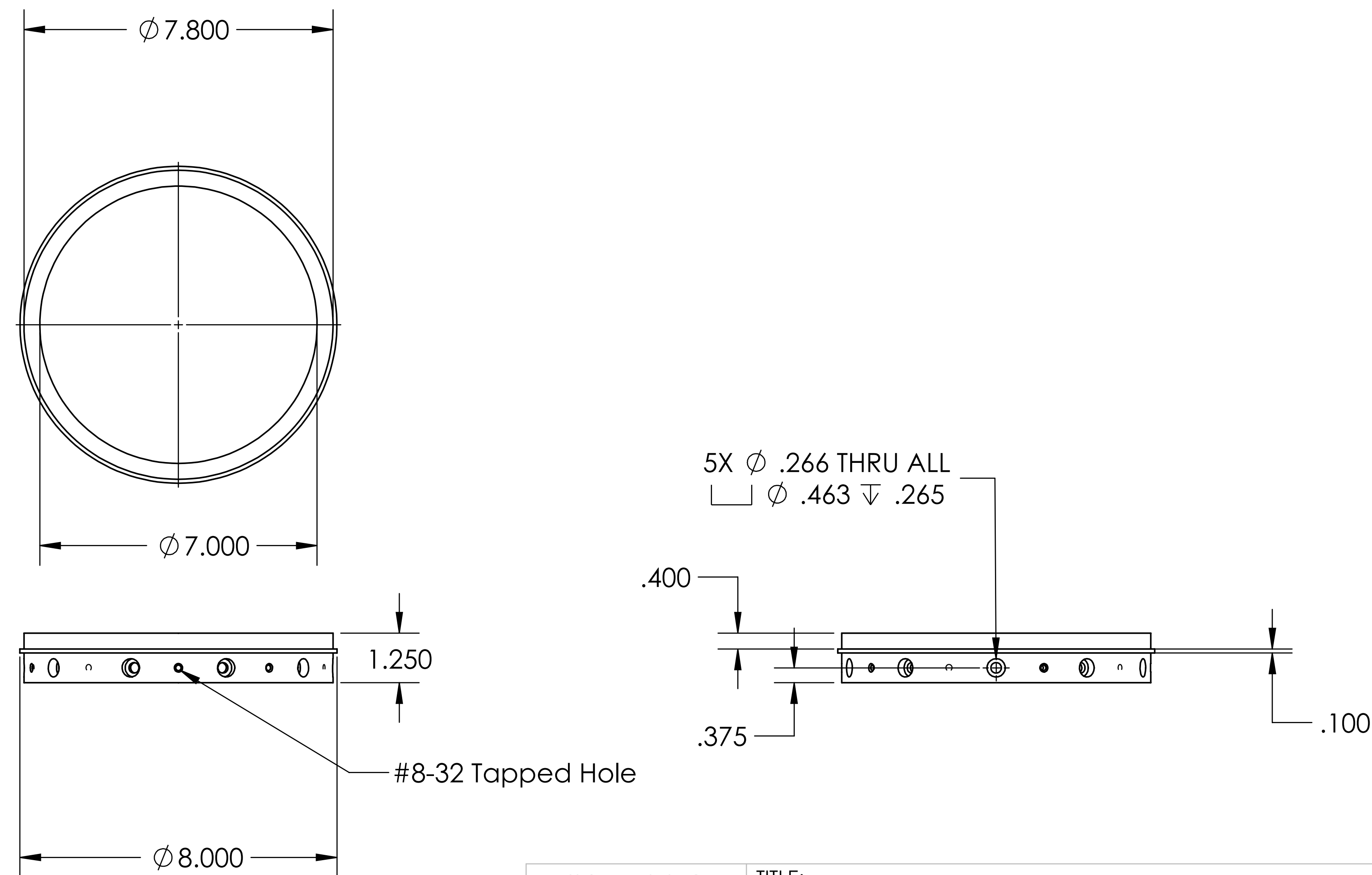
UNLESS OTHERWISE SPECIFIED:		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		
INTERPRET GEOMETRIC TOLERANCING PER:		
MATERIAL		
FINISH	NEXT ASSY	USED ON
DO NOT SCALE DRAWING	APPLICATION	

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

TITLE:

18-PR-06001-
Combustion tube

SIZE	DWG. NO.	REV
B		
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-06002-Outer retaining ring
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL Aluminum		
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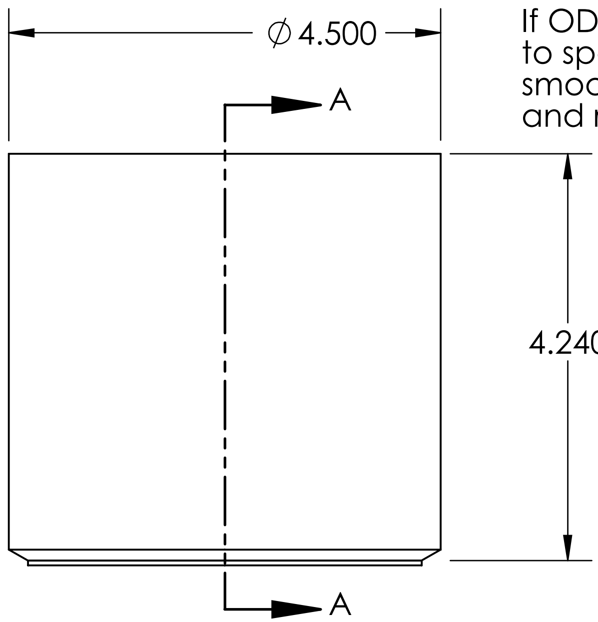
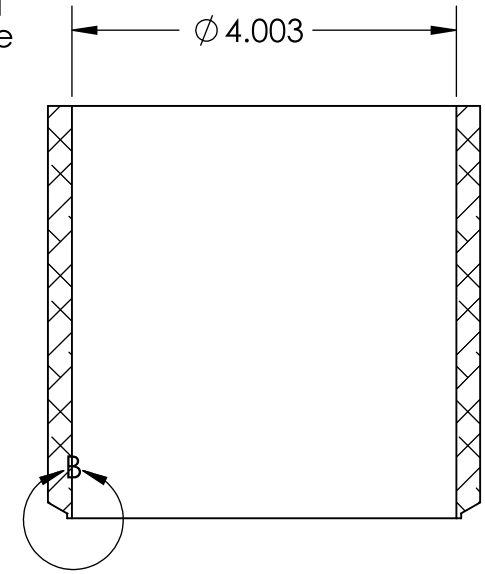
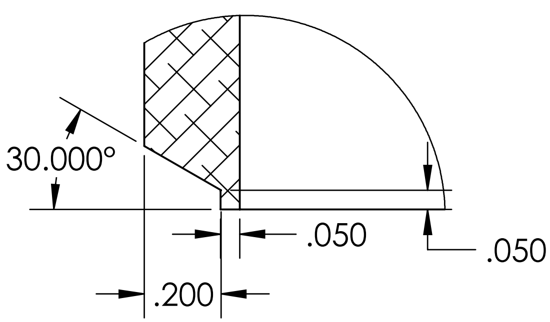


If OD and/or ID can't be machine
to specified dimenions, machine a
smooth surface as close as possible
and record the new dimenion.



SECTION A-A



DETAIL B
SCALE 2 : 1

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DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-06003-Nozzle tube
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
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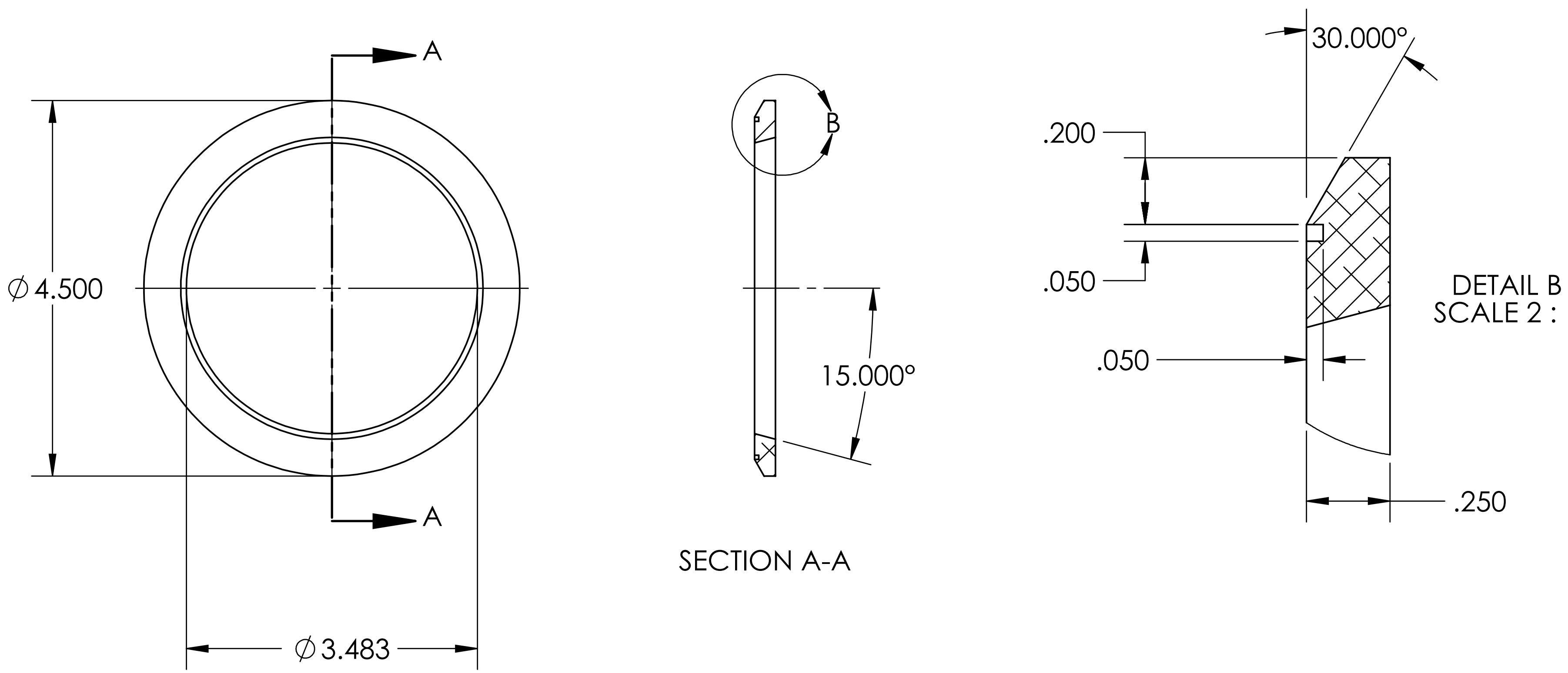

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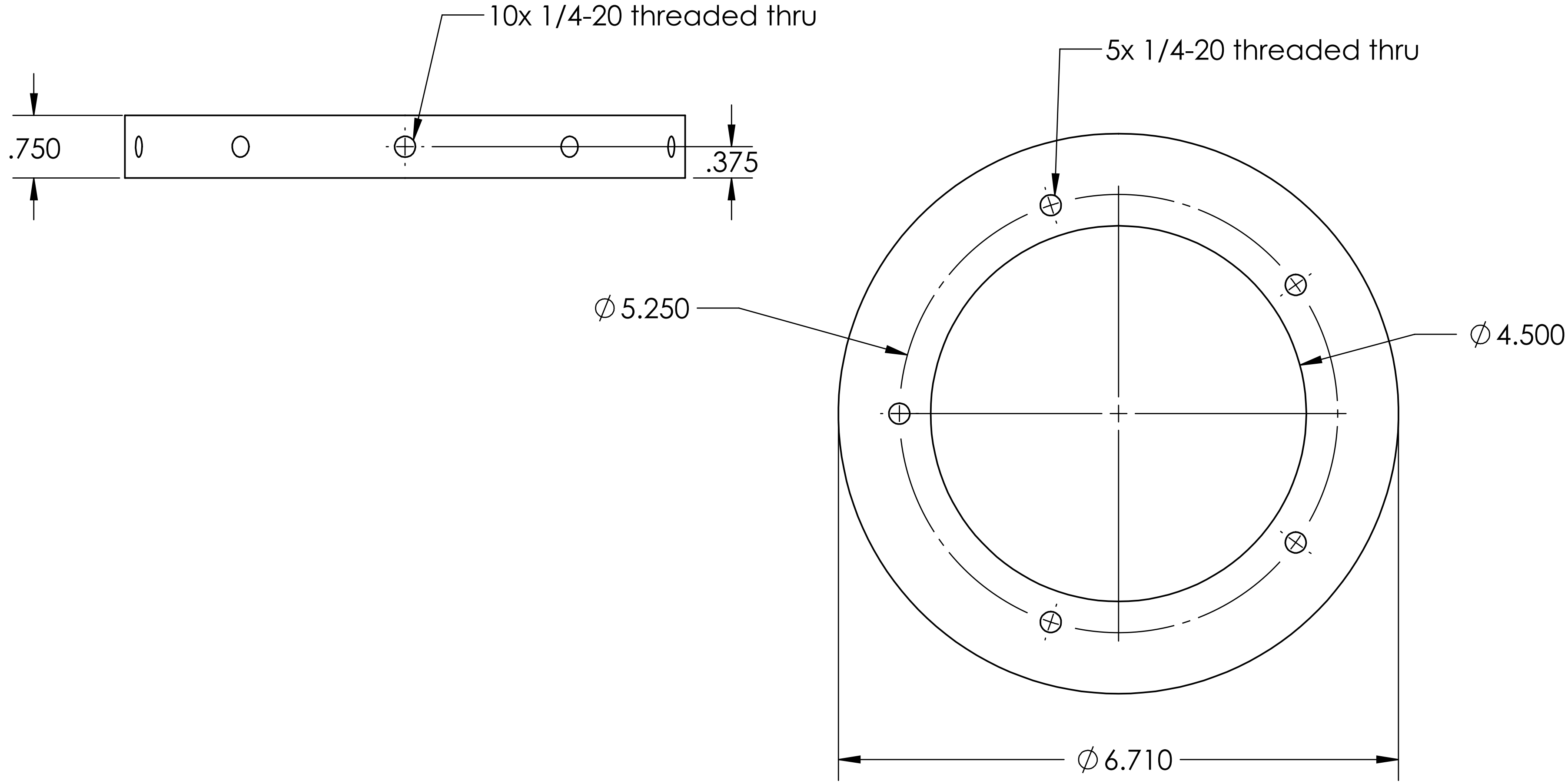
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-06003-Nozzle tube end
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: SHEET 1 OF 1



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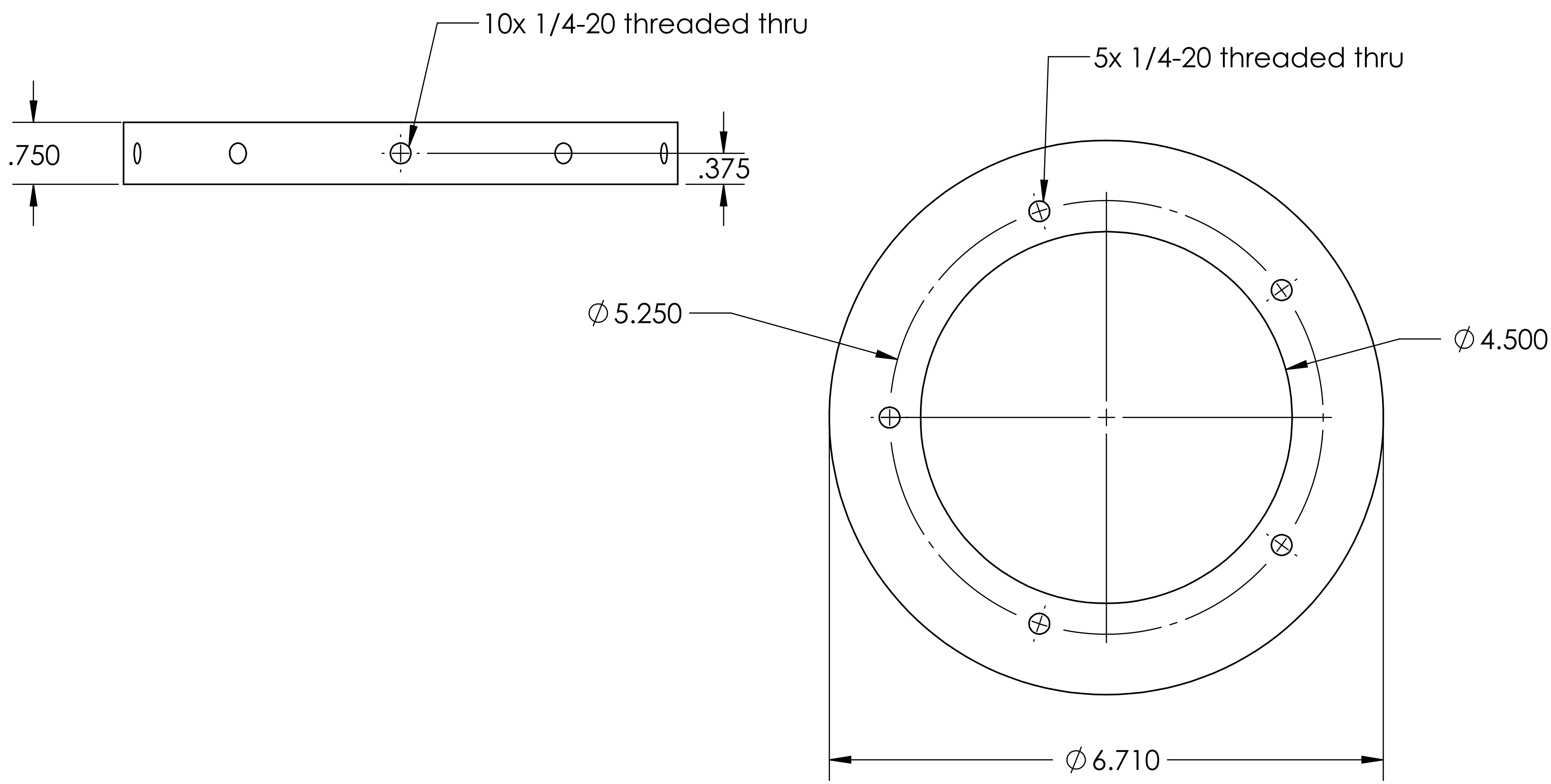
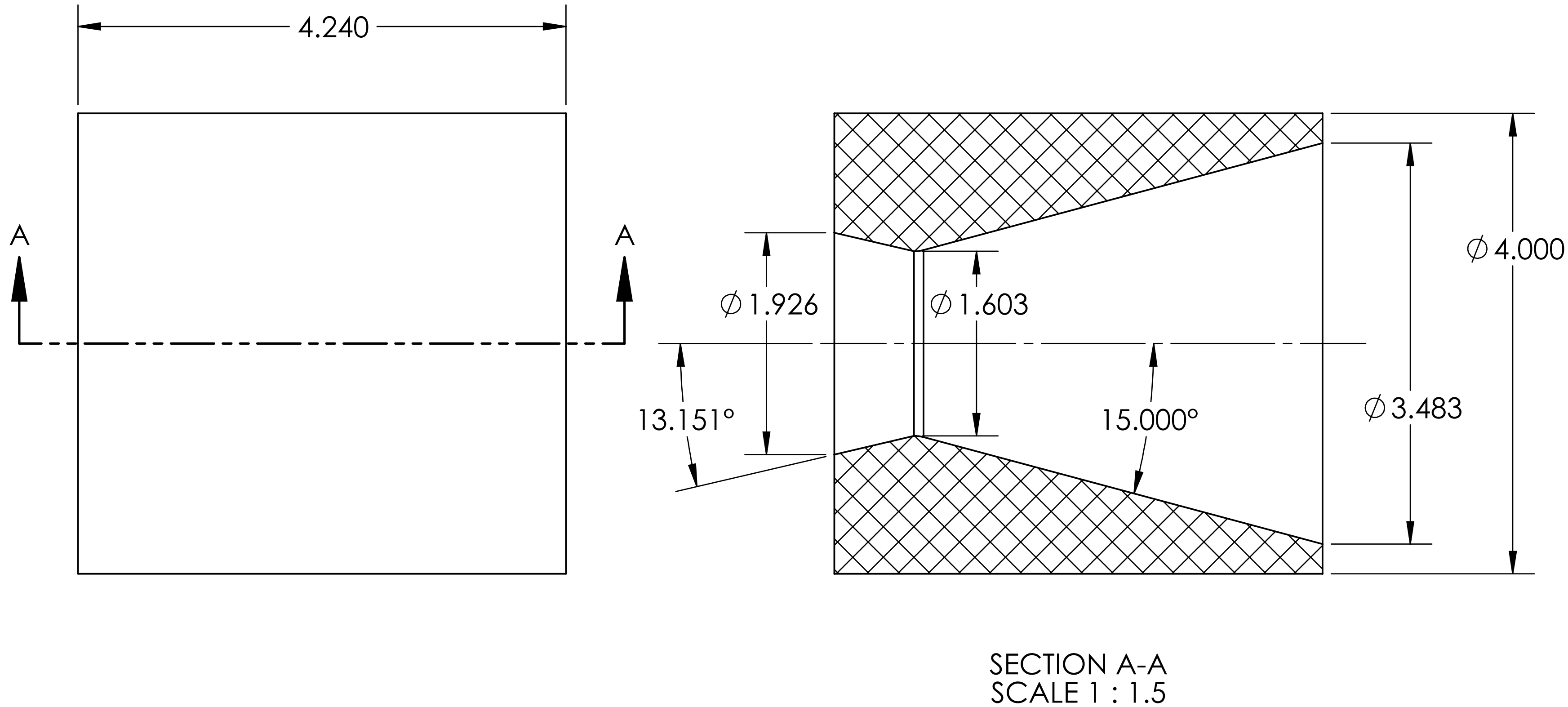
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-06004-Inner retaining ring	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-06004-Inner retaining ring	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



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DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE: A — DWG. NO. 18-PR-06005-Graphite nozzle
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL	
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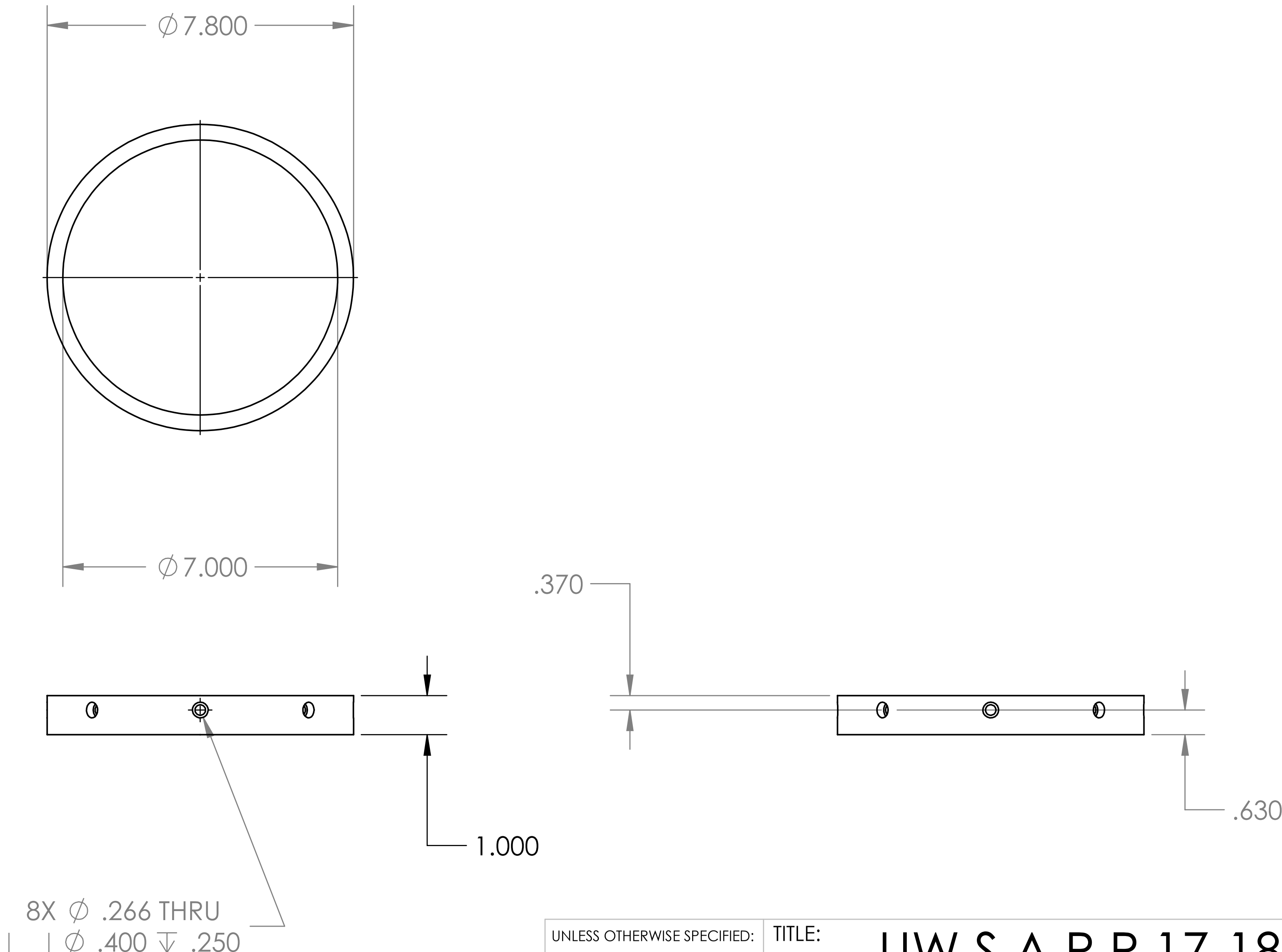

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DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-06009-Bulkhead retaining ring
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL Aluminum		
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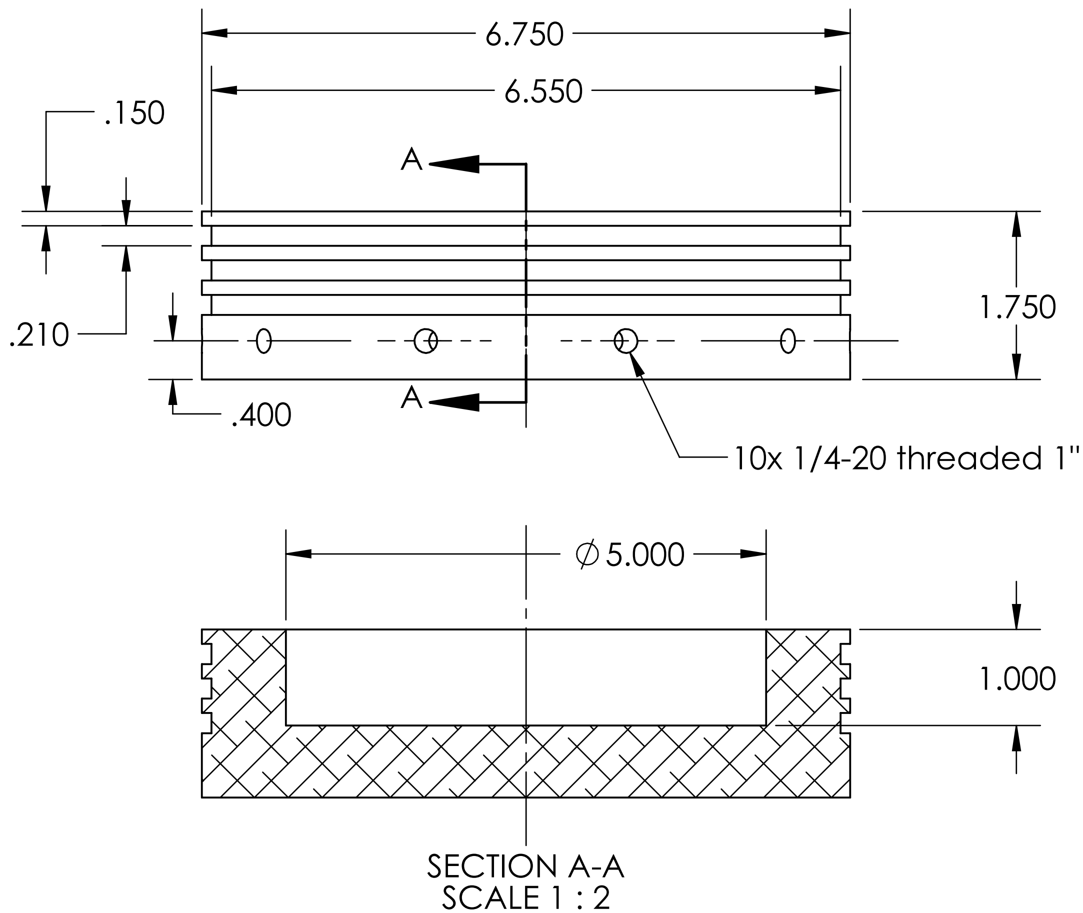


UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.02
THREE PLACE DECIMAL ± 0.01

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL

DO NOT SCALE DRAWING

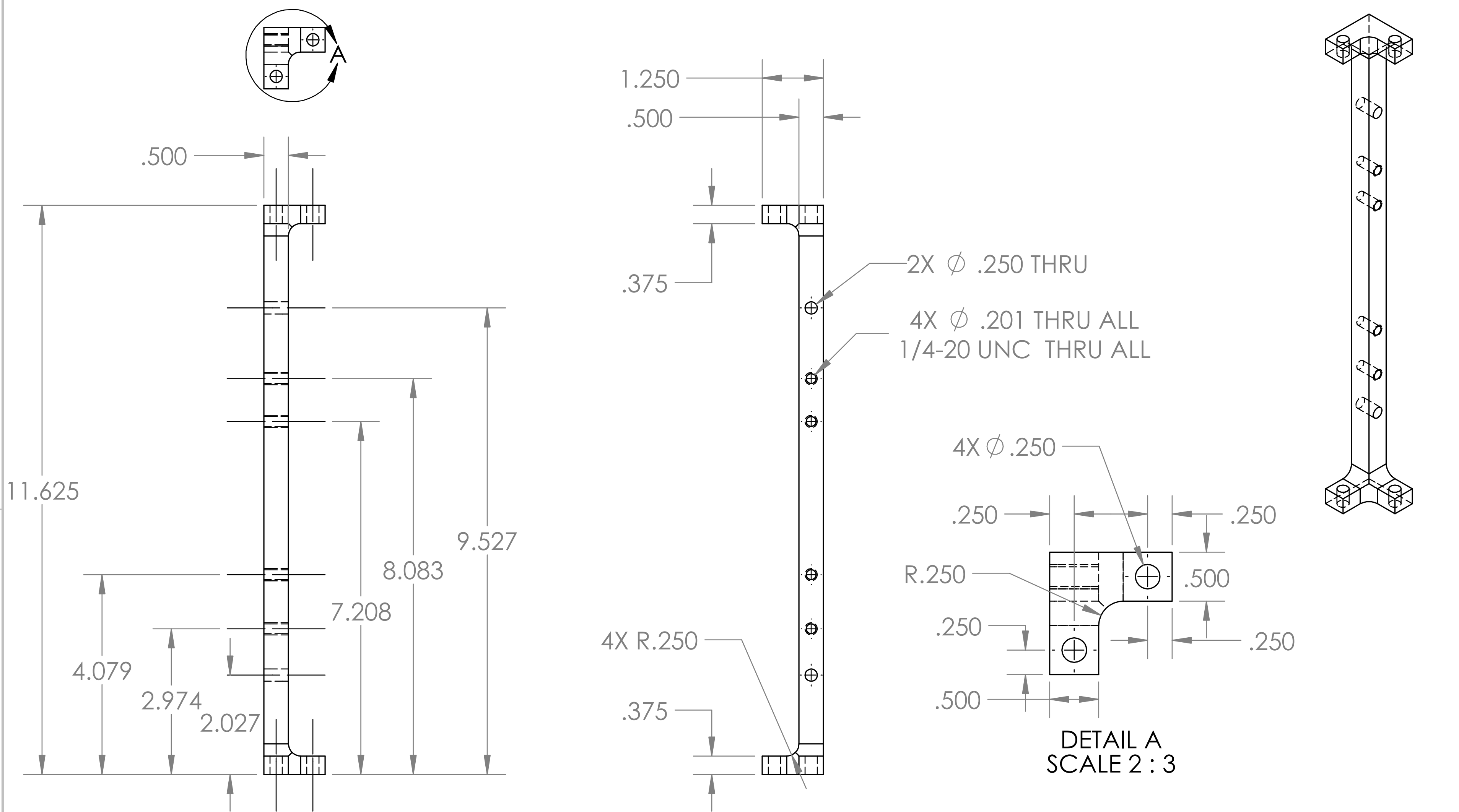
TITLE: UW S.A.R.P 17-18'

SIZE: A

DWG. NO. 18-PR-06011-Hydro Test Plug.SLDPRT

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

Actuated Valve



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INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
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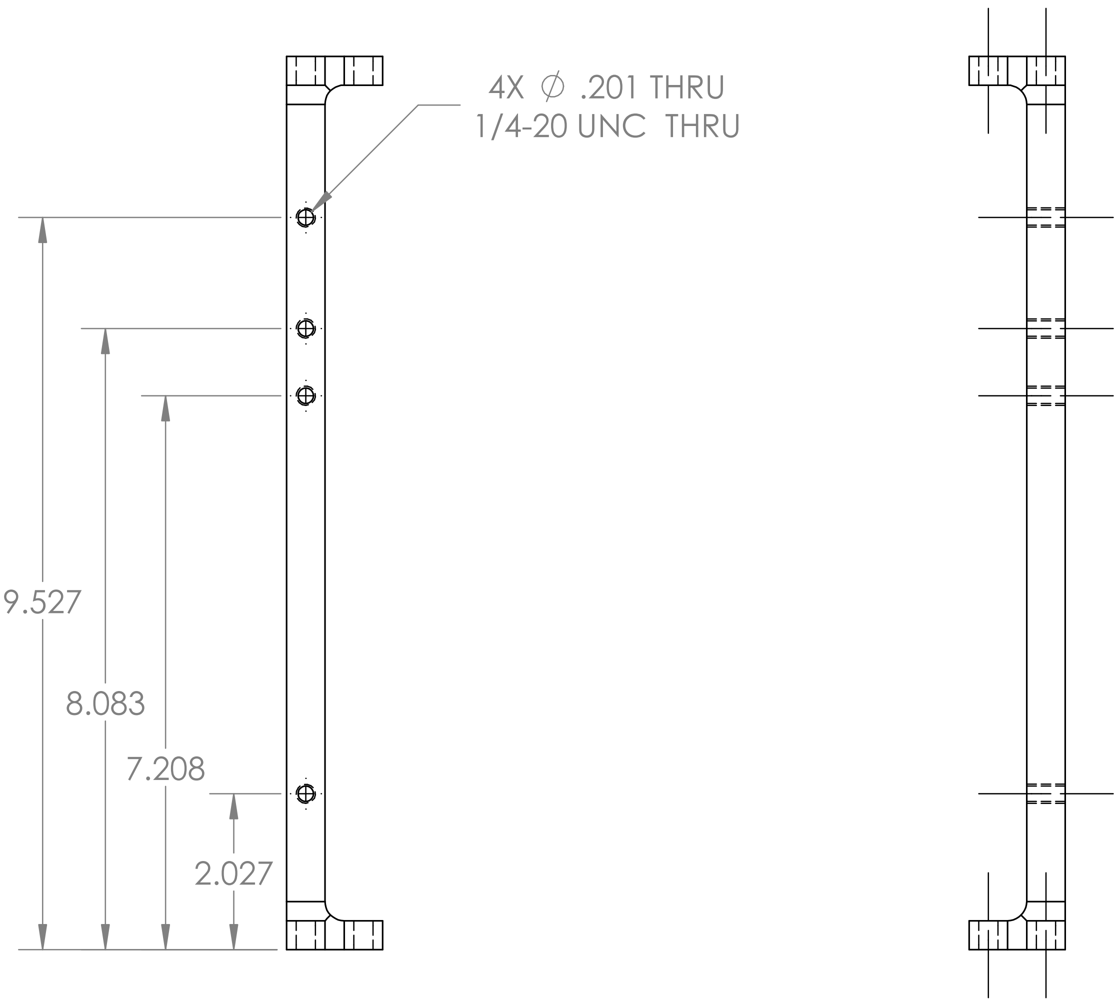

See 18-PR-03001-Structural Support Front Right for further dimensions

UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-03002-Structural Support Front Left
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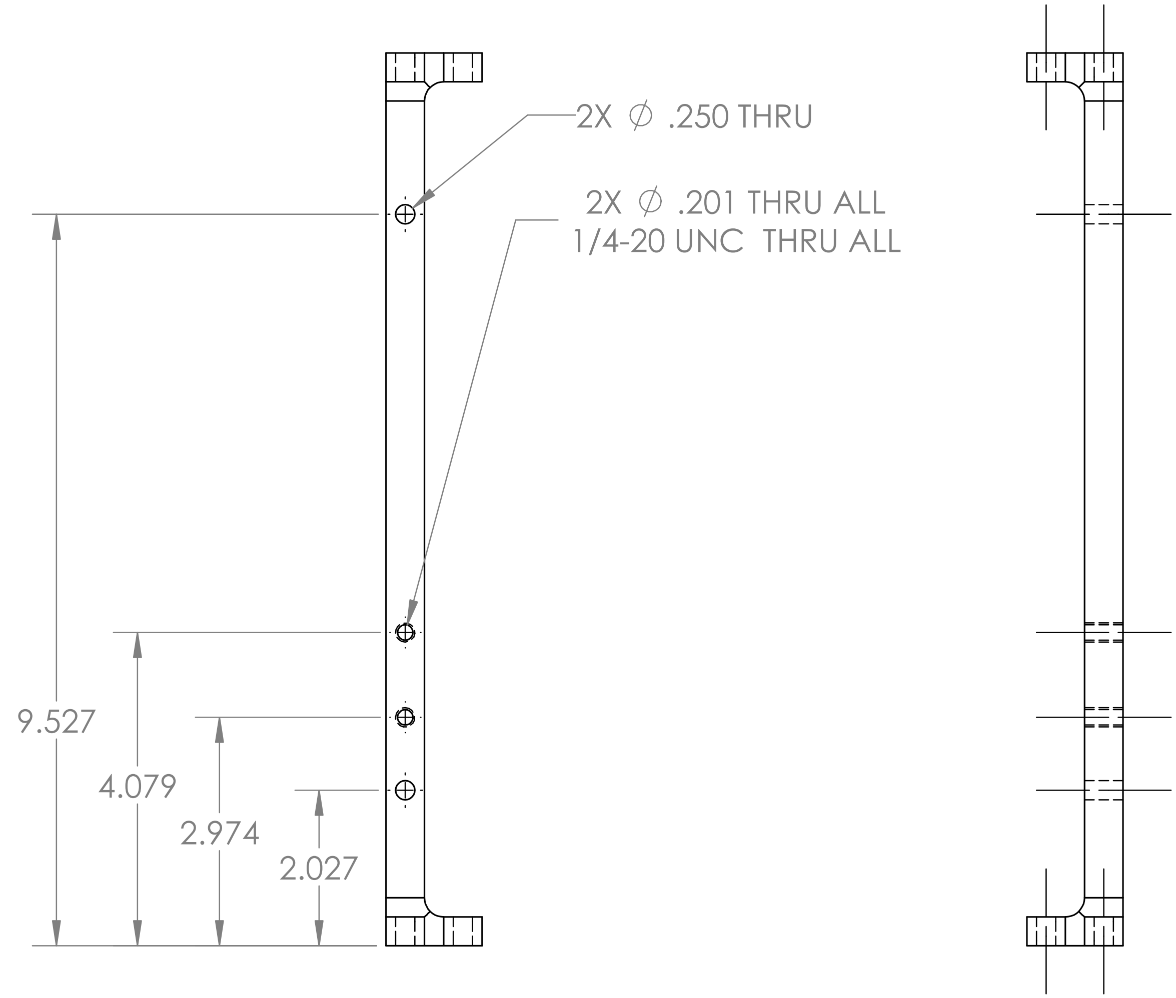

See 18-PR-03001-Structural Support Front Right for further dimensions

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DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-03003-Structural Support Back Right	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
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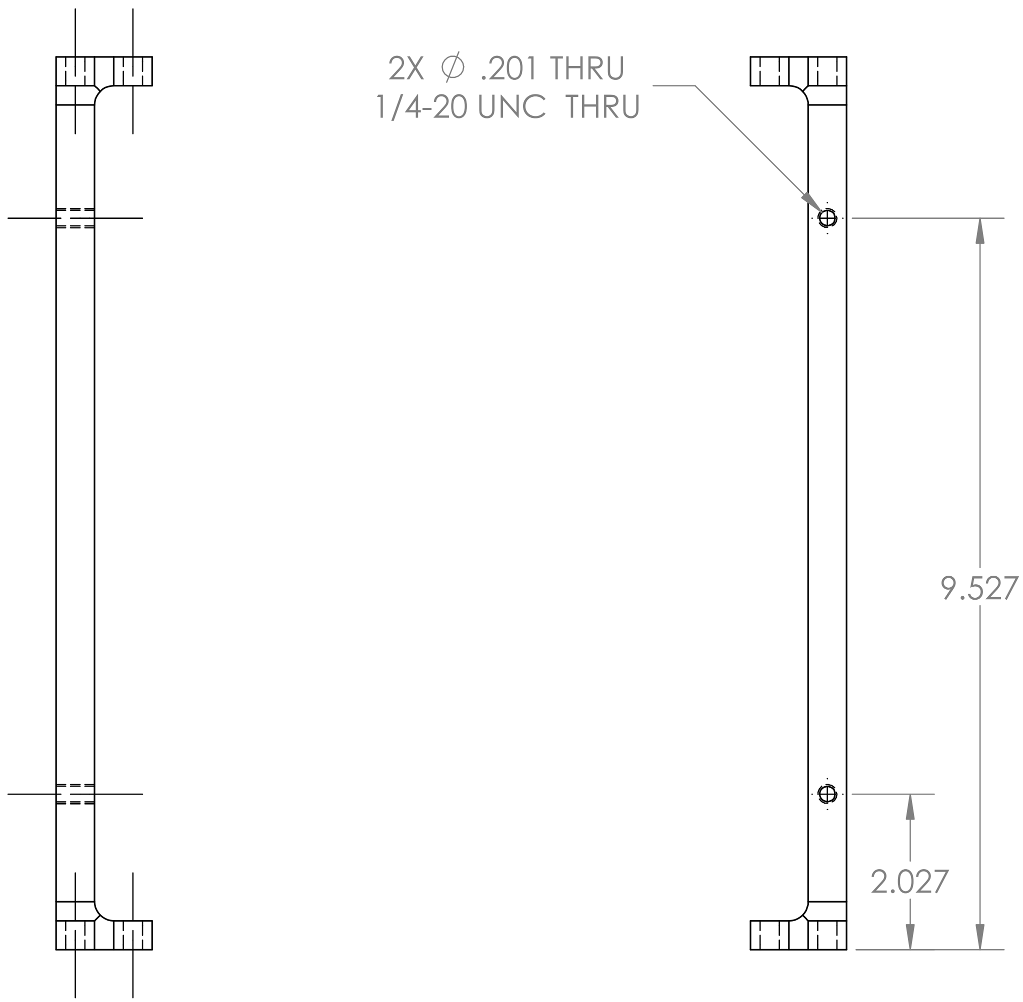
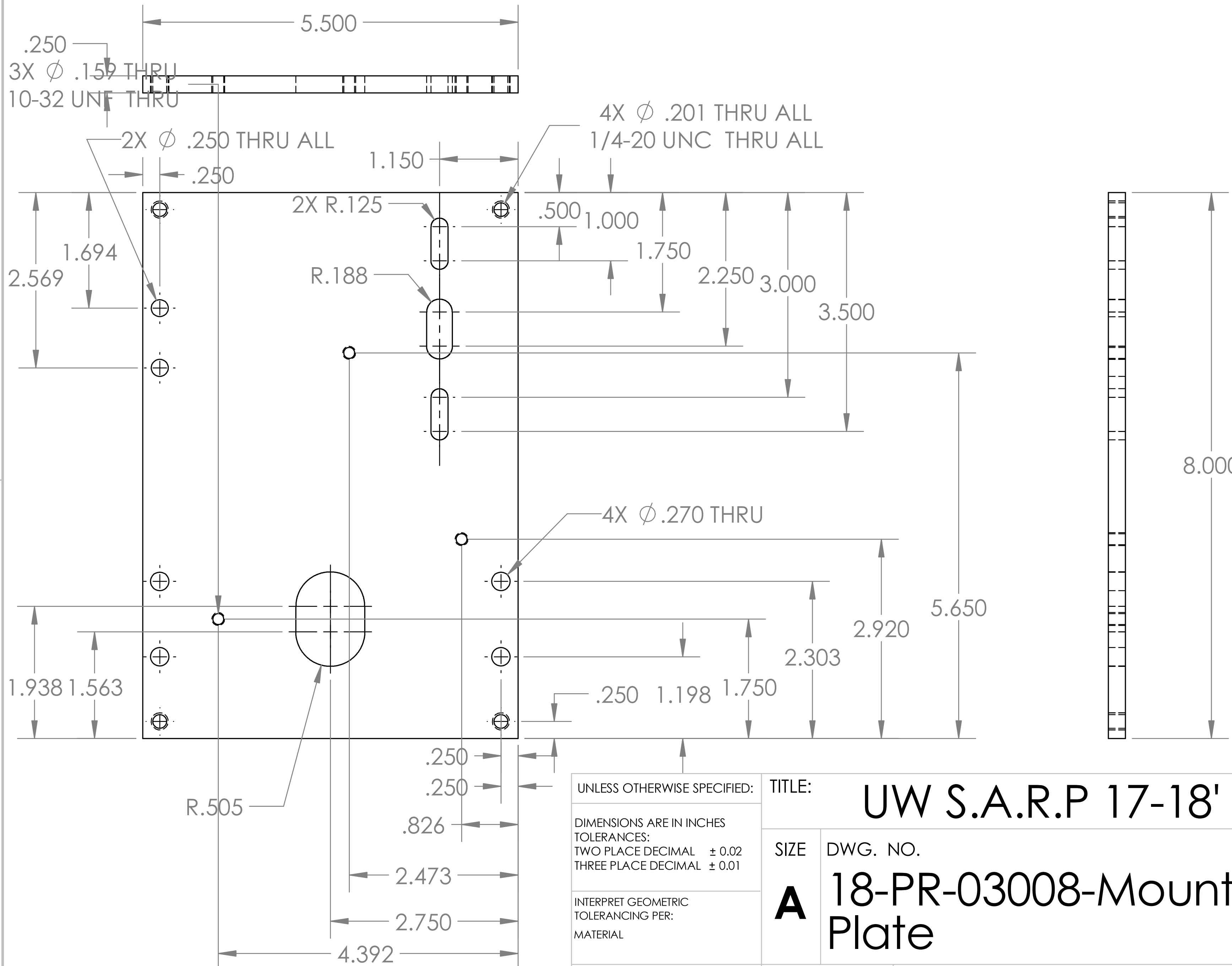
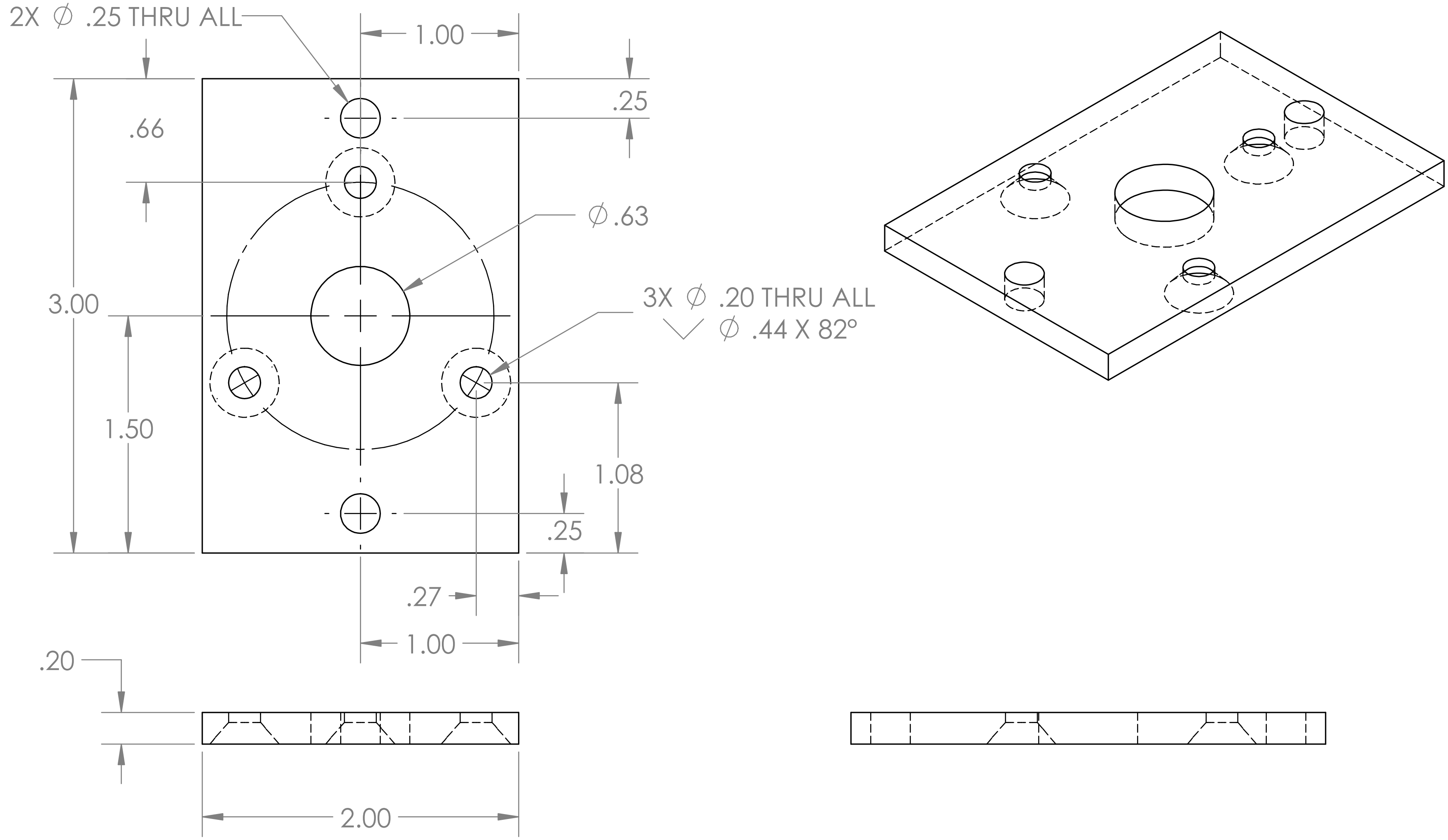


See 18-PR-03001-Structural Support Front Right for further dimensions

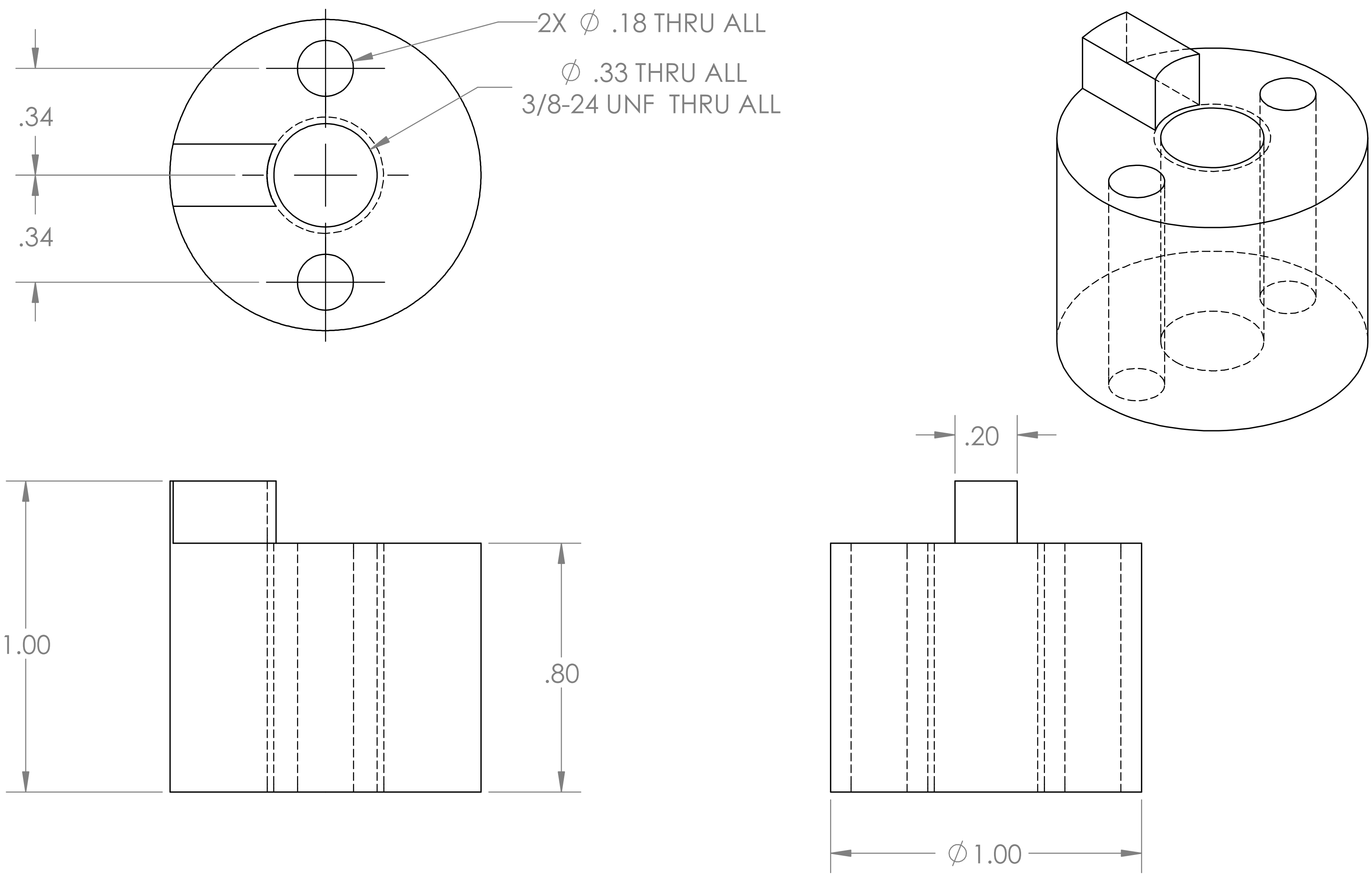
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03004-Structural Support Back Left	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



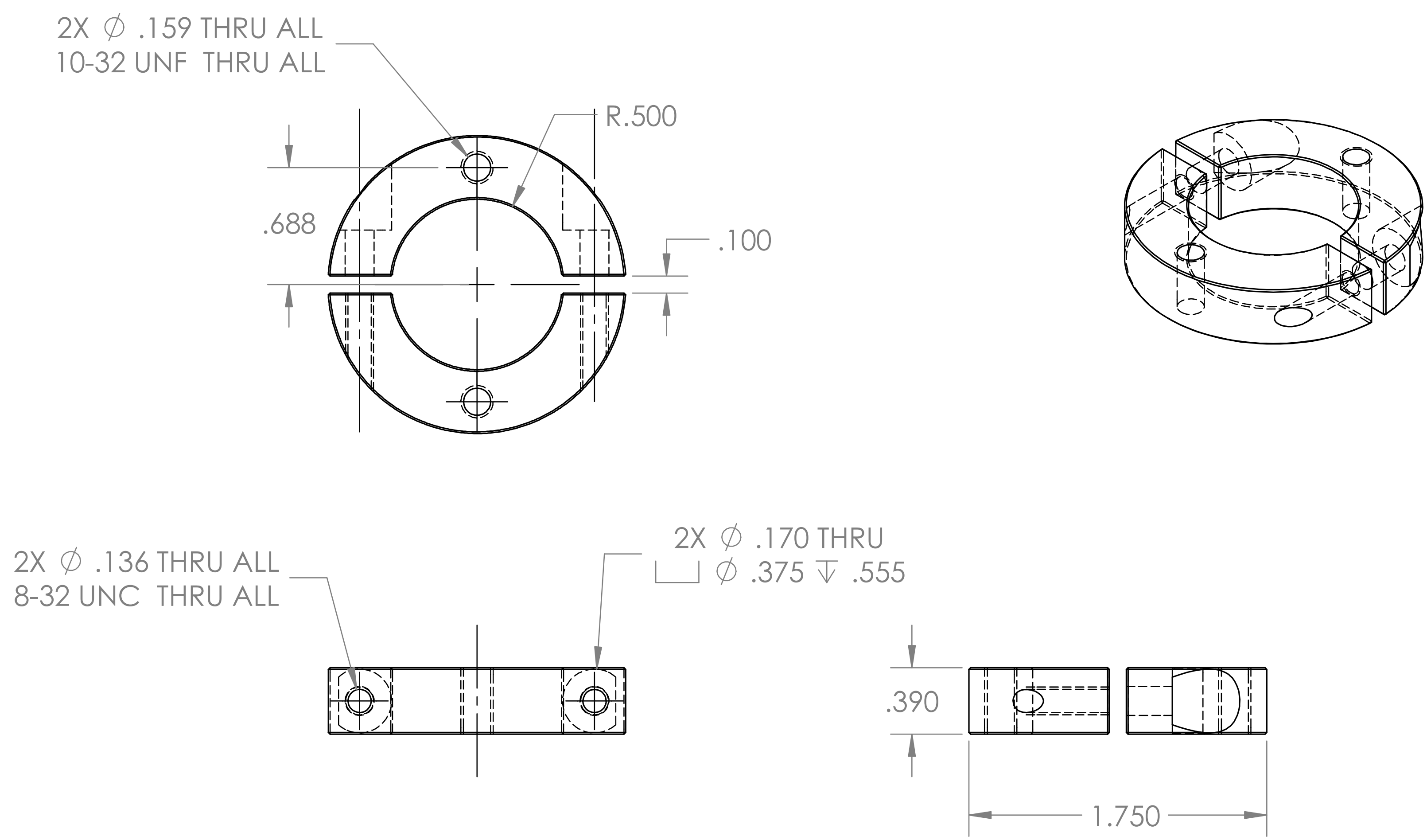
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-03008-Mounting Plate
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT: SHEET 1 OF 1



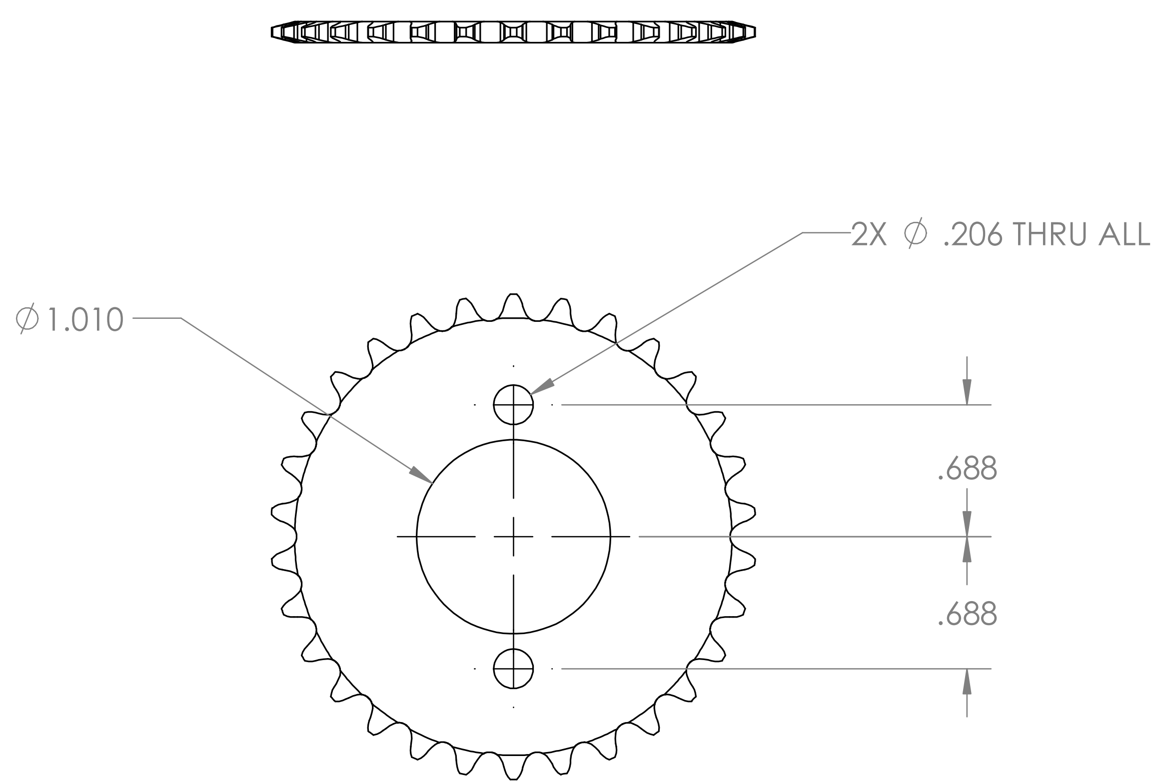
UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03009-Motor Actuator Mount
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: SHEET 1 OF 1



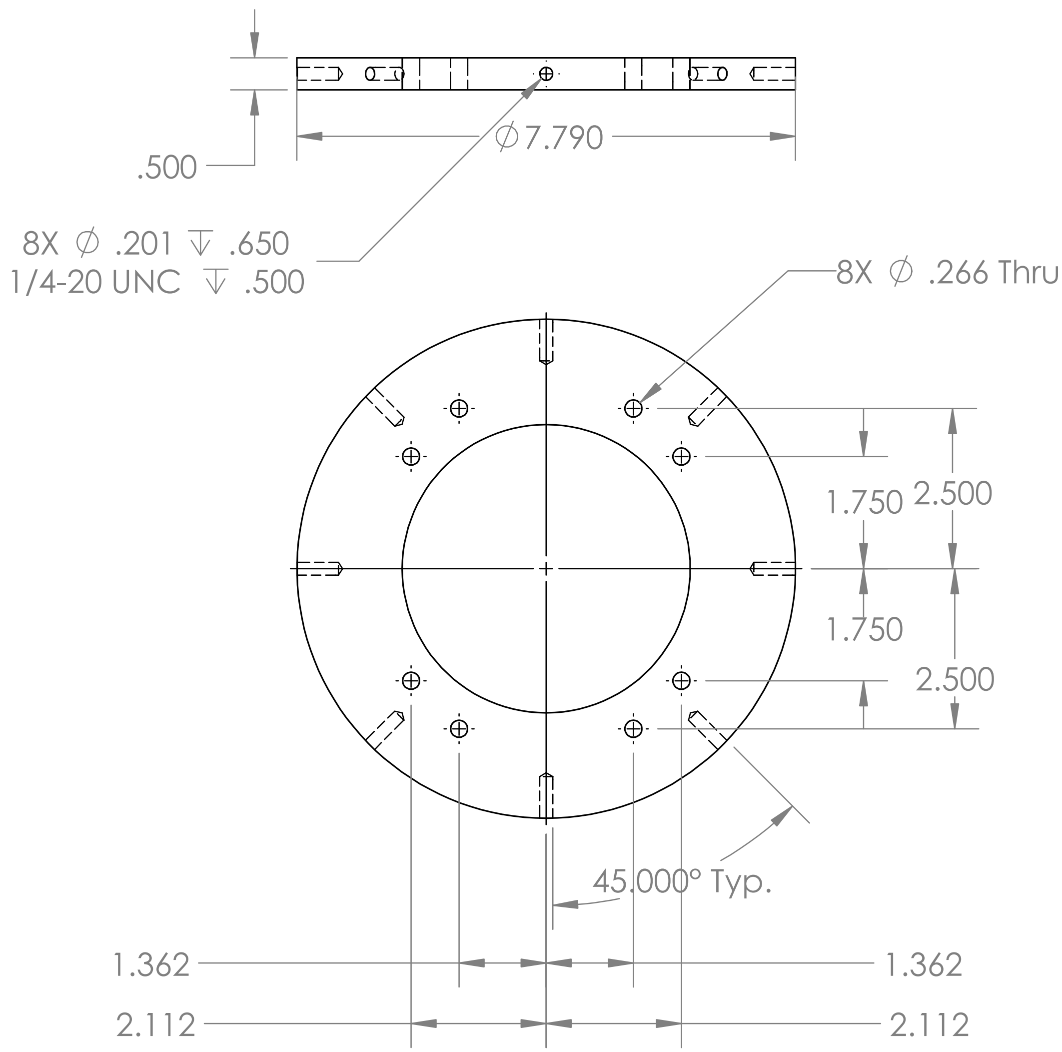
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-03011-Sprocket Coupler
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 2:1	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03012-Shaft Collar
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03013-6793K190 30 tooth Sprocket	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT:	SHEET 1 OF 1



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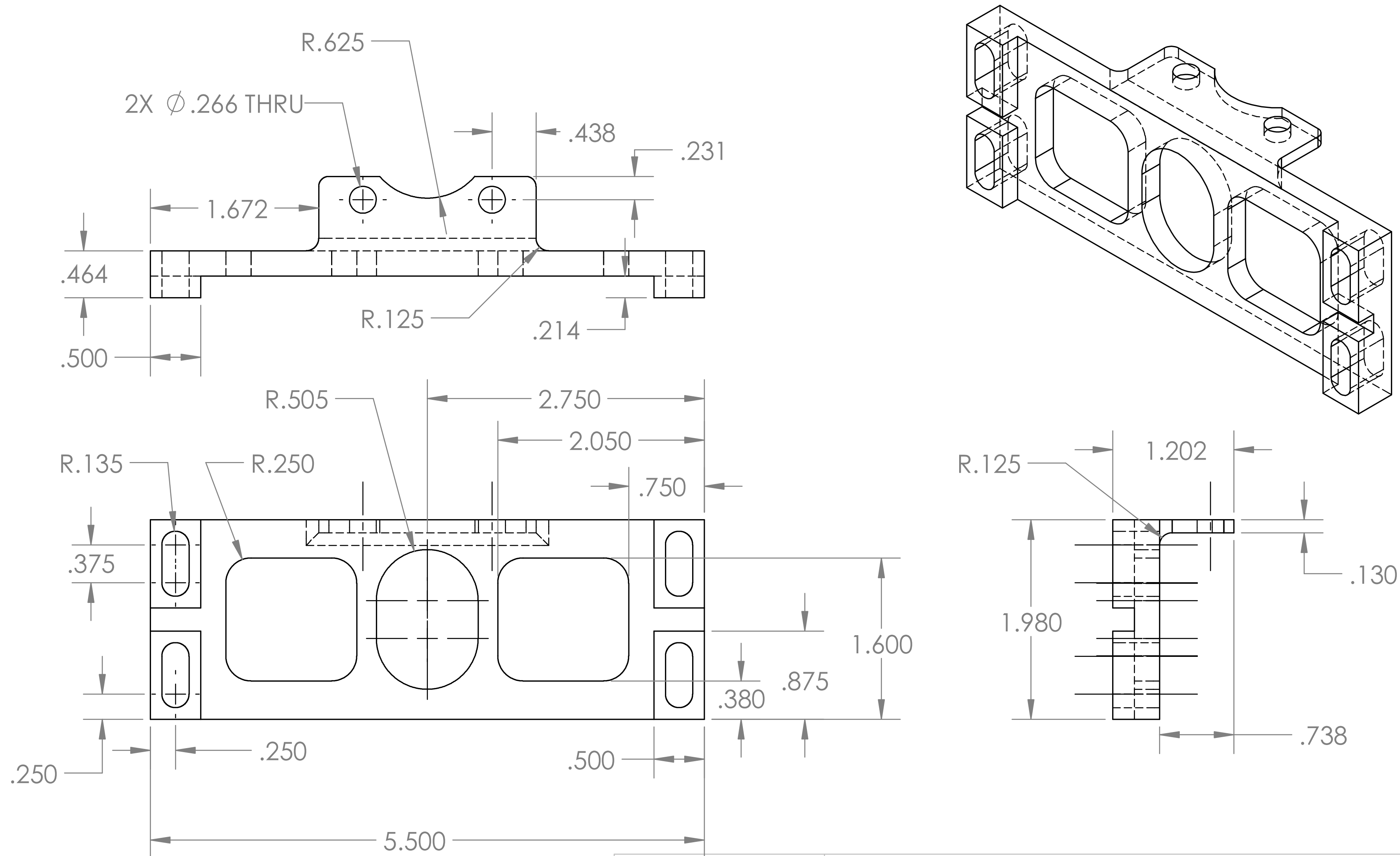
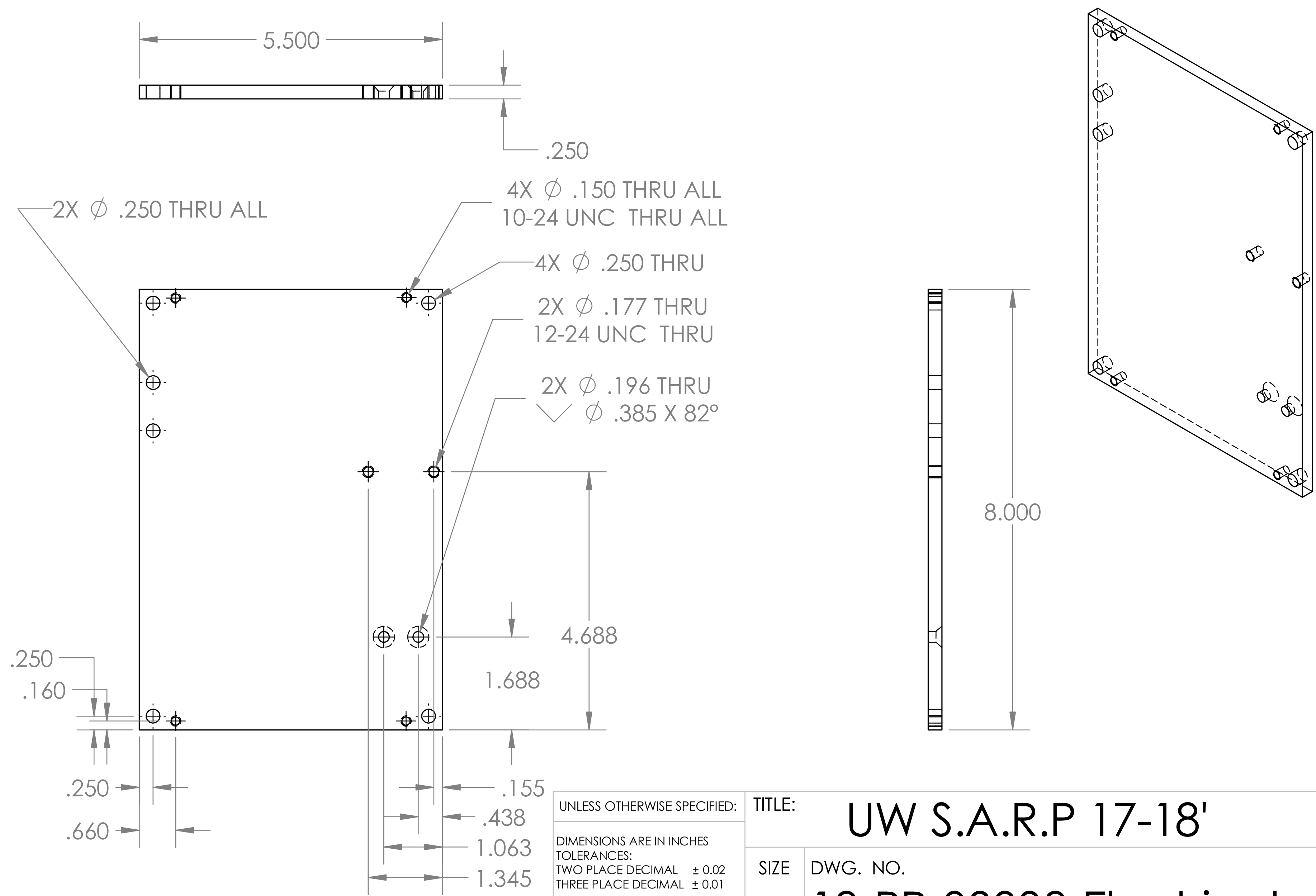
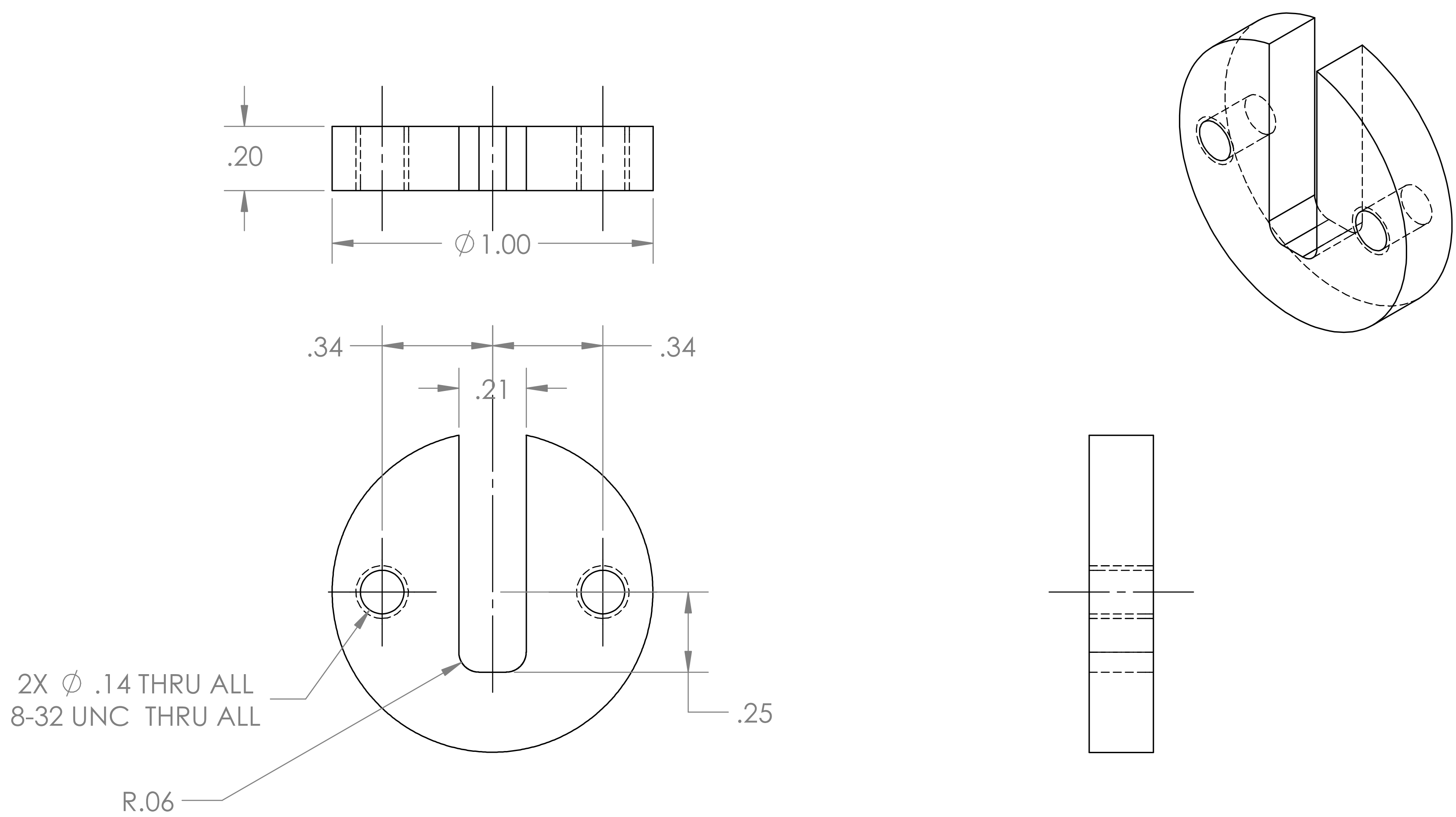
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03029-Ox Adapter	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



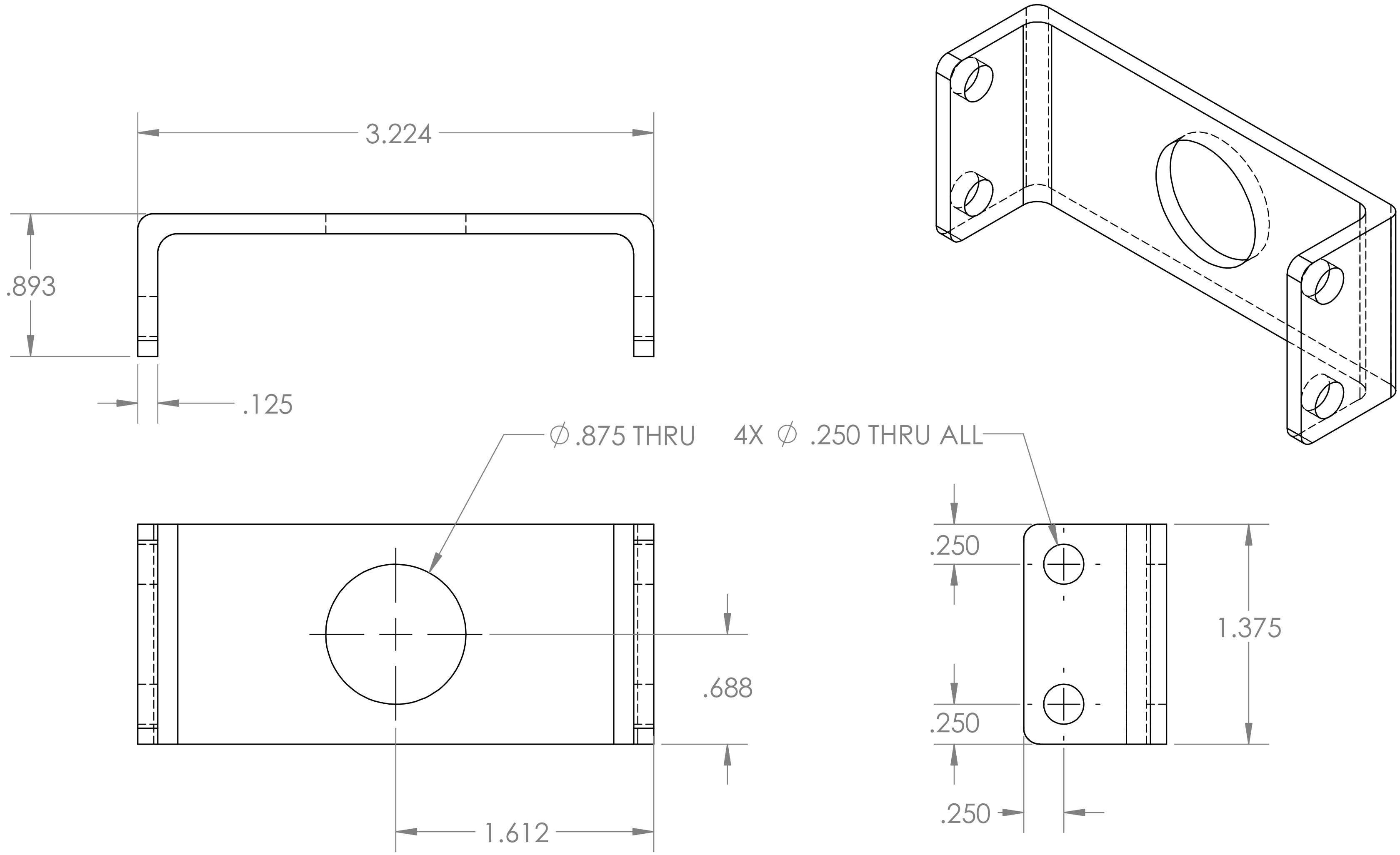
UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-03033-Ball Valve Mounting Plate
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03038-Electrical and Pnuematic Plate	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

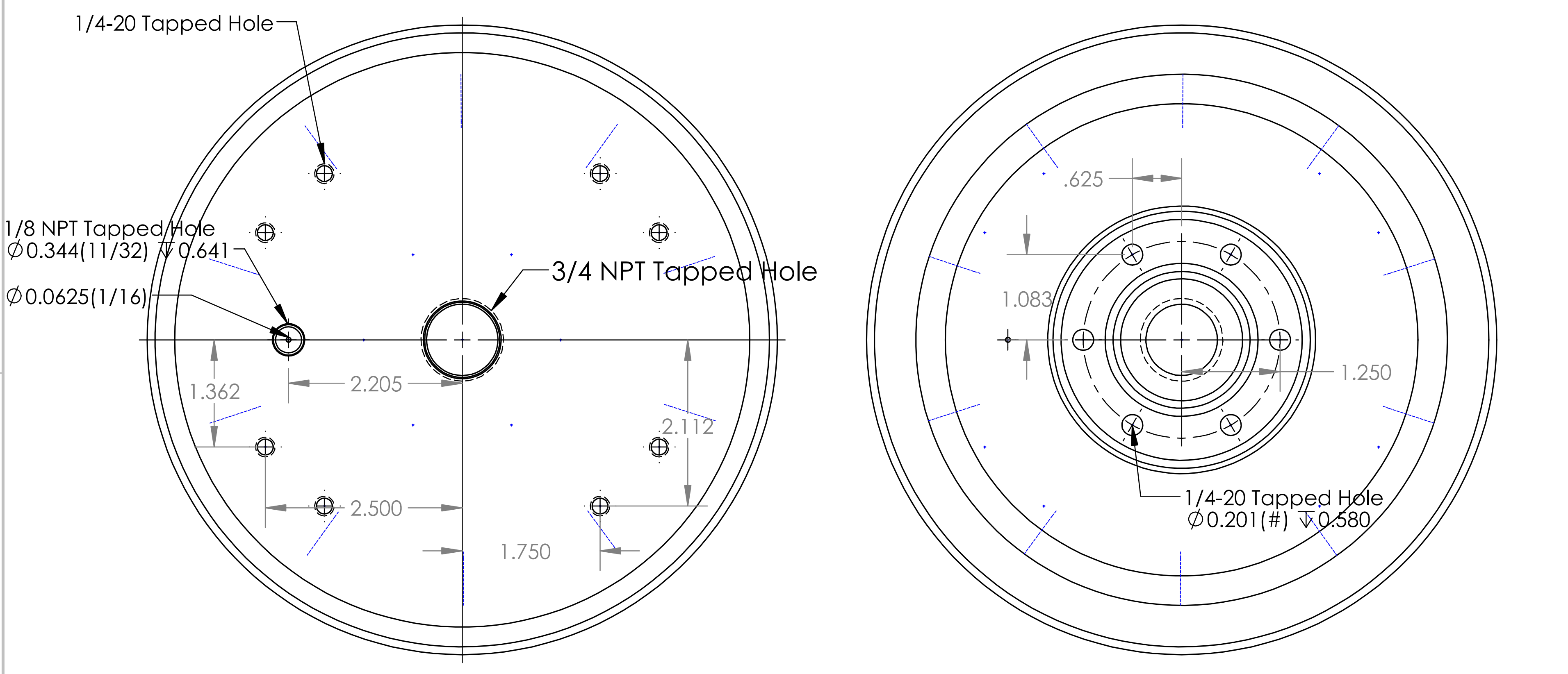


UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03044-Lock Plate	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

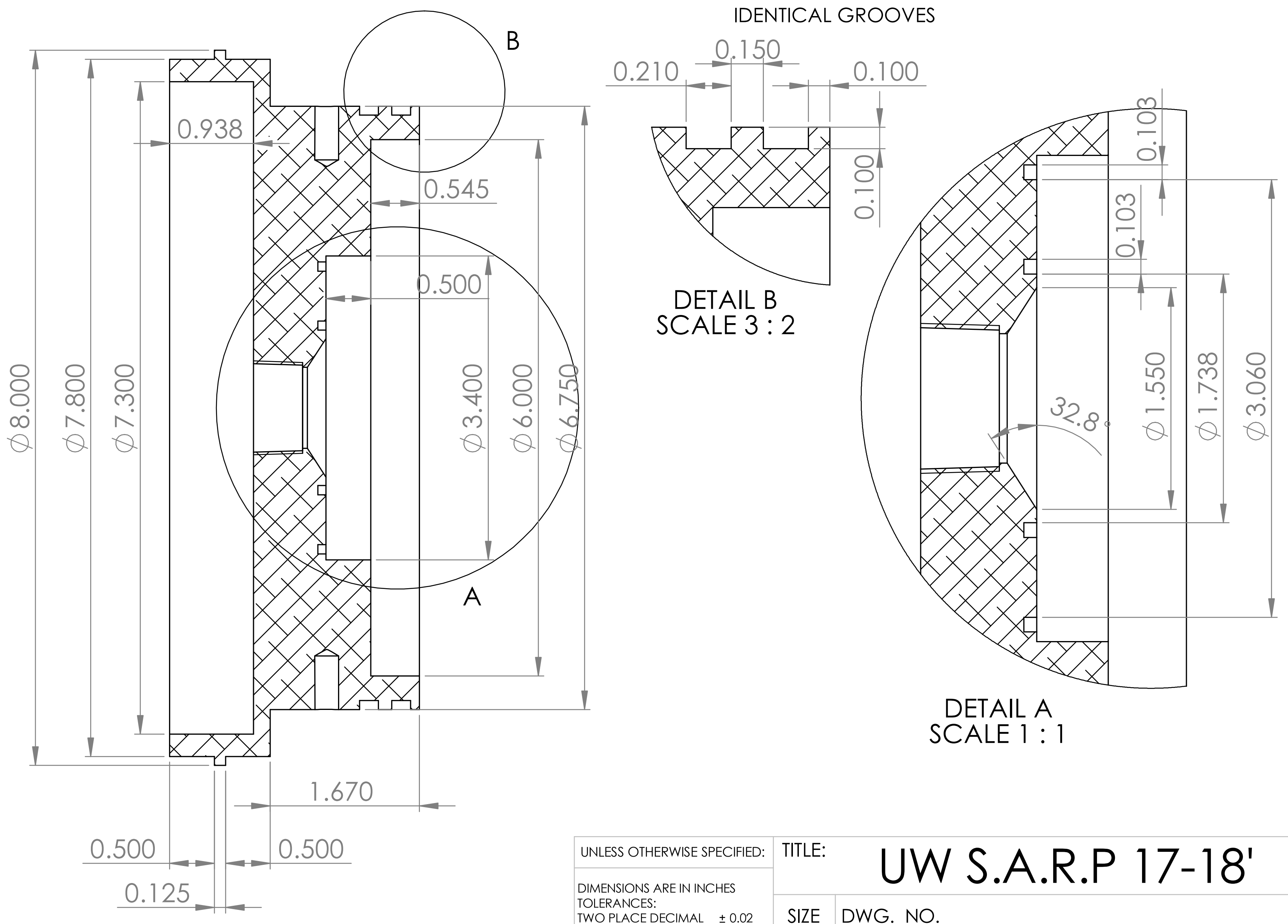


UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-03047-Remote Fill Support	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

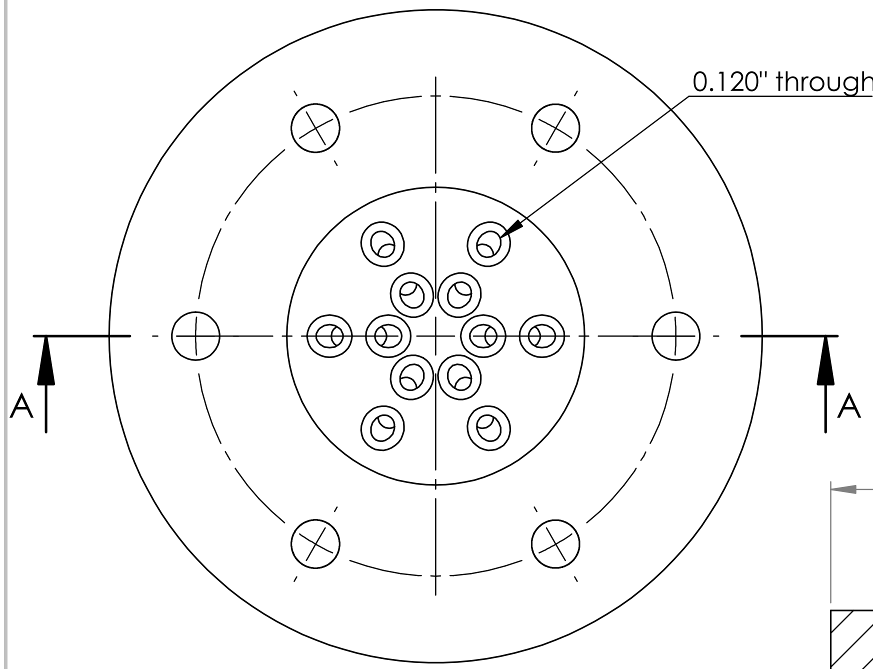
Oxidizer Injector

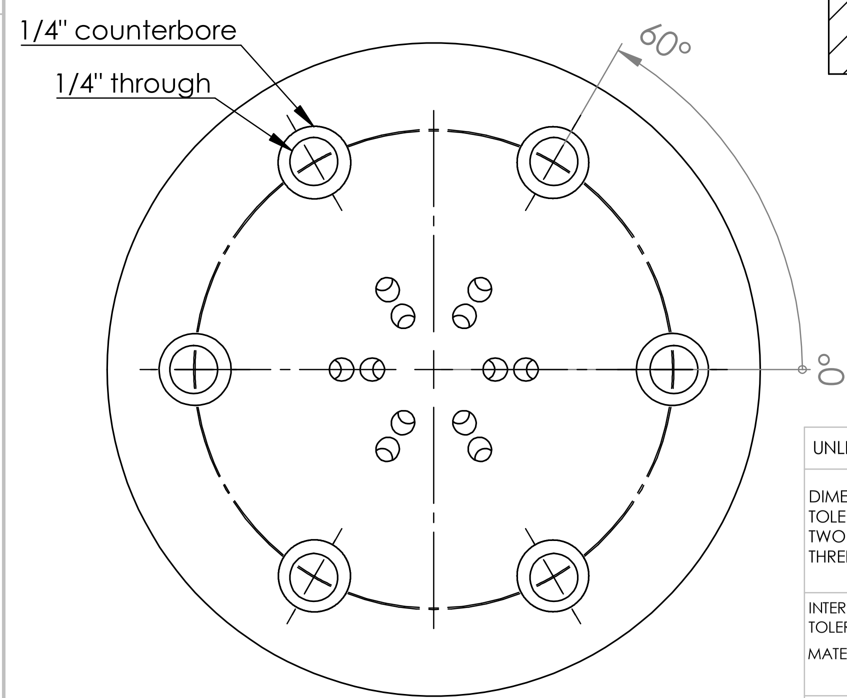


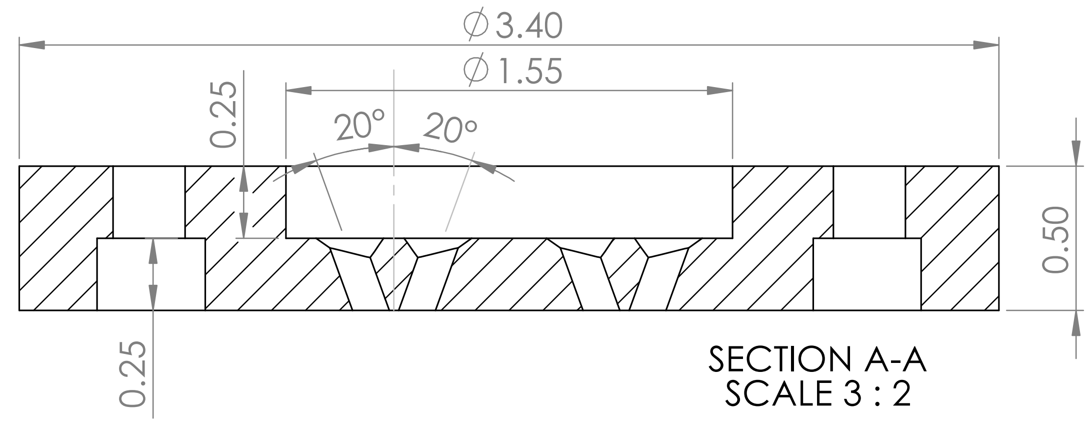
UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-10001-Injector Bulkhead Hole Pattern
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-10001-Injector Bulkhead
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:5	WEIGHT: SHEET 1 OF 1



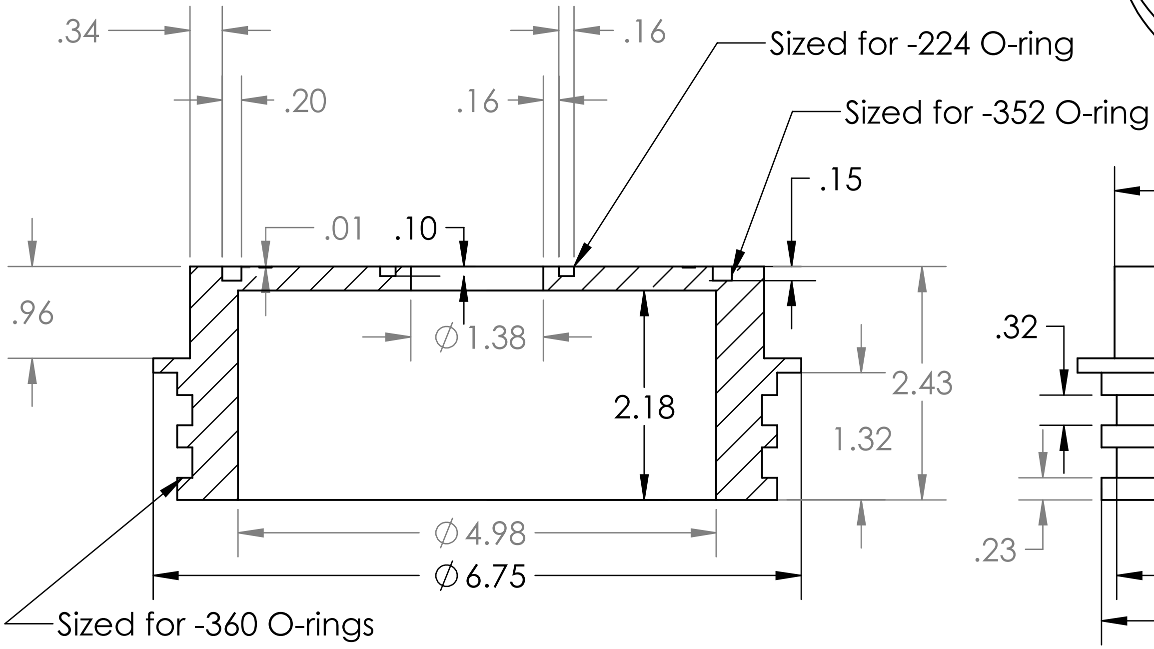


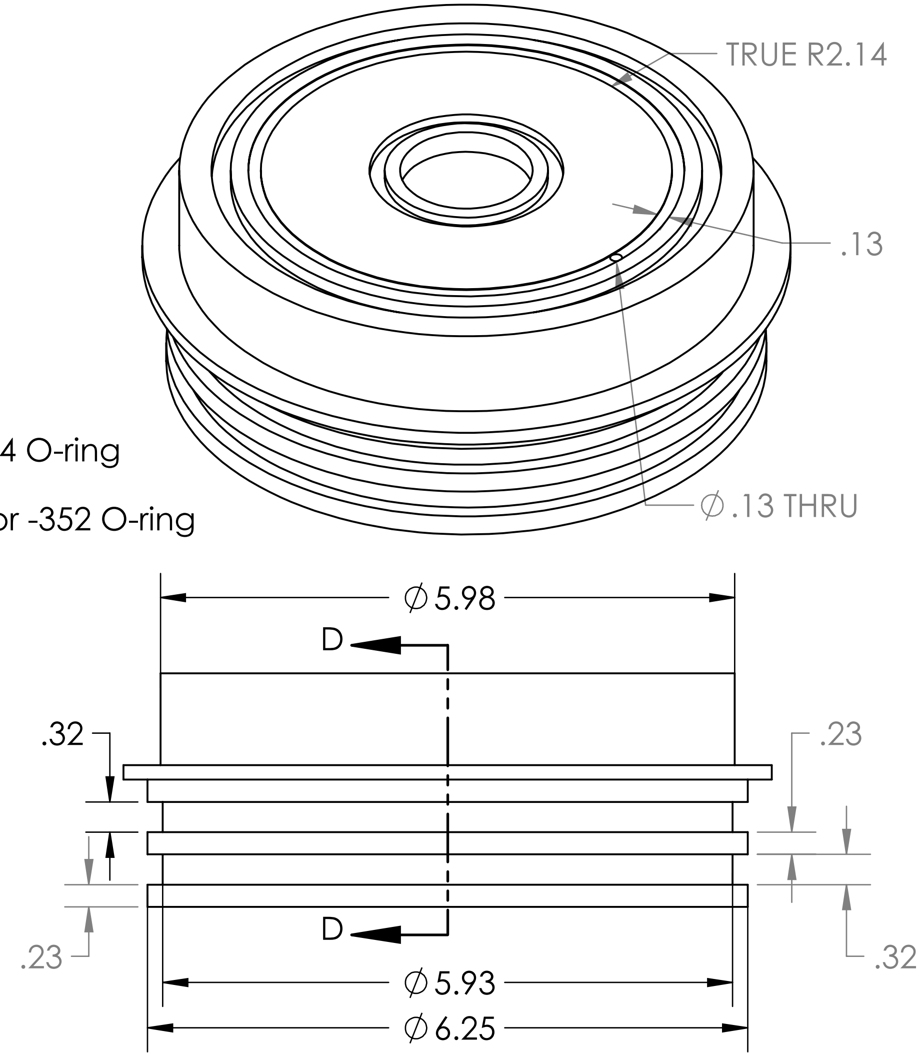


UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-10002-Injector Plate		
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL				
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT:		SHEET 1 OF 1

Thermal Protection System

SECTION D-D
SCALE 1 : 2





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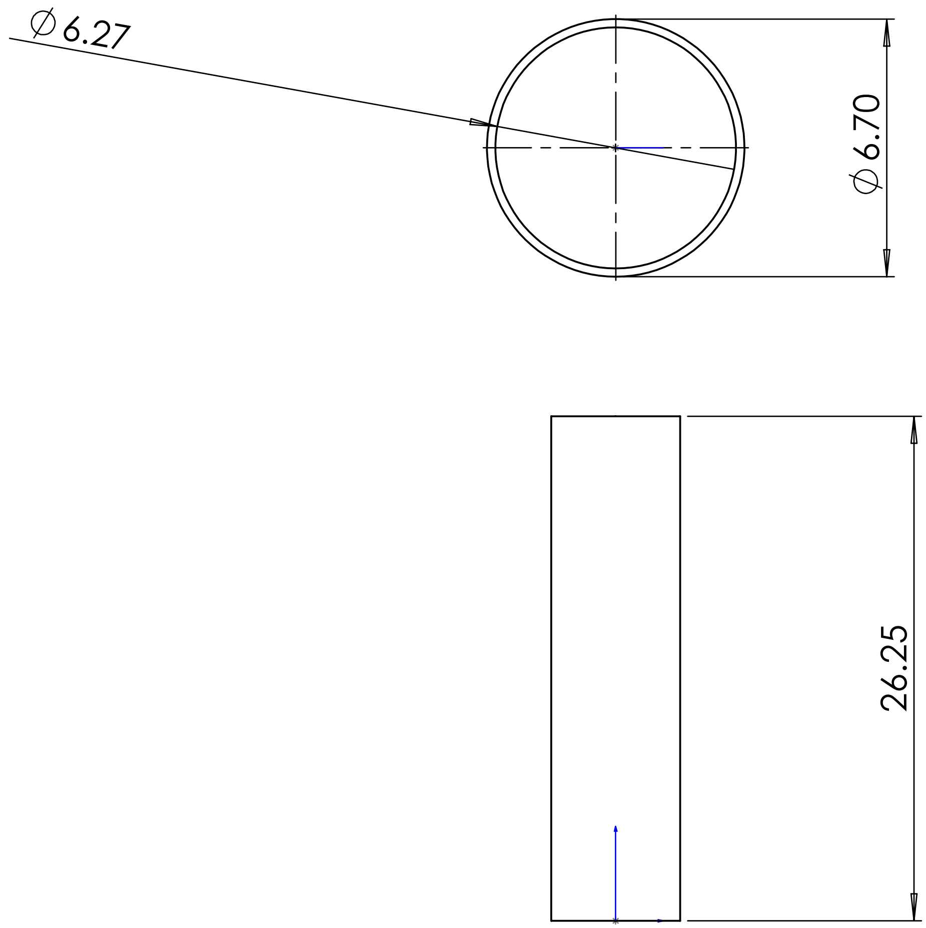
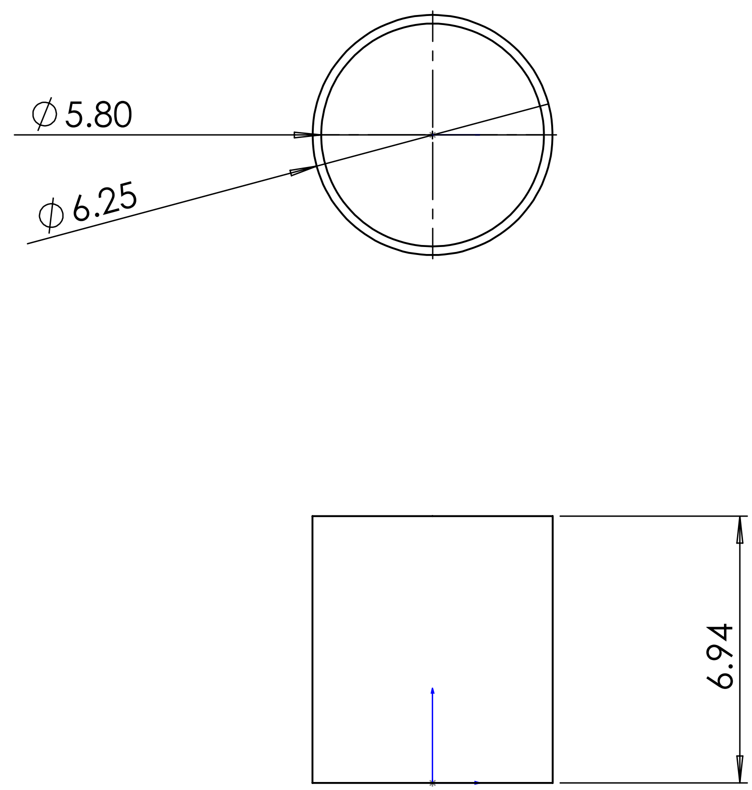
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-07001- Precombustor
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-07002-Outer Liner	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:10	WEIGHT:	SHEET 1 OF 1



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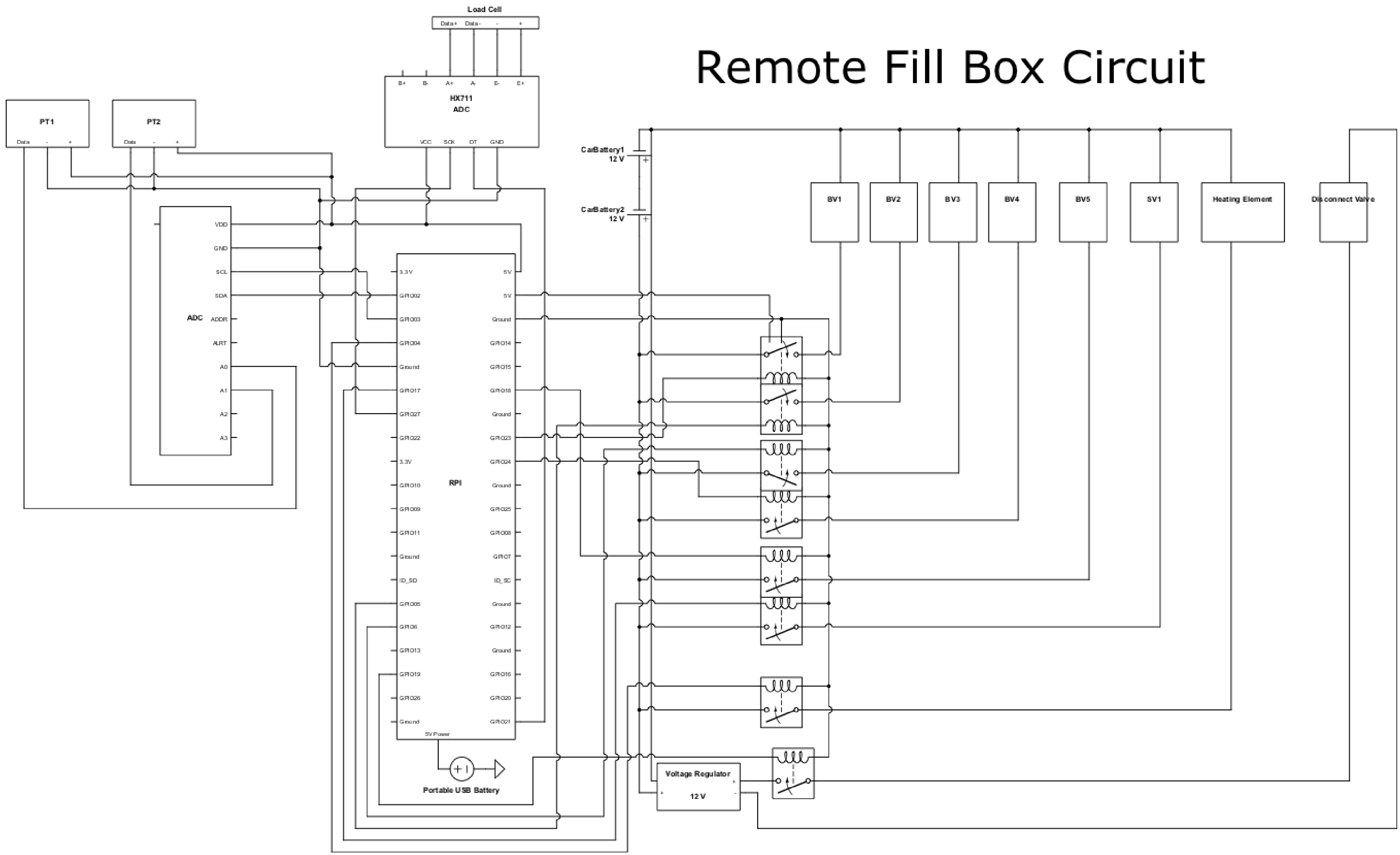
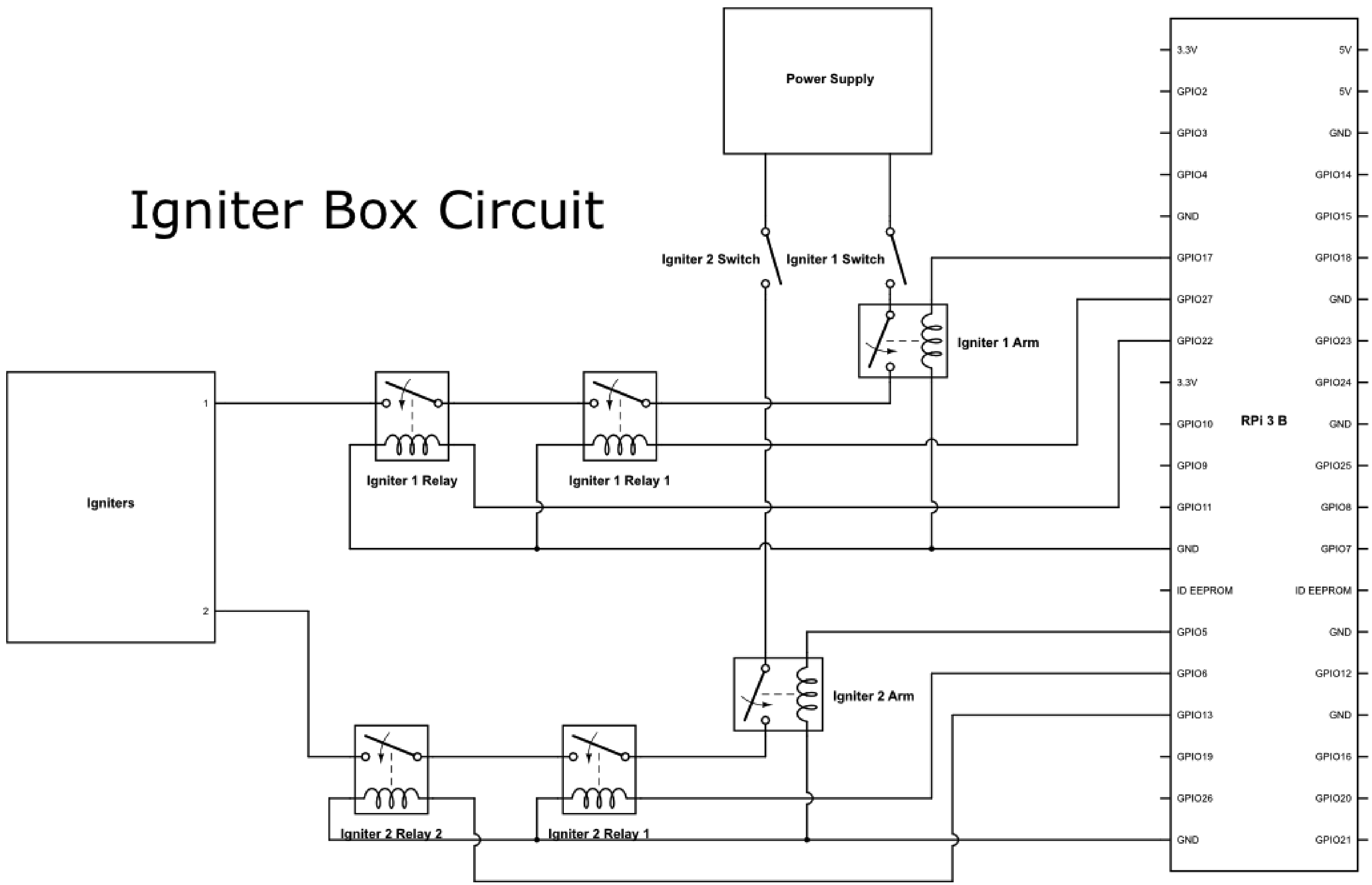
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PR-07003-Post Combustor
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:5	WEIGHT: SHEET 1 OF 1

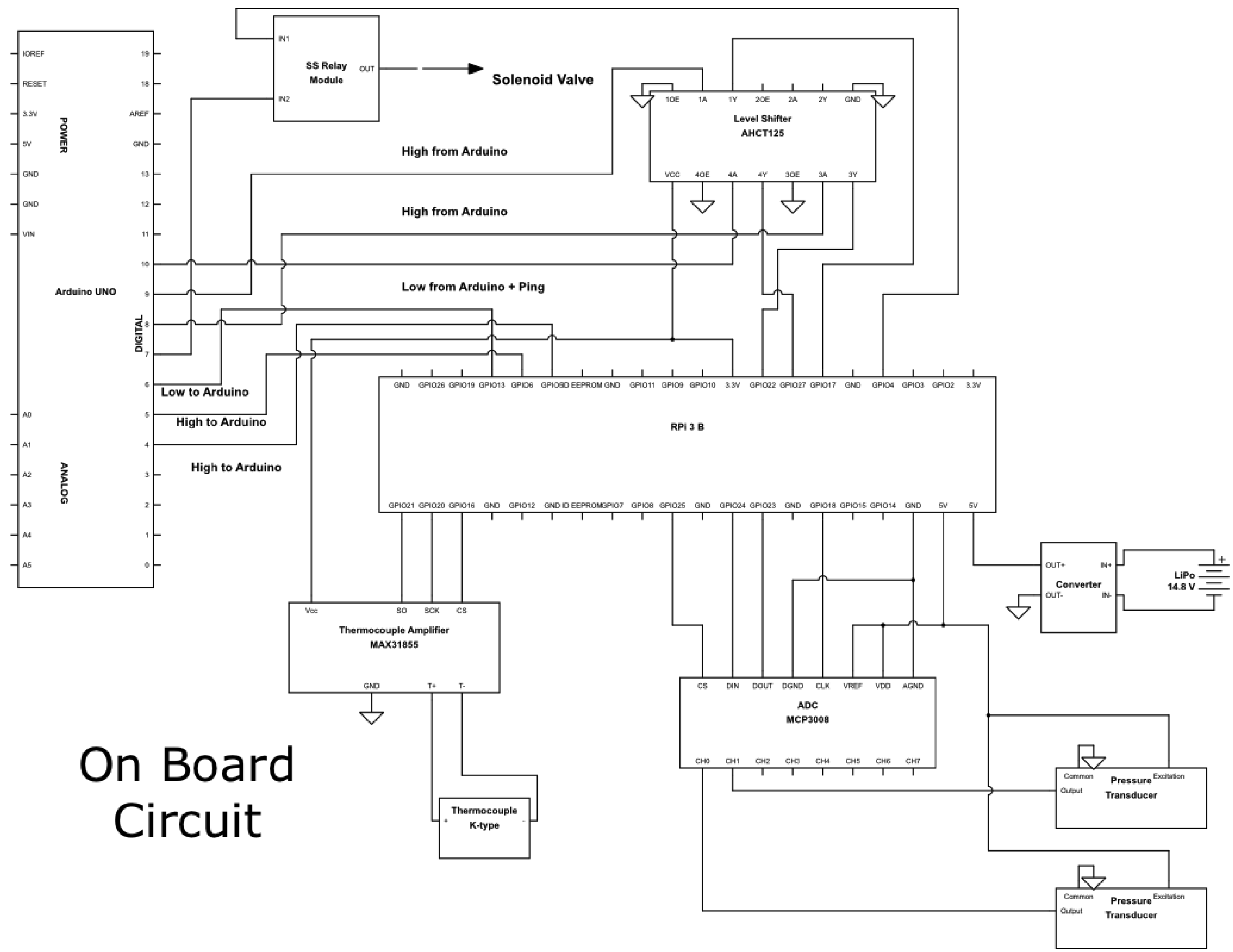
Remote Fill and Launch Control

Remote Fill Box Circuit



Igniter Box Circuit

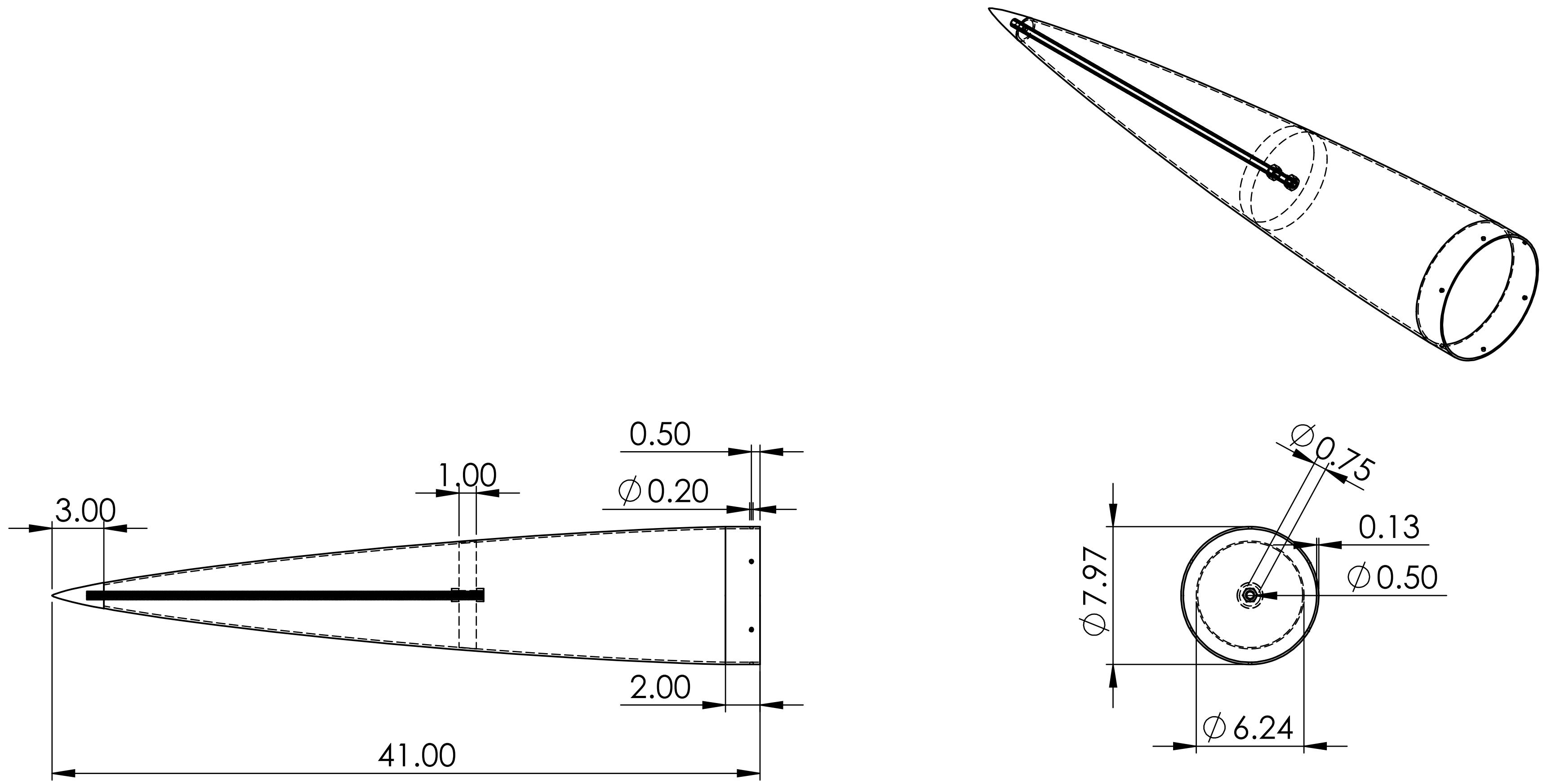




On Board Circuit

Structures

Nose Cone



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

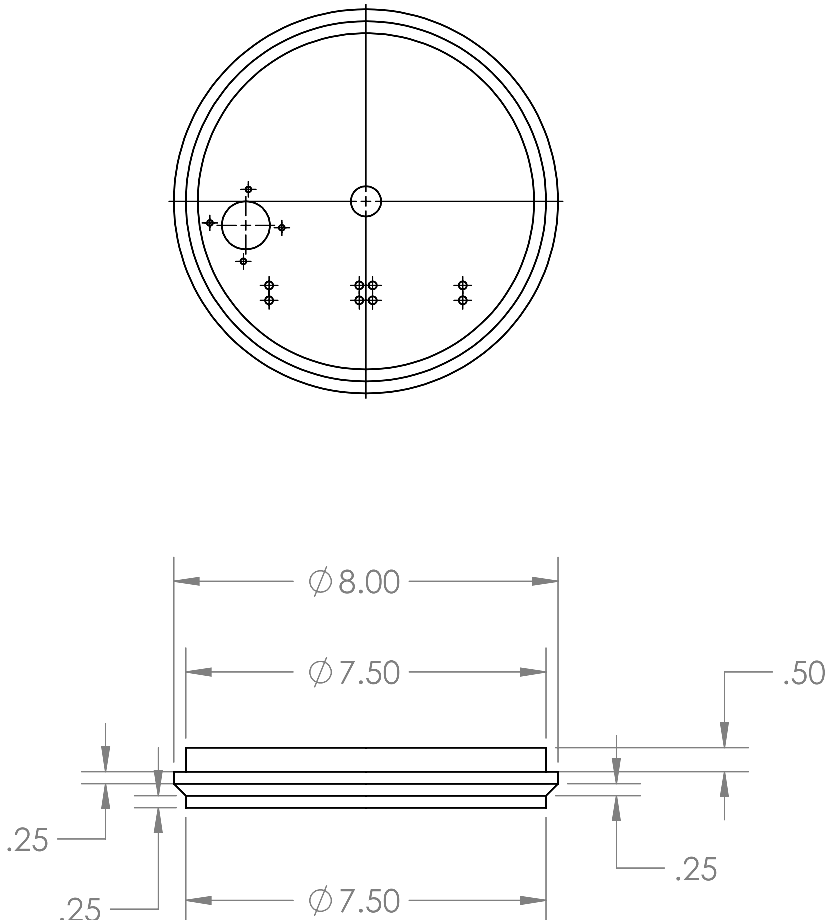
COMMENTS:

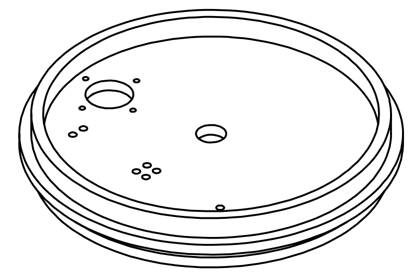
TITLE:

SIZE	DWG. NO.	REV
A	Nosecone-Assembly	

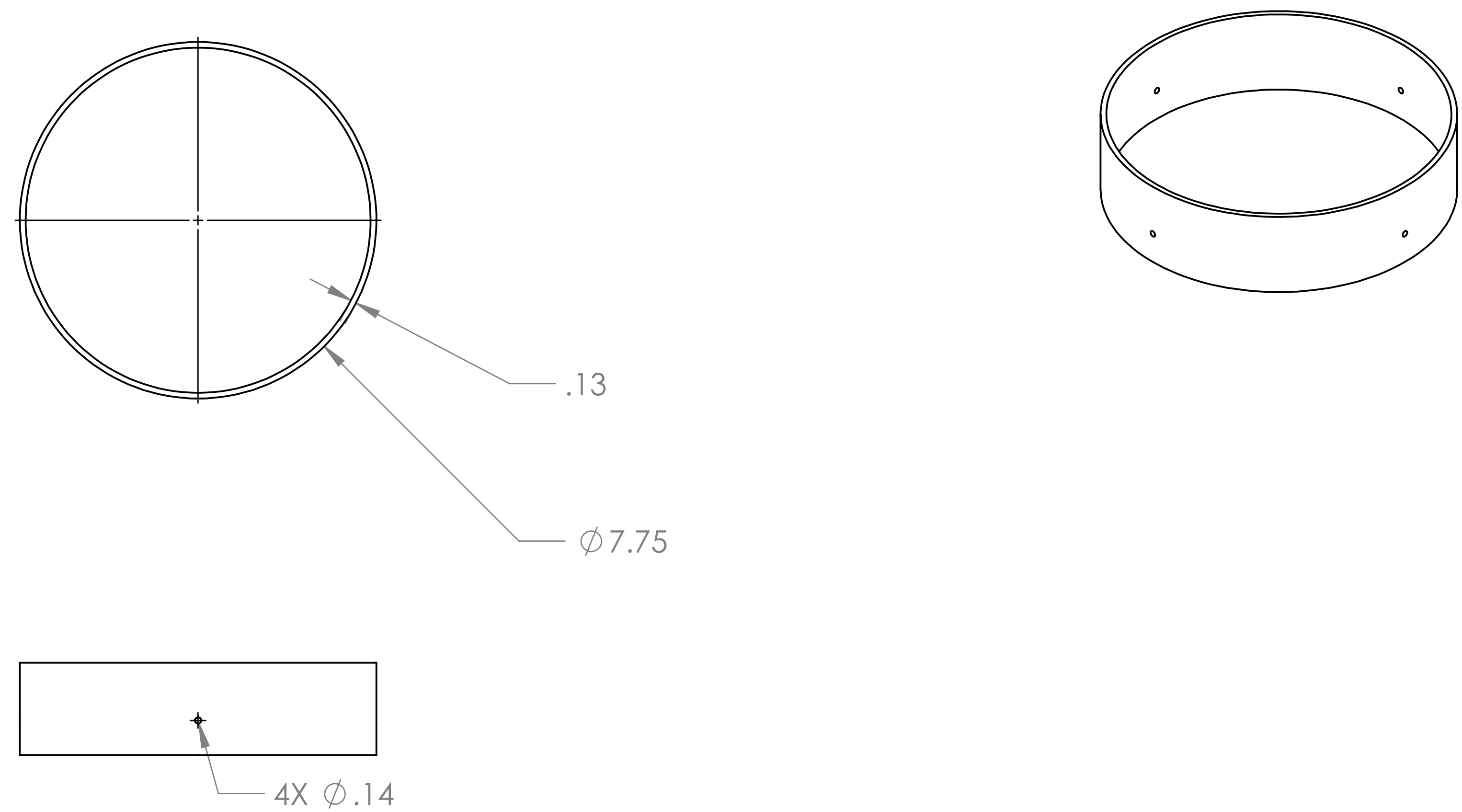
SCALE: 1:10 WEIGHT: SHEET 1 OF 1

Couplers

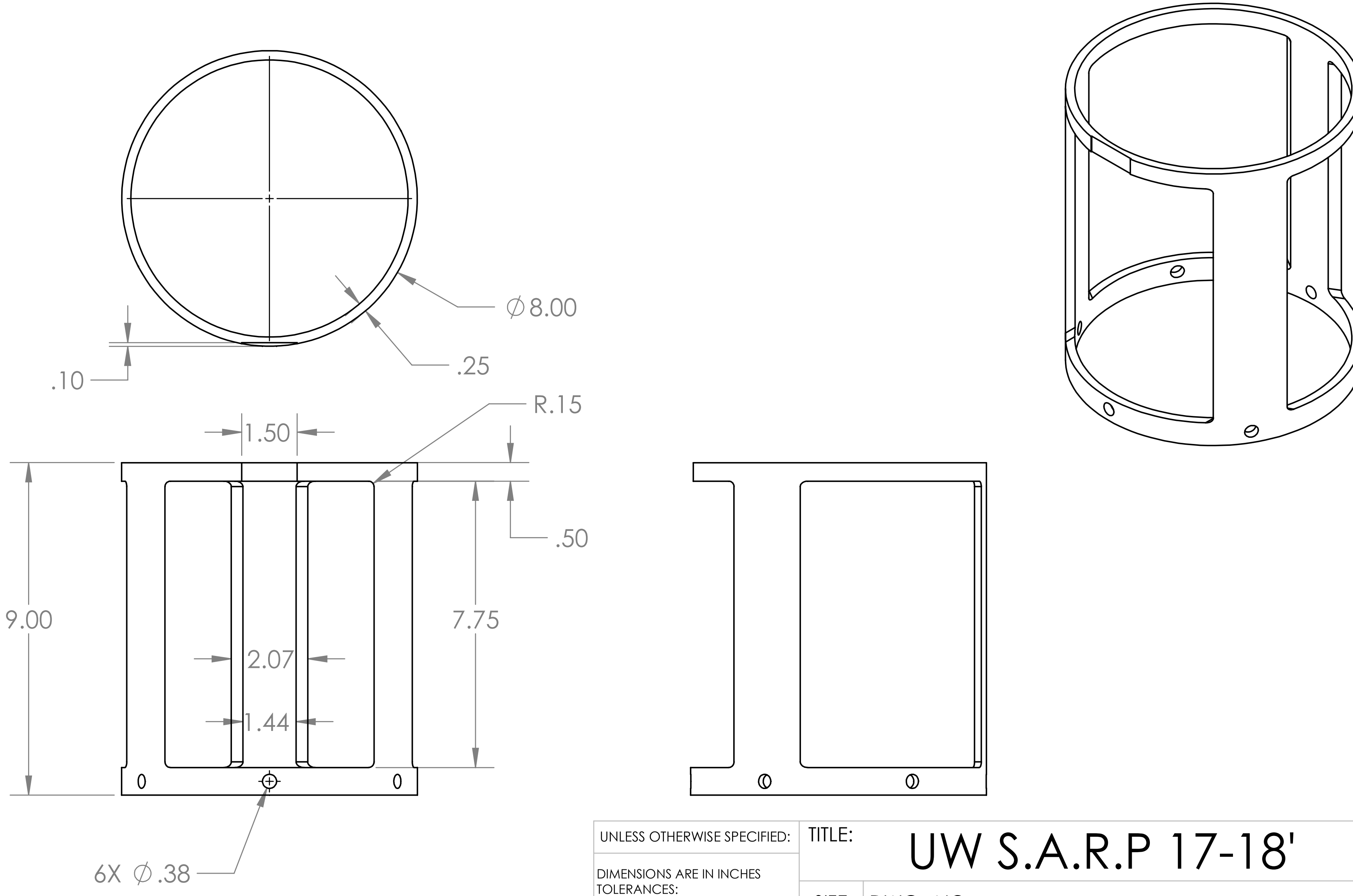




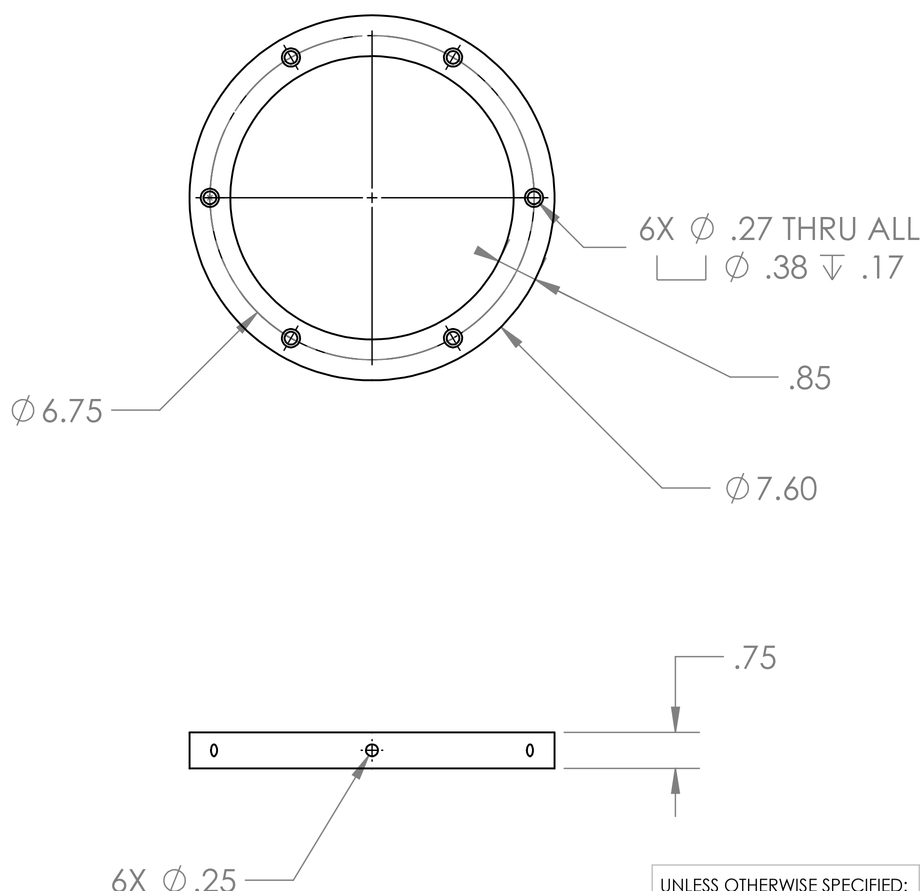
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-RC-01001-Recovery Bulkhead	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL Aluminum 6061			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1

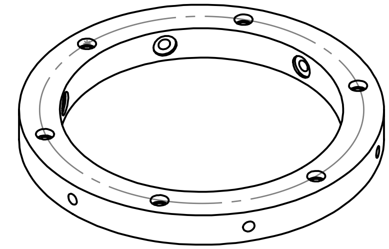


UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-RC-01001b-Recovery Bulkhead	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL: Aluminum 6061			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1

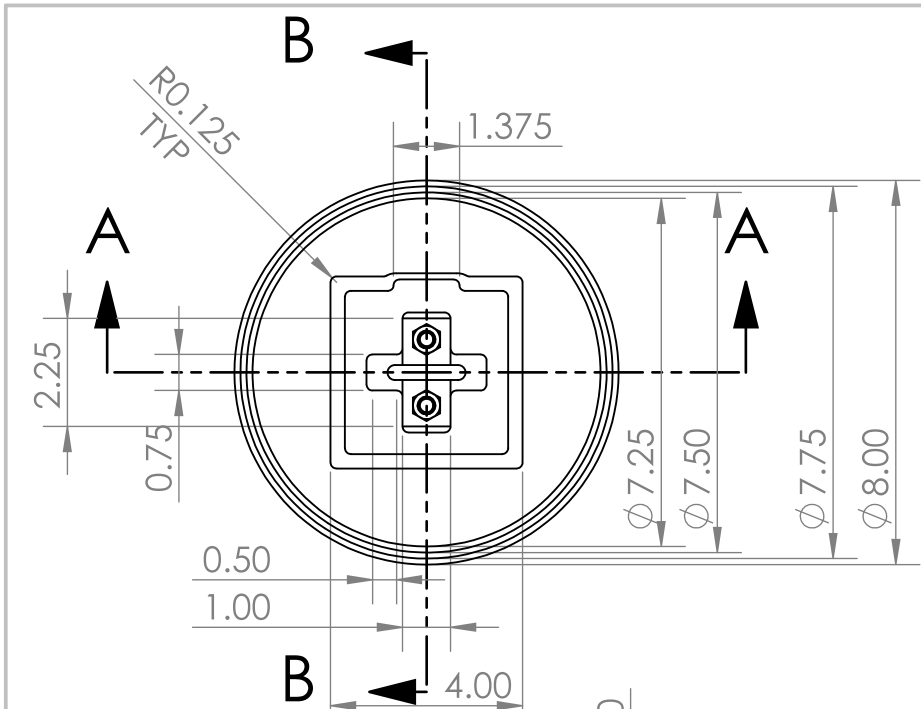


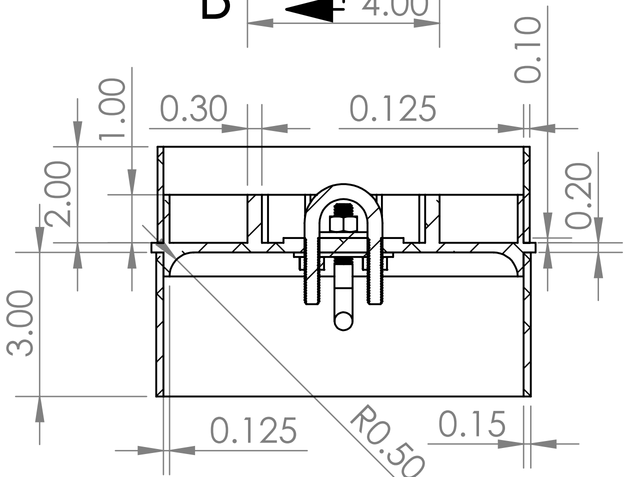
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-RC-01002-Recovery Cage	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL: Aluminum 6061			
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



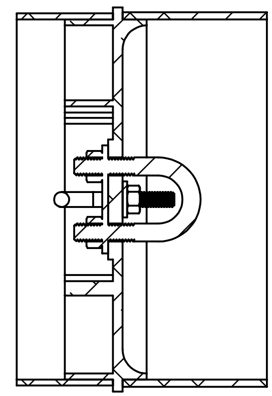


UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-RC-01003-Ox Ring
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL: Aluminum 6061		
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT: SHEET 1 OF 1

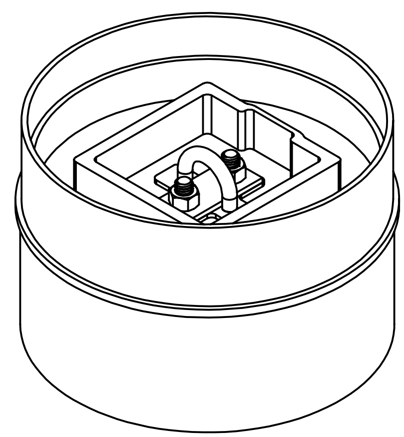




SECTION A-A
SCALE 1 : 4

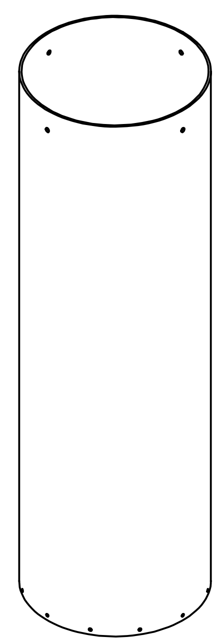


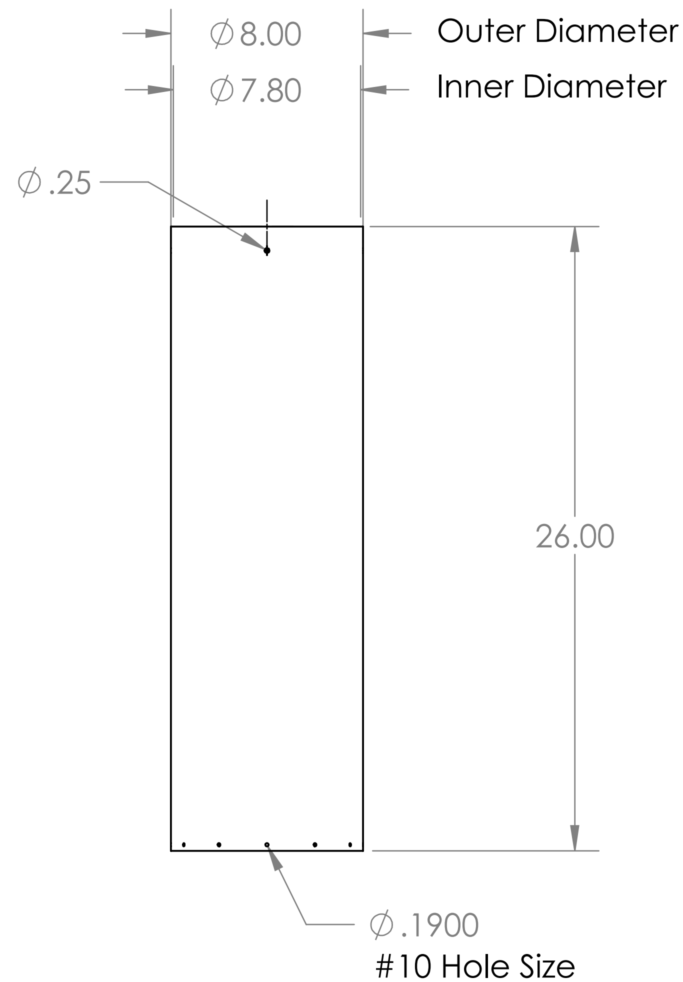
SECTION B-B
SCALE 1 : 4



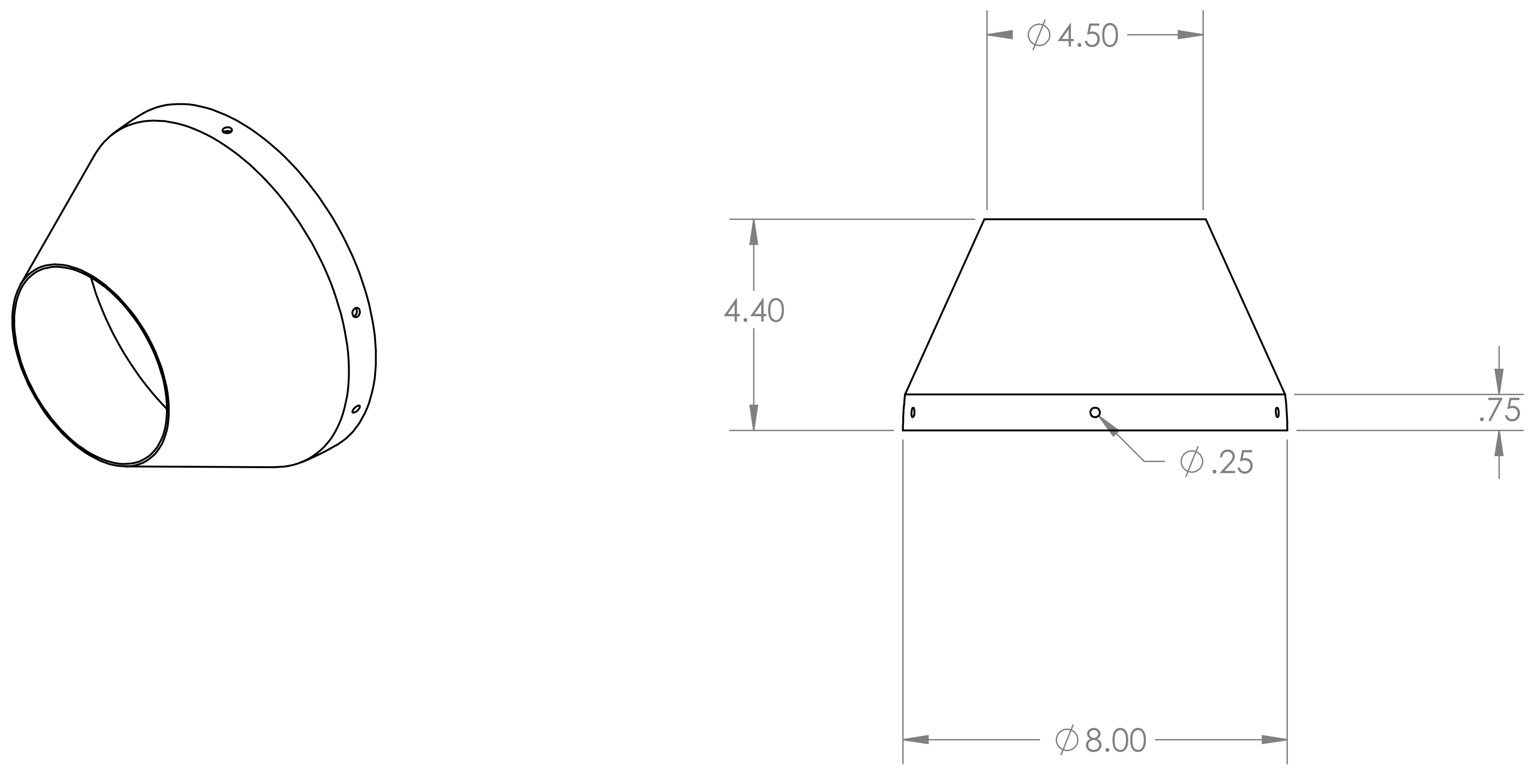
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.001 THREE PLACE DECIMAL ± 0.001	SIZE **A**	DWG. NO. 18-NS-A02 Payload Coupler	
INTERPRET GEOMETRIC TOLERANCING PER: AI 6061 T651			
DO NOT SCALE DRAWING	SCALE 1:4	WEIGHT: 3.5272 lbs	SHEET 1 OF 1

Body Tubes





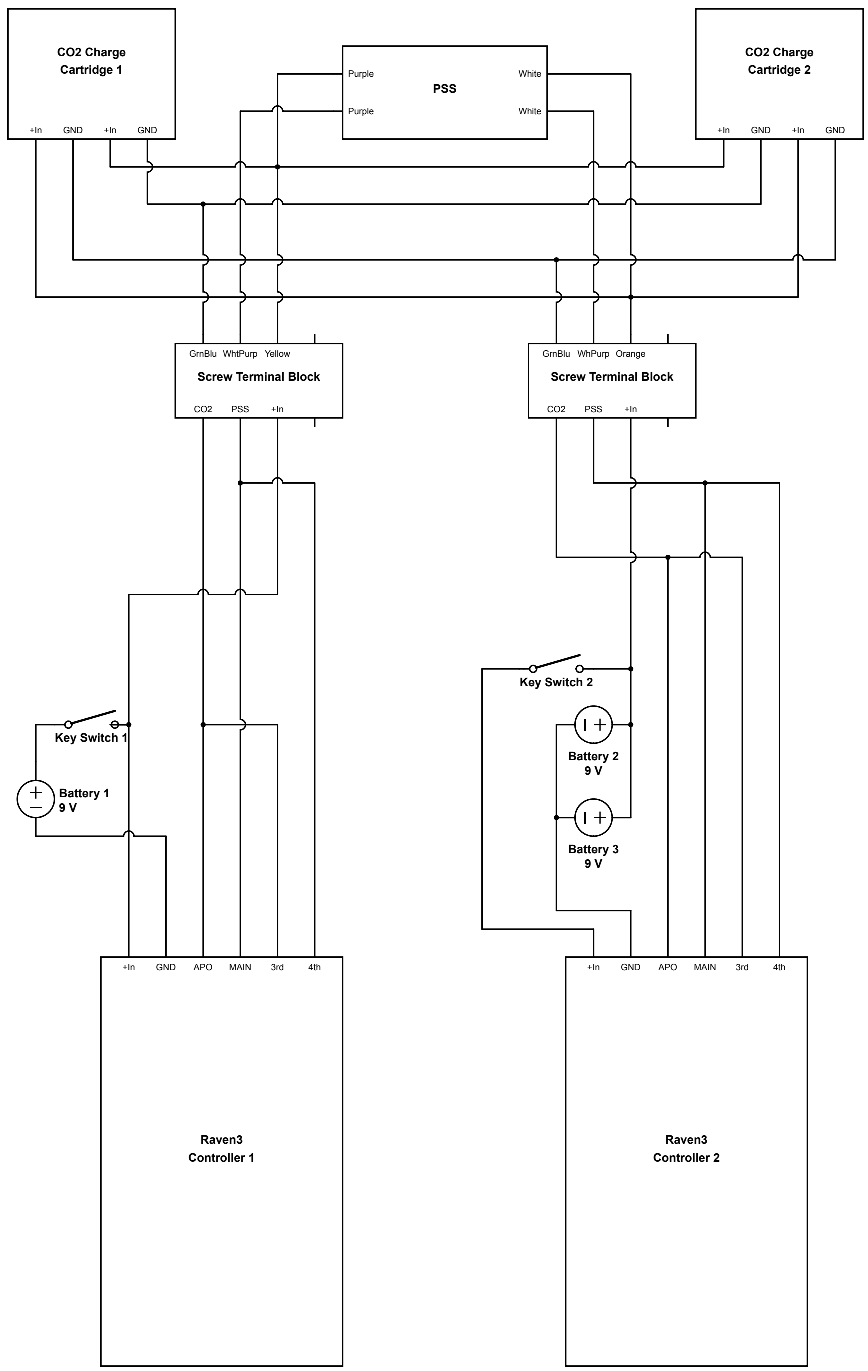
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-AF-03001-Upper-Body-Tube	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

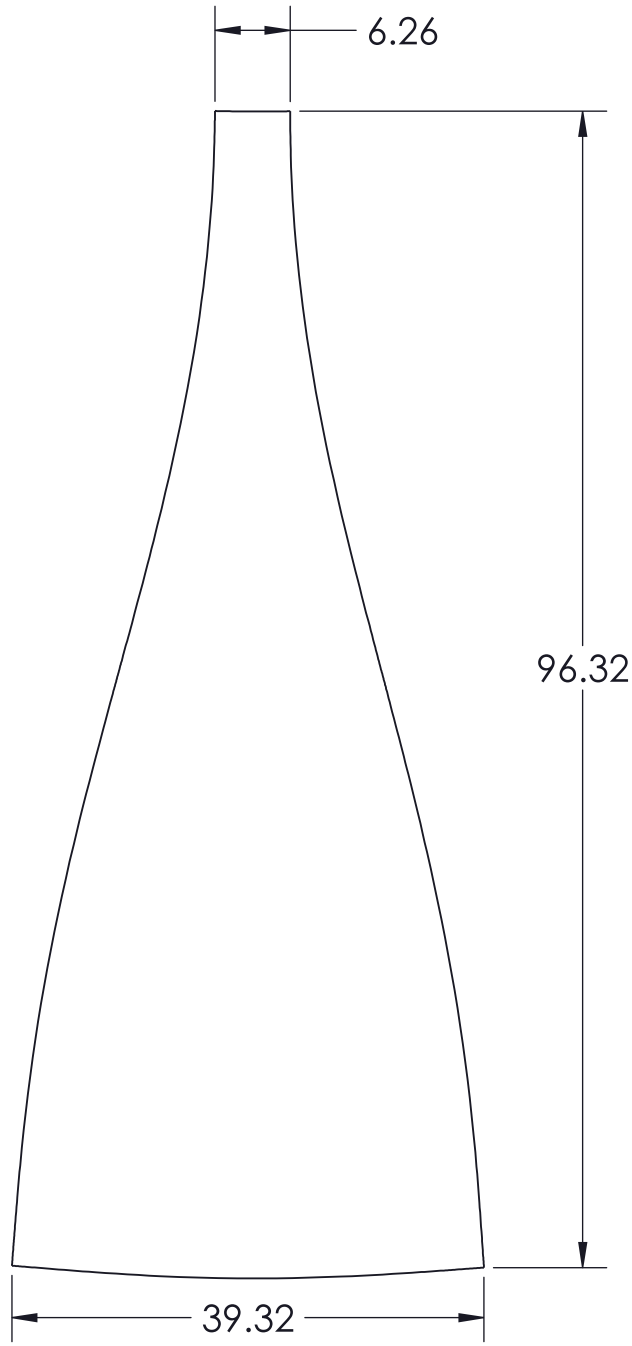


UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PR-06008-Tailcone
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:4	WEIGHT: SHEET 1 OF 1

Recovery

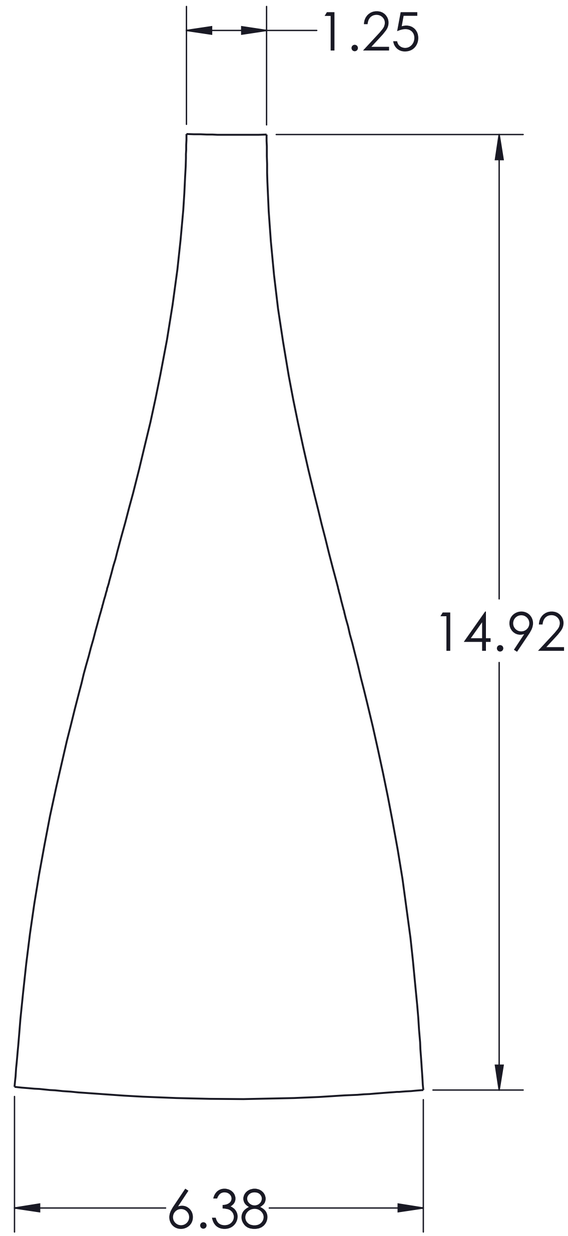
Recovery Wiring Diagram





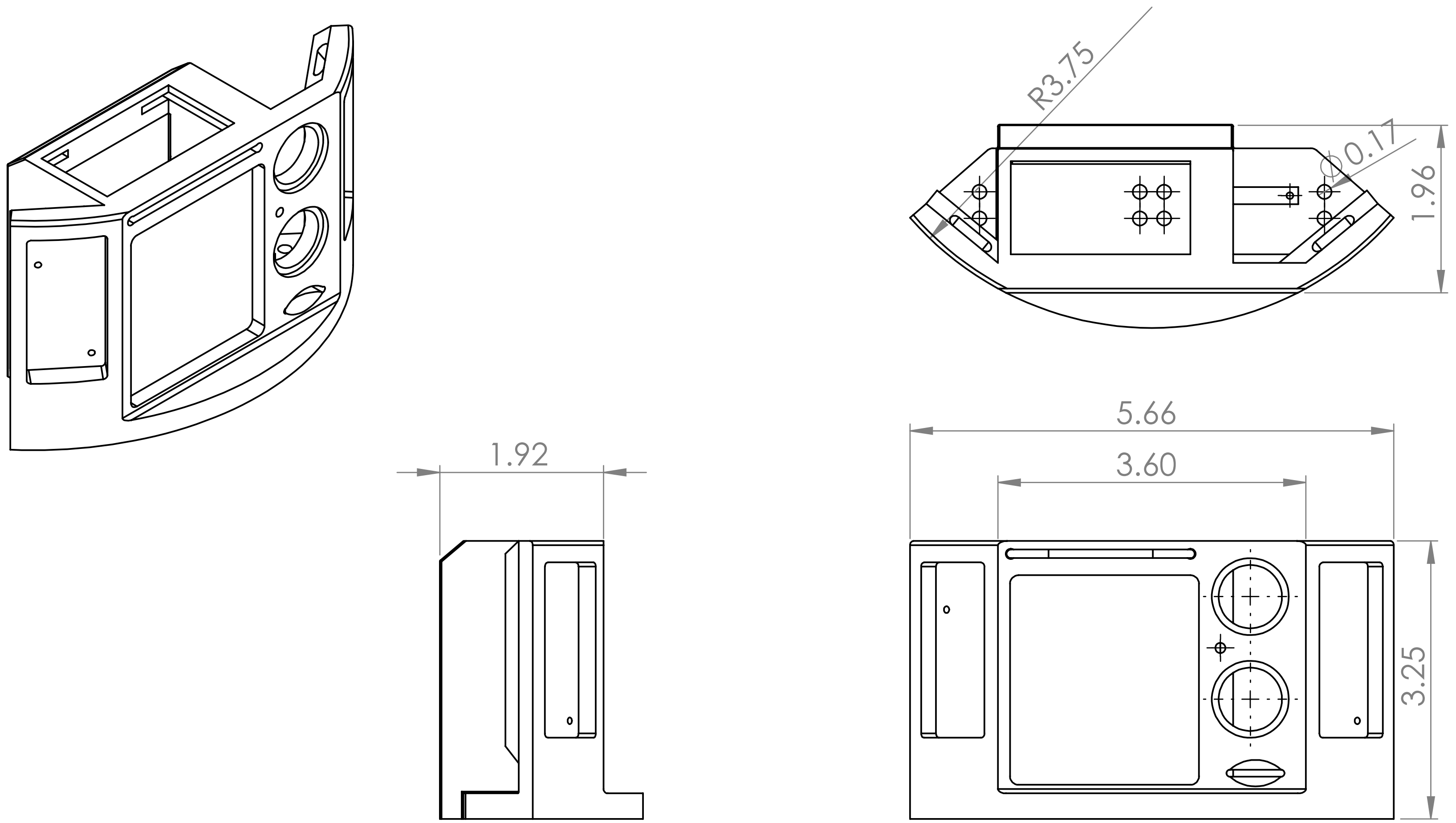
Curvature derived from half of a toroid with a central hole 20% the diameter of the outer diameter.

UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE: A DWG. NO. Main Parachute Pattern
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL	
DO NOT SCALE DRAWING	SCALE: 1:16 · WEIGHT: · SHEET 1 OF 1

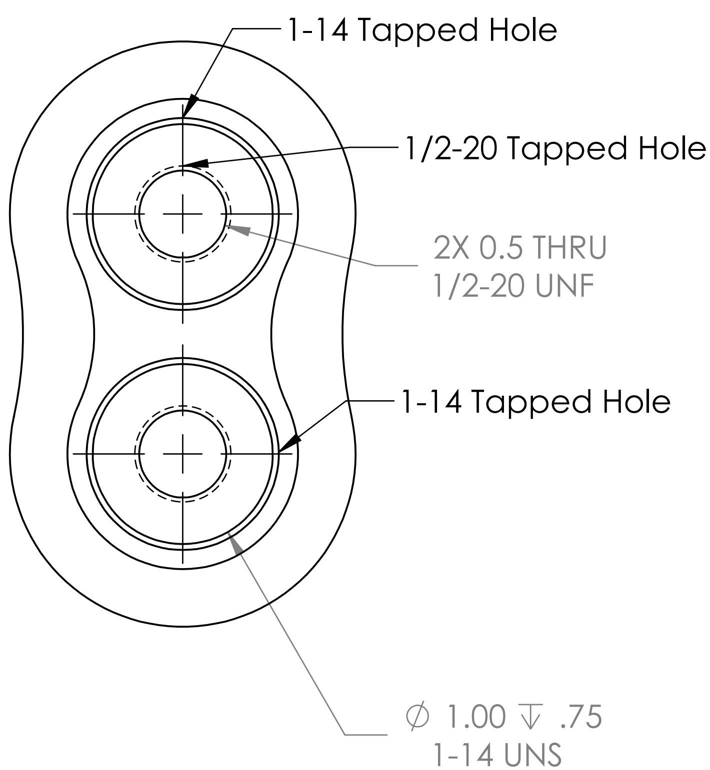


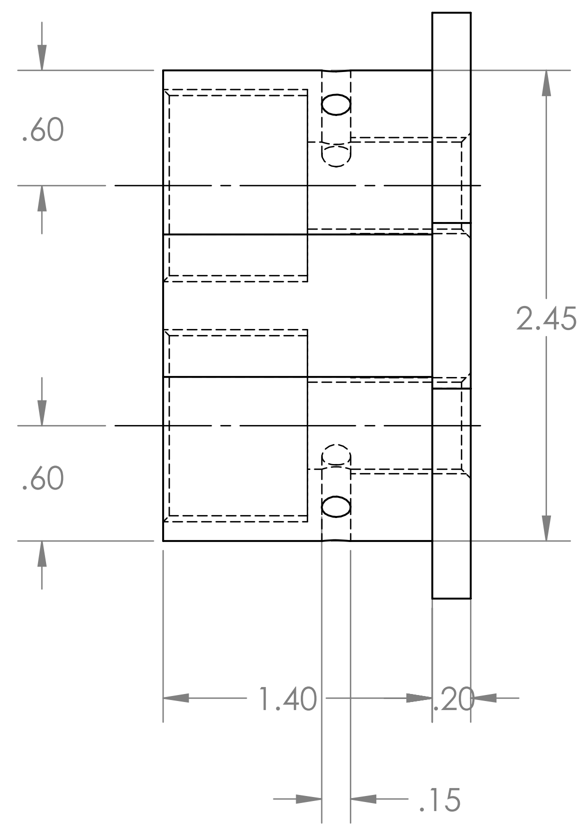
Curvature derived from half of a toroid with a central hole 20% the diameter of the outer diameter.

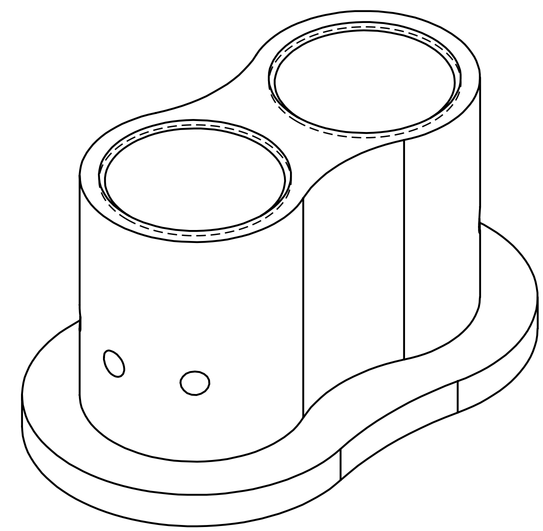
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. Drogue Parachute Pattern	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:3	WEIGHT:	SHEET 1 OF 1



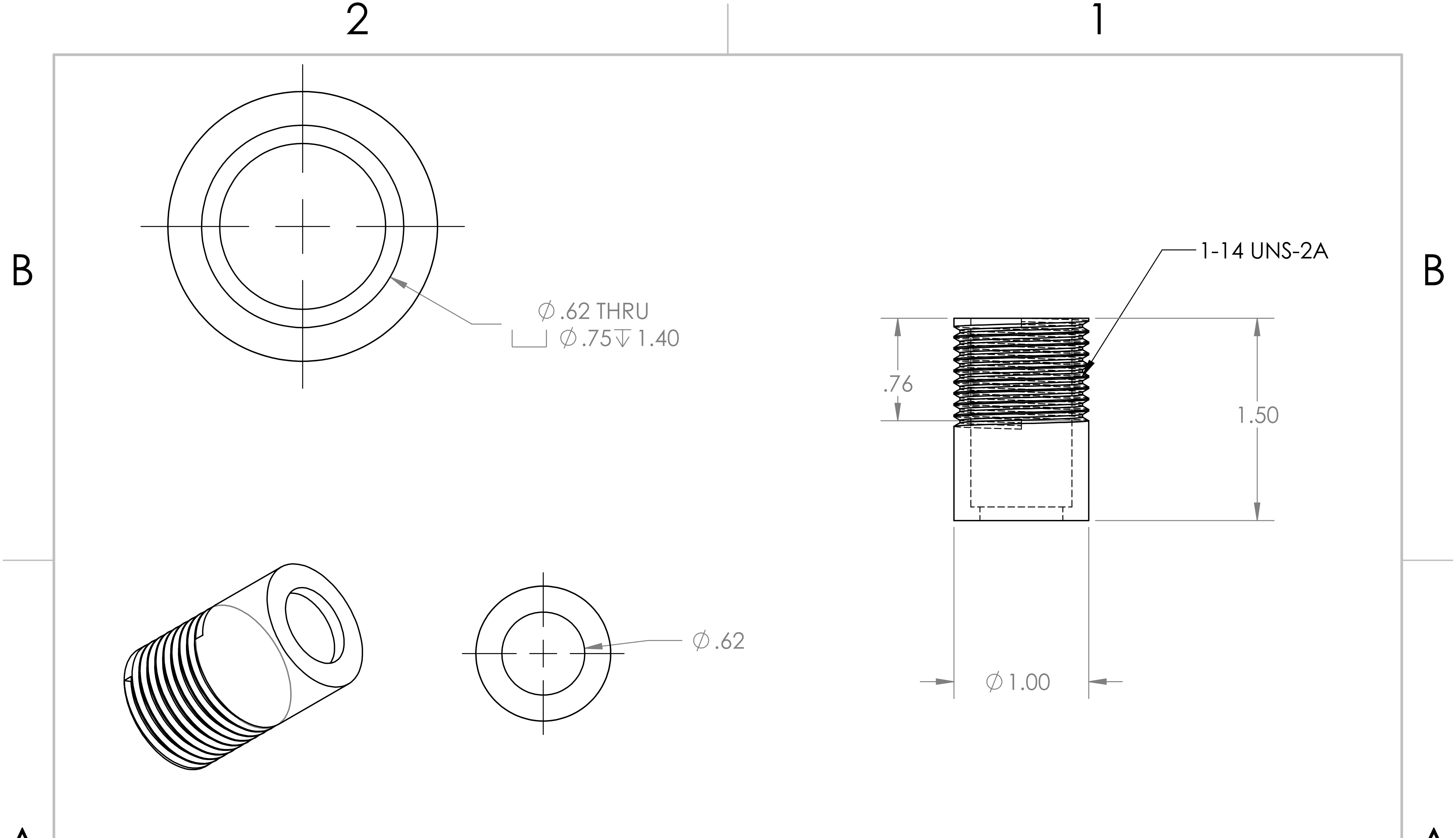
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-RC-01016-Electronics Housing Prototype	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT:	SHEET 1 OF 1





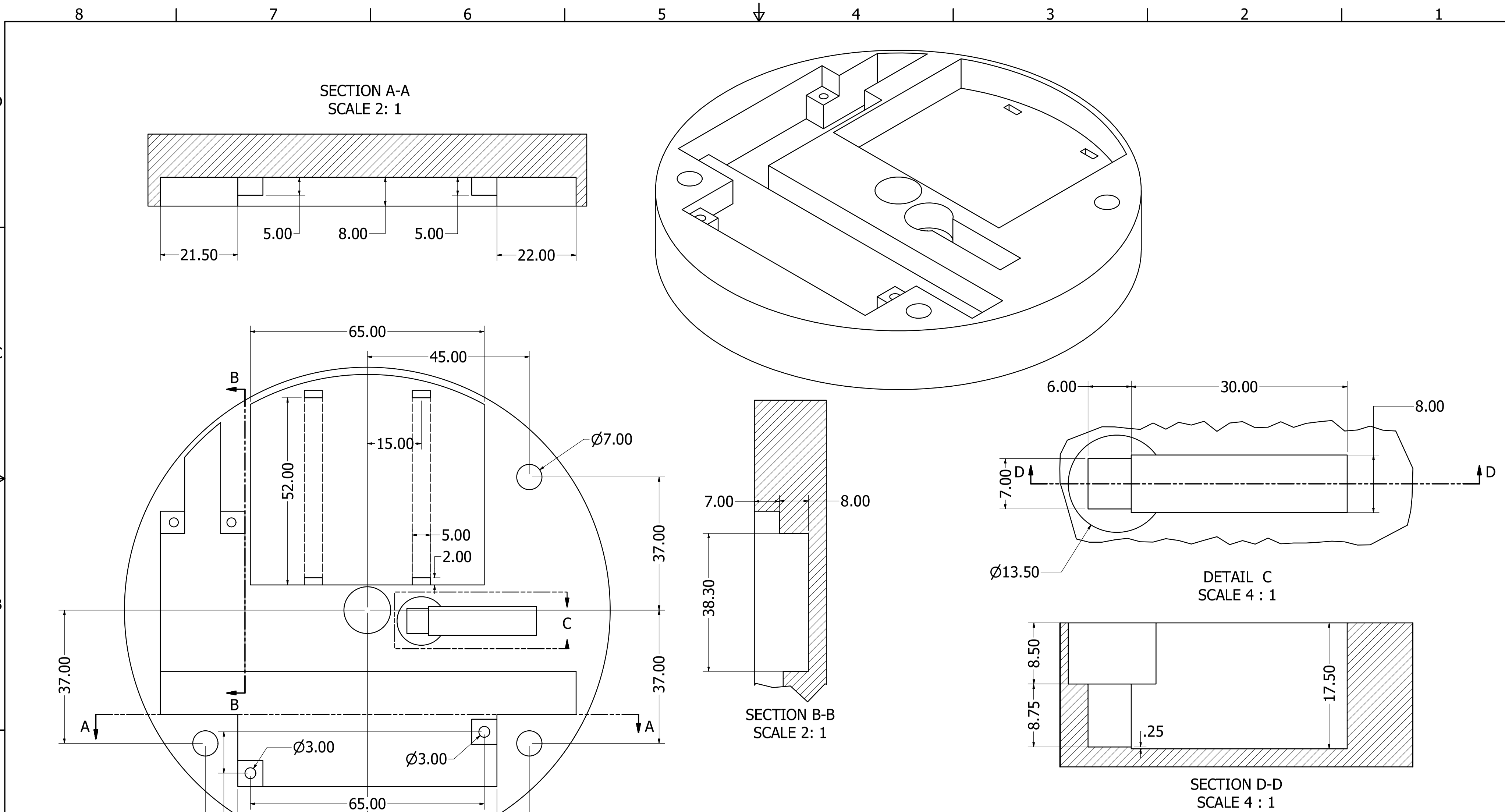


UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-RC-04002-Cylinder Base
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-RC-04003-Top Cap
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: SHEET 1 OF 1

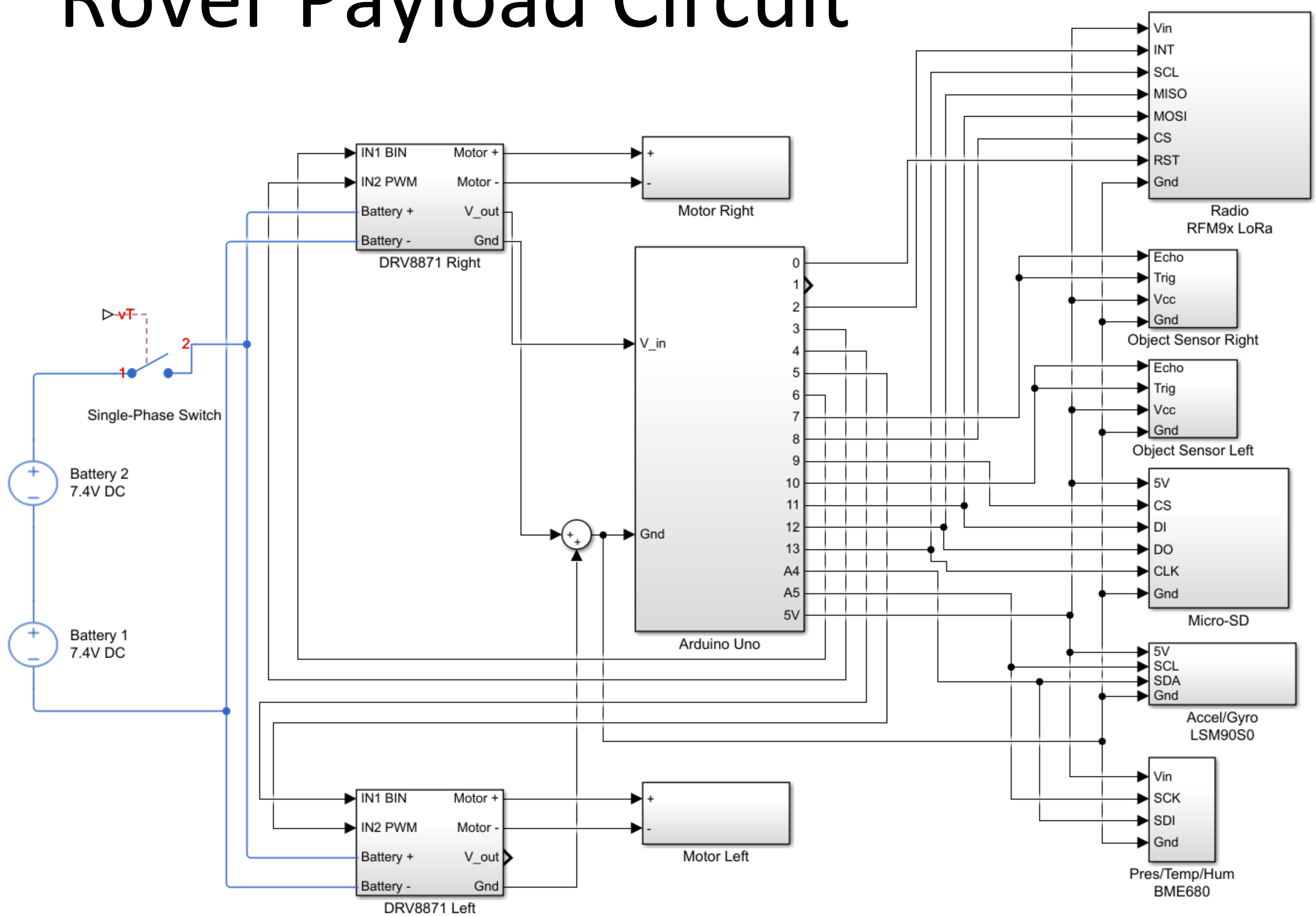
Avionics

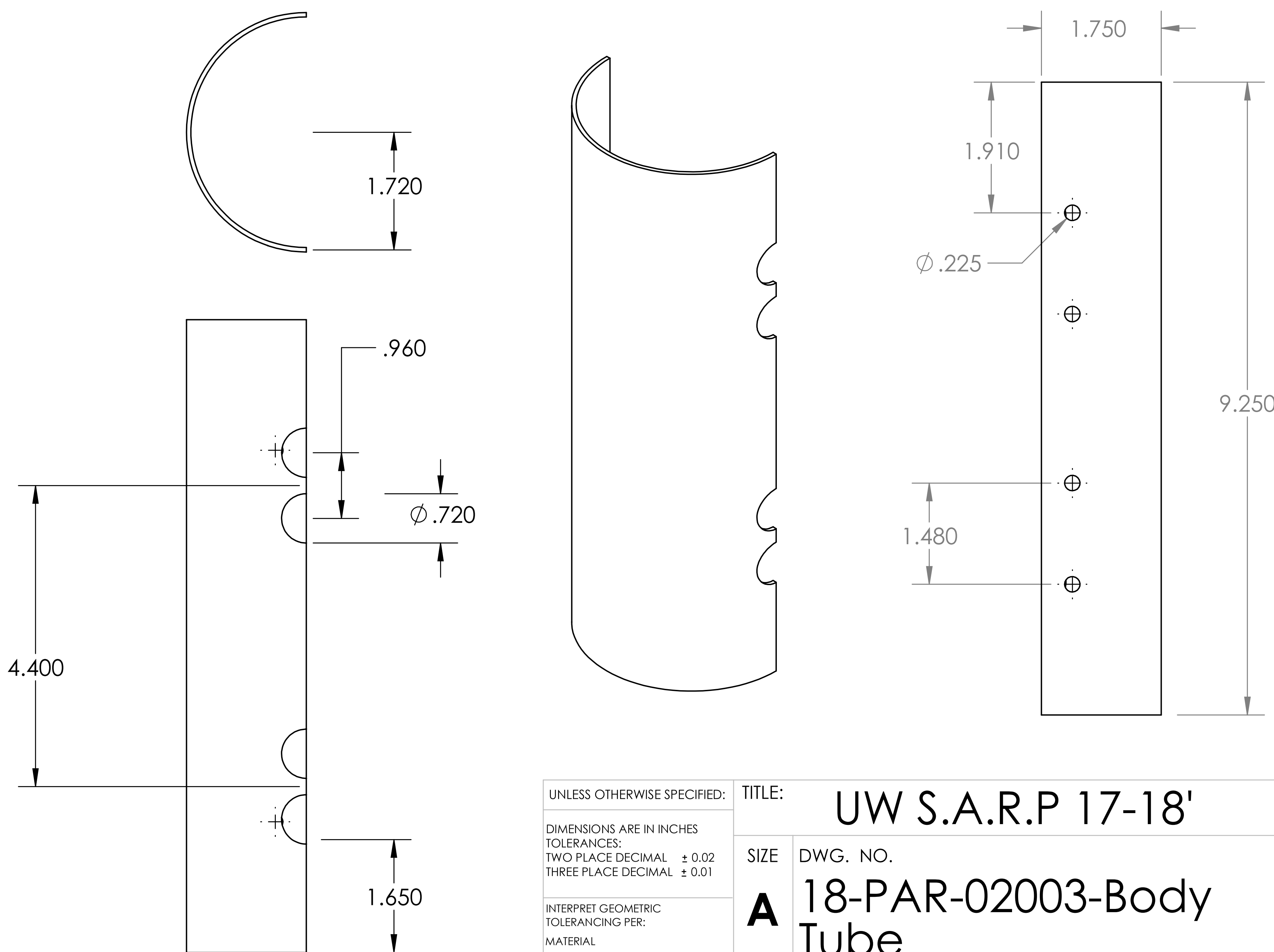


DRAWN Matthew Suhy	5/21/2018	
CHECKED		TITLE
QA		Nosecone Avionics Suite
MFG		
APPROVED		
SIZE D	DWG NO	REV
SCALE 2: 1	SHEET 1 OF 1	

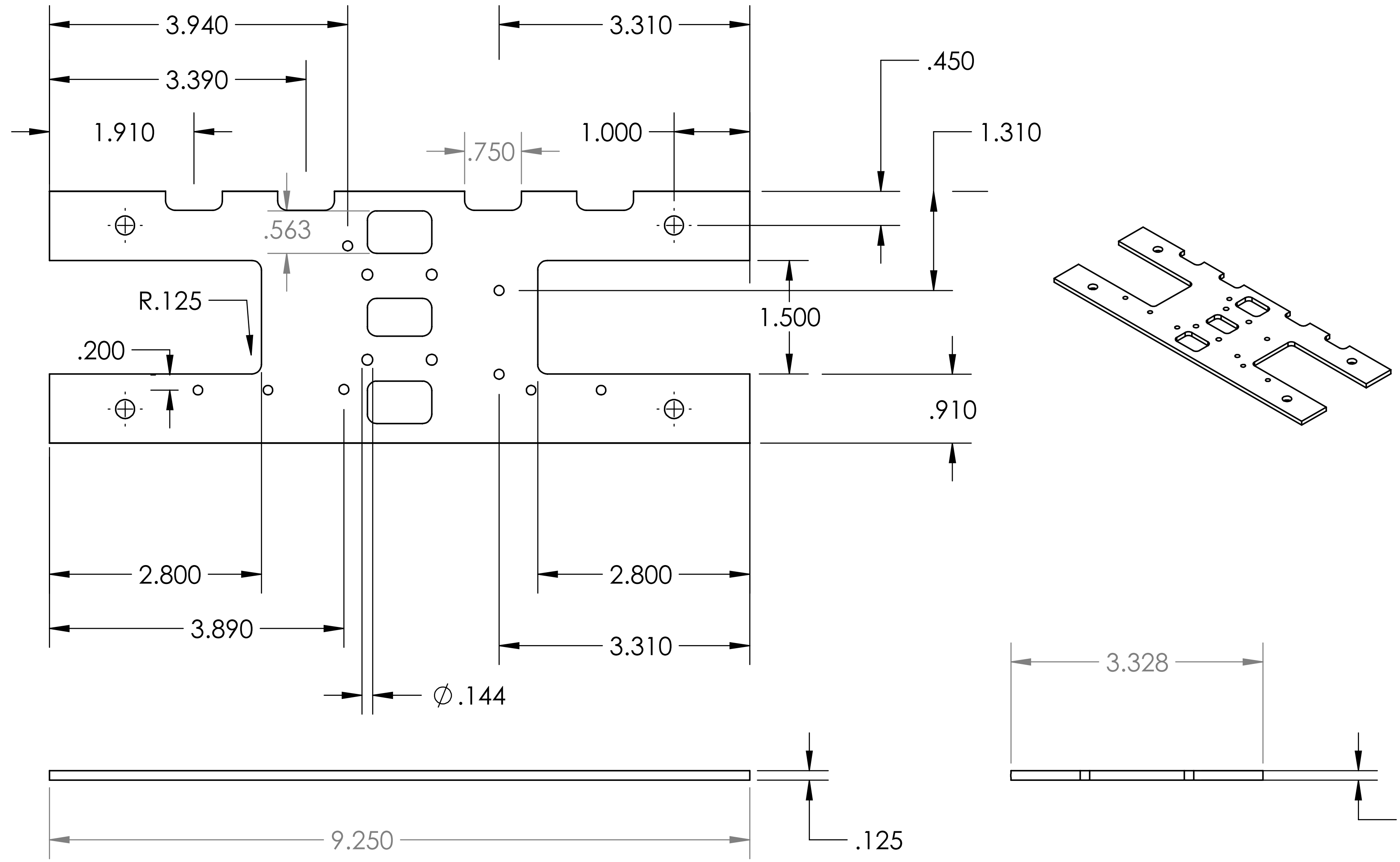
Payload

Rover Payload Circuit

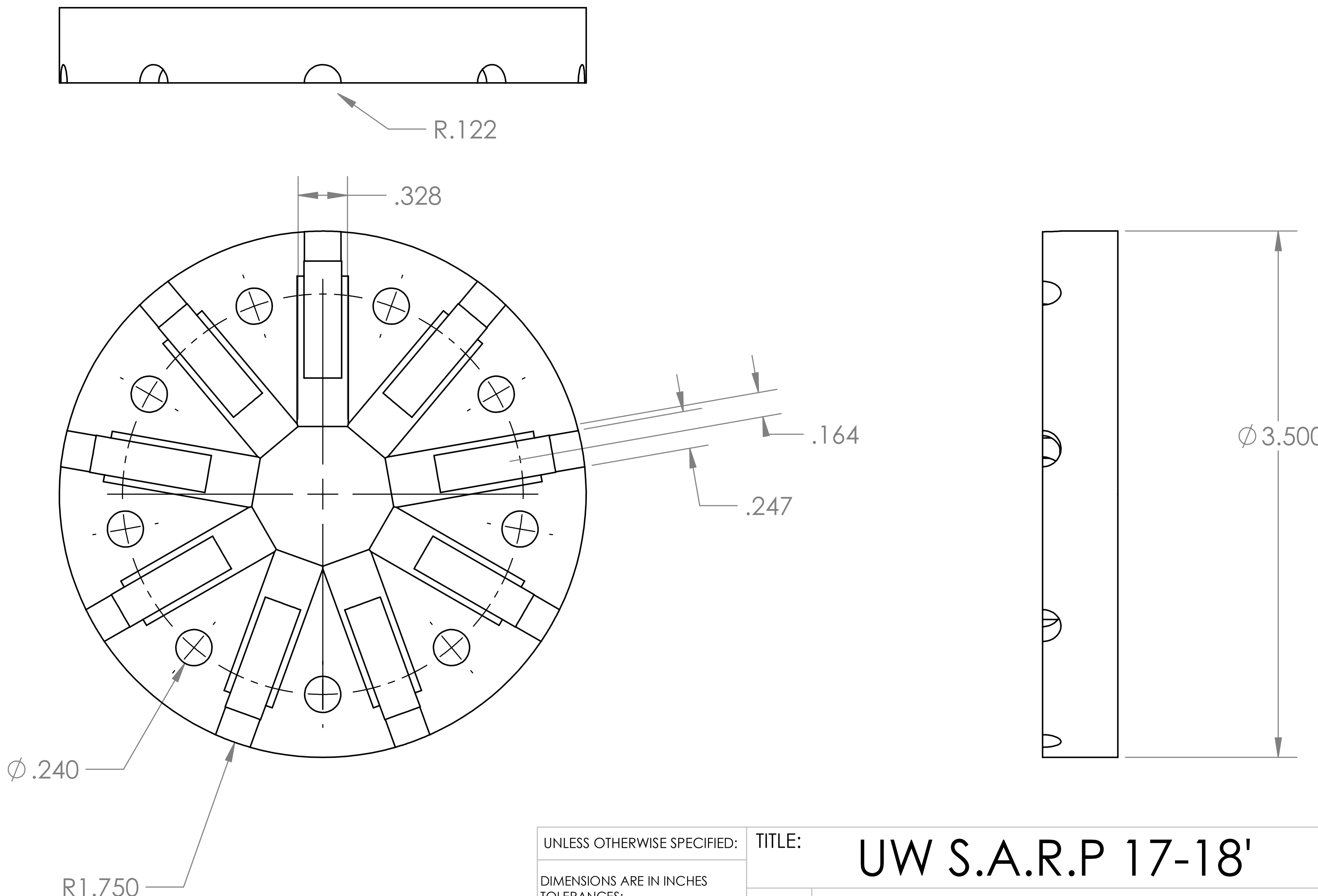




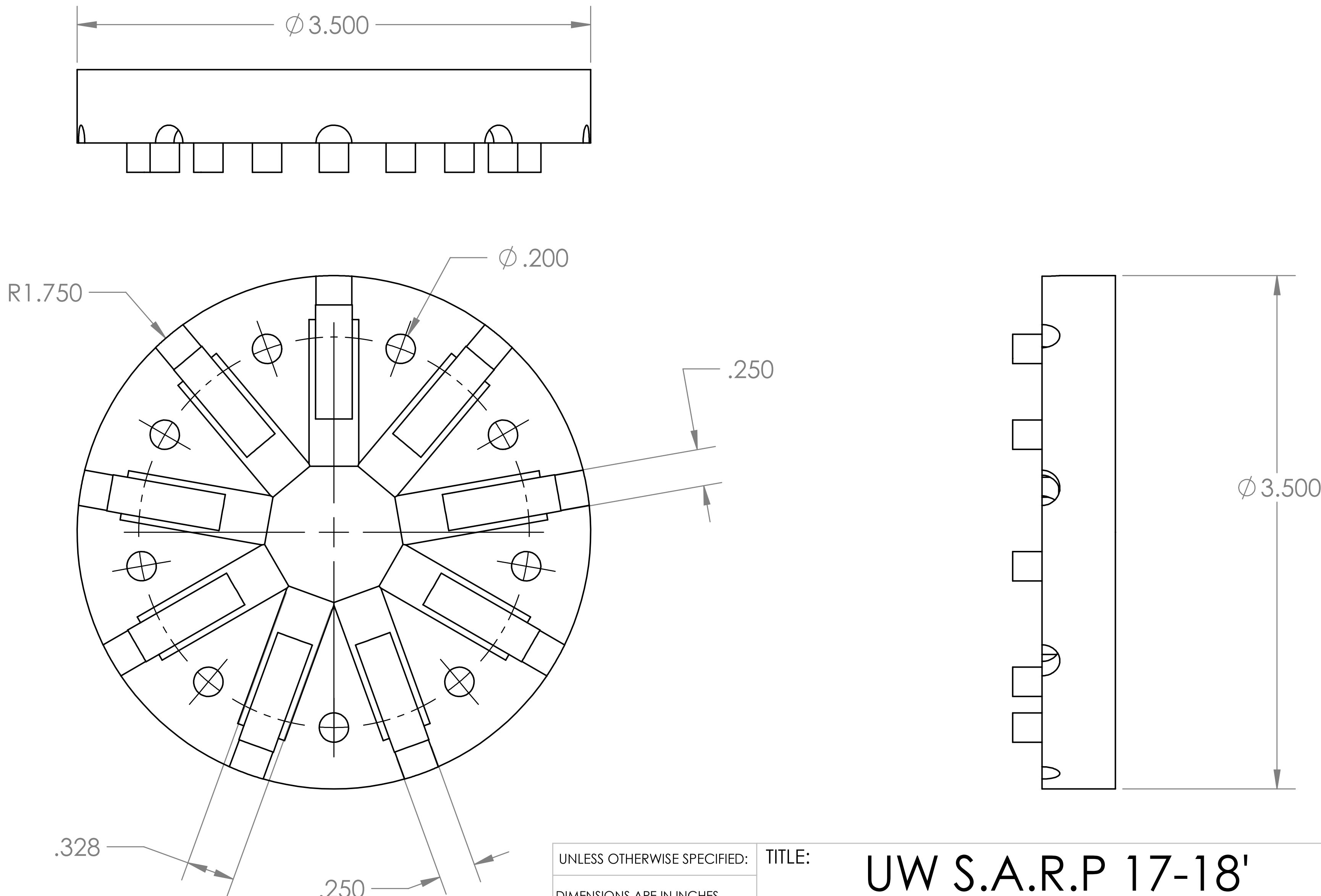
UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR-02003-Body Tube
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: SHEET 1 OF 1



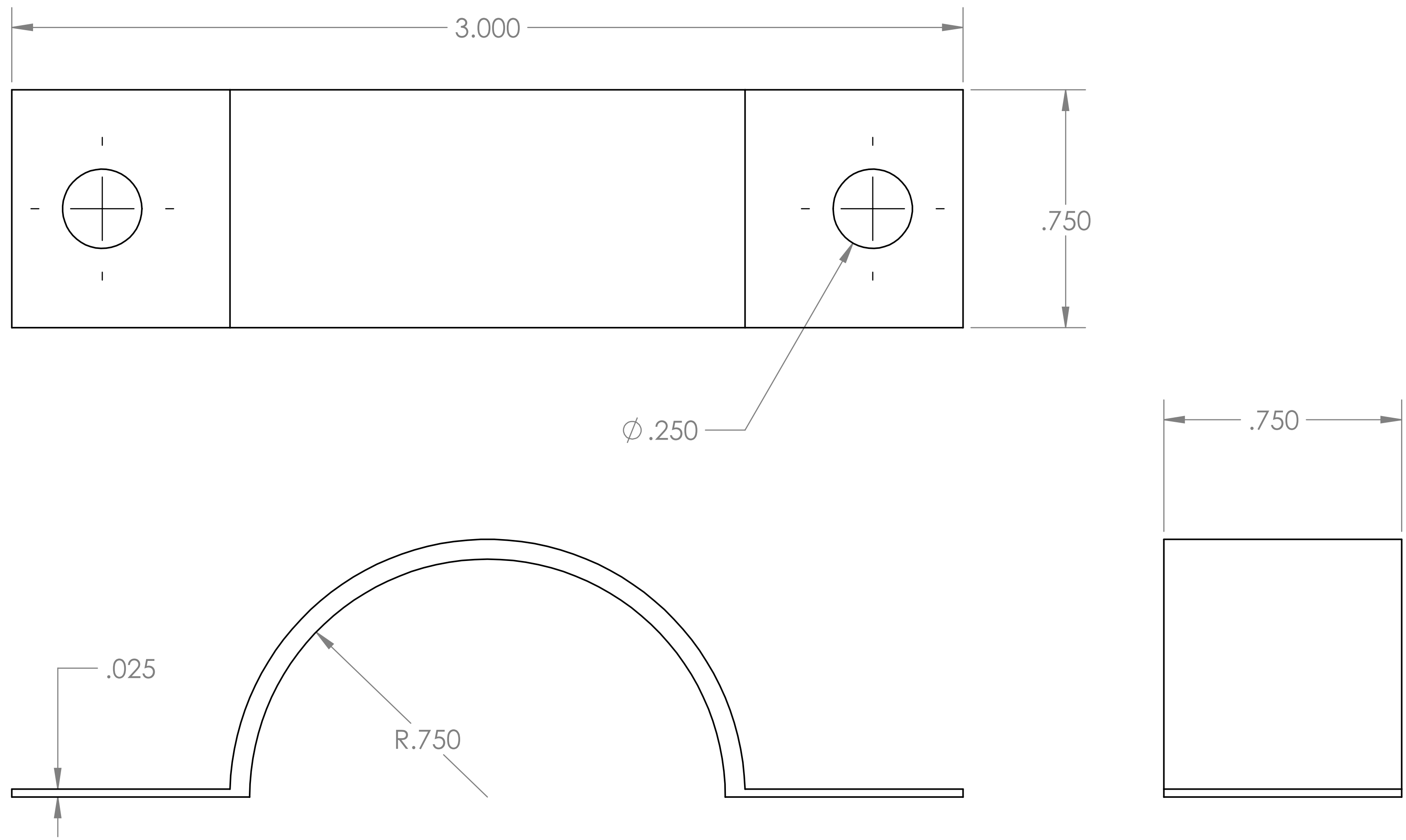
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-02004- Connector Plate
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: SHEET 1 OF 1



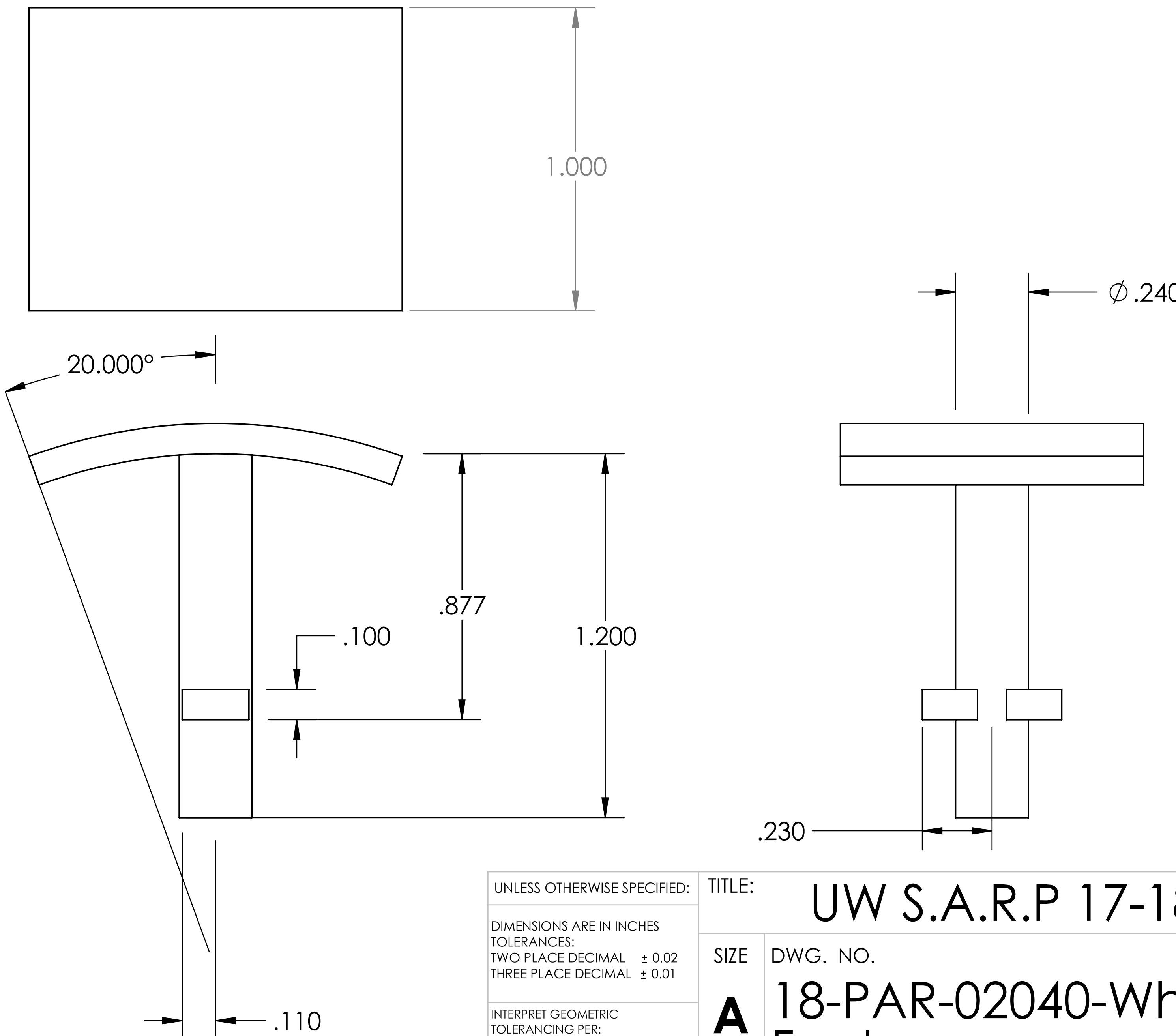
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-02027-Wheel Hub Female
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: SHEET 1 OF 1



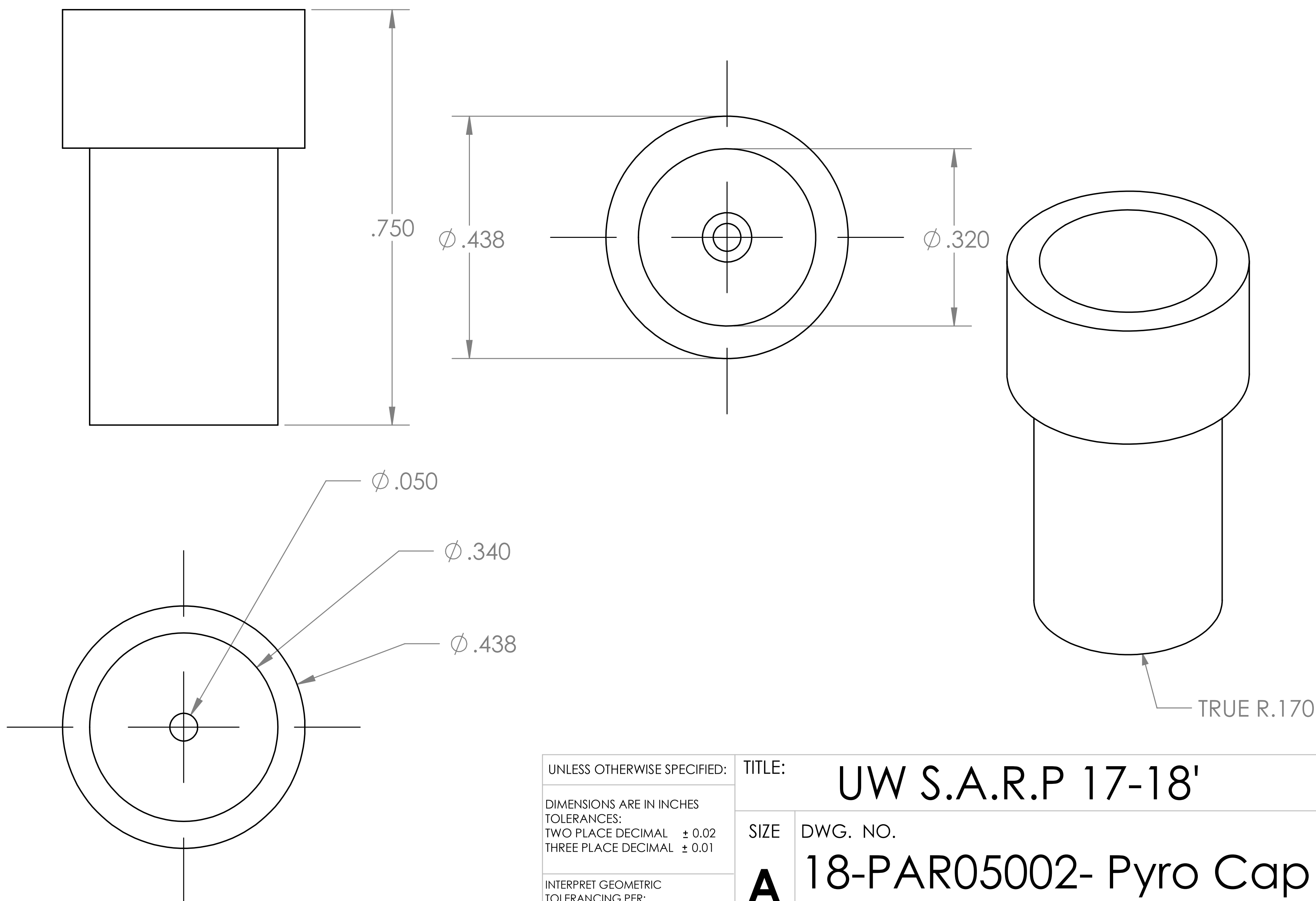
UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-02027-Wheel Hub Male
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:1	WEIGHT: SHEET 1 OF 1



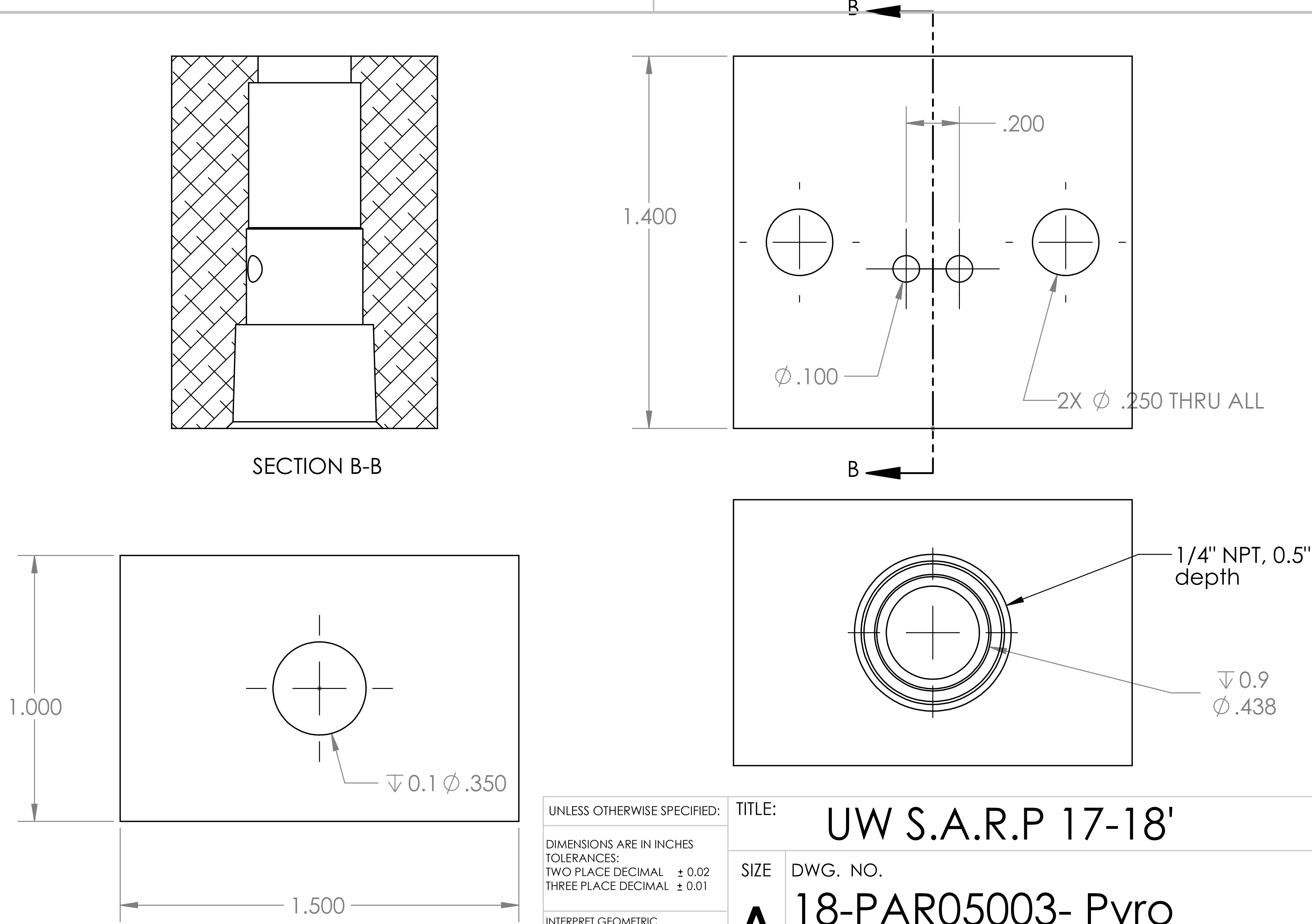
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR-02031-Motor Mount	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 2:1	WEIGHT:	SHEET 1 OF 1



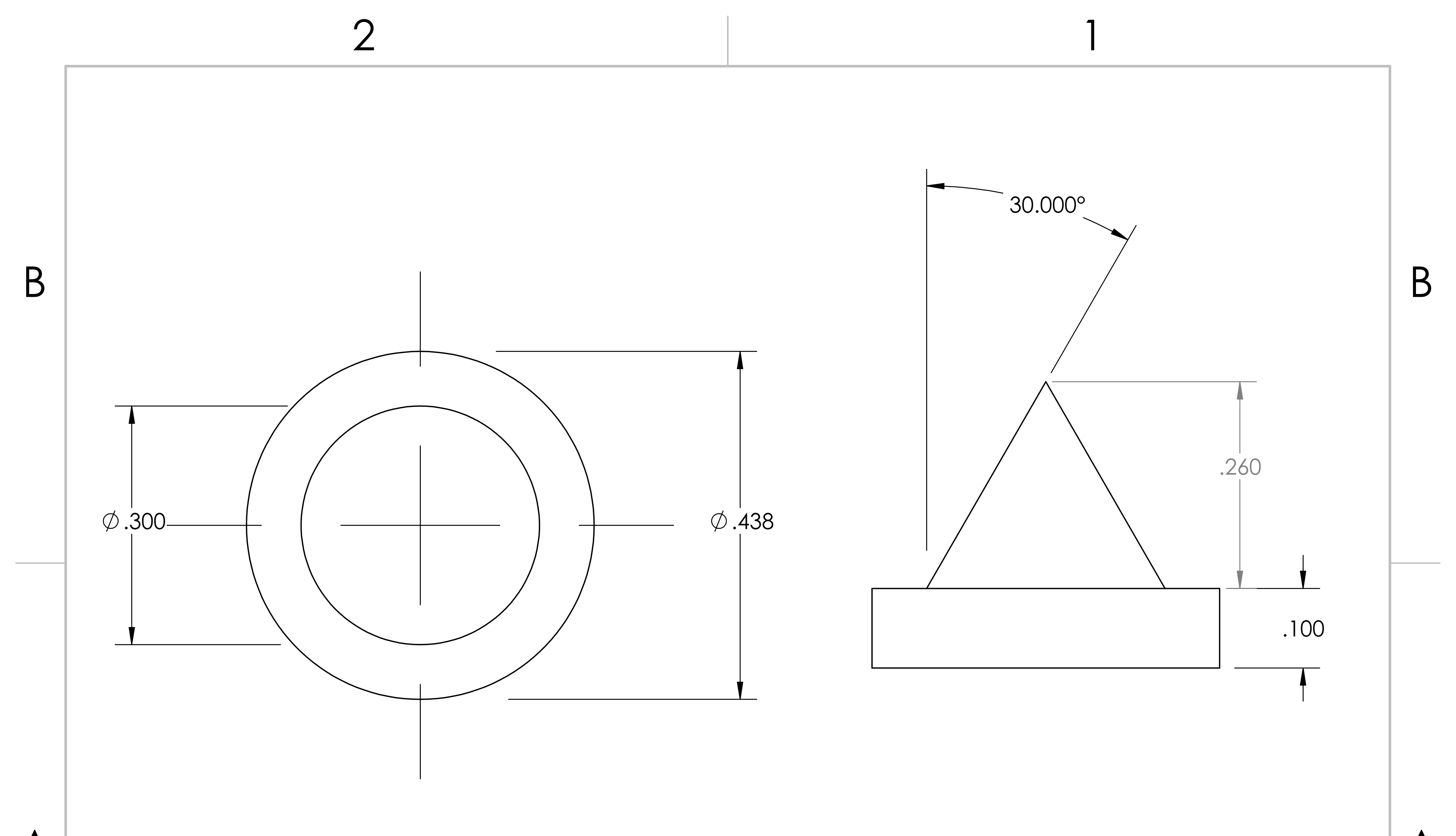
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR-02040-Wheel Foot	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 2:1	WEIGHT:	SHEET 1 OF 1



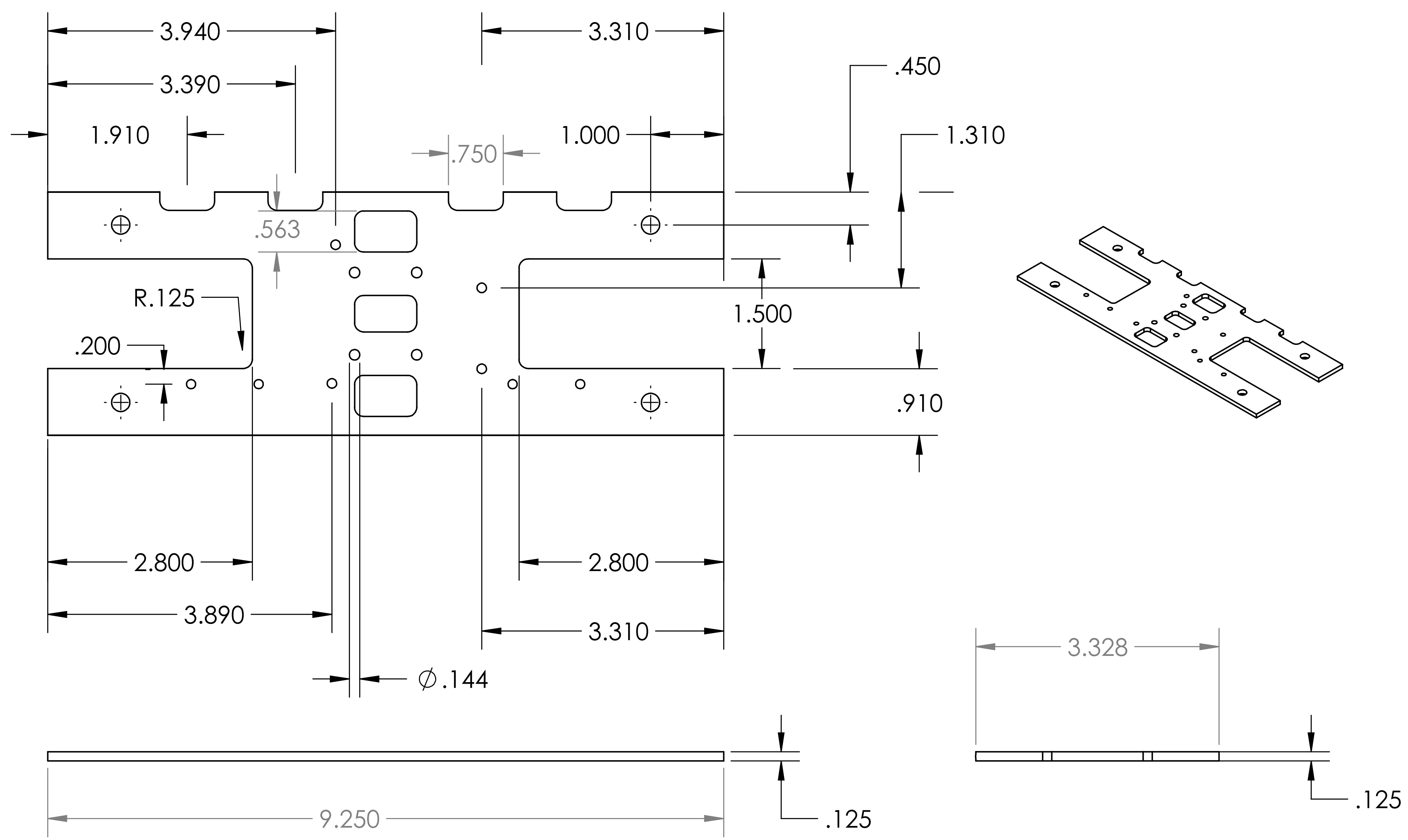
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR05002- Pyro Cap
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 4:1	WEIGHT: SHEET 1 OF 1



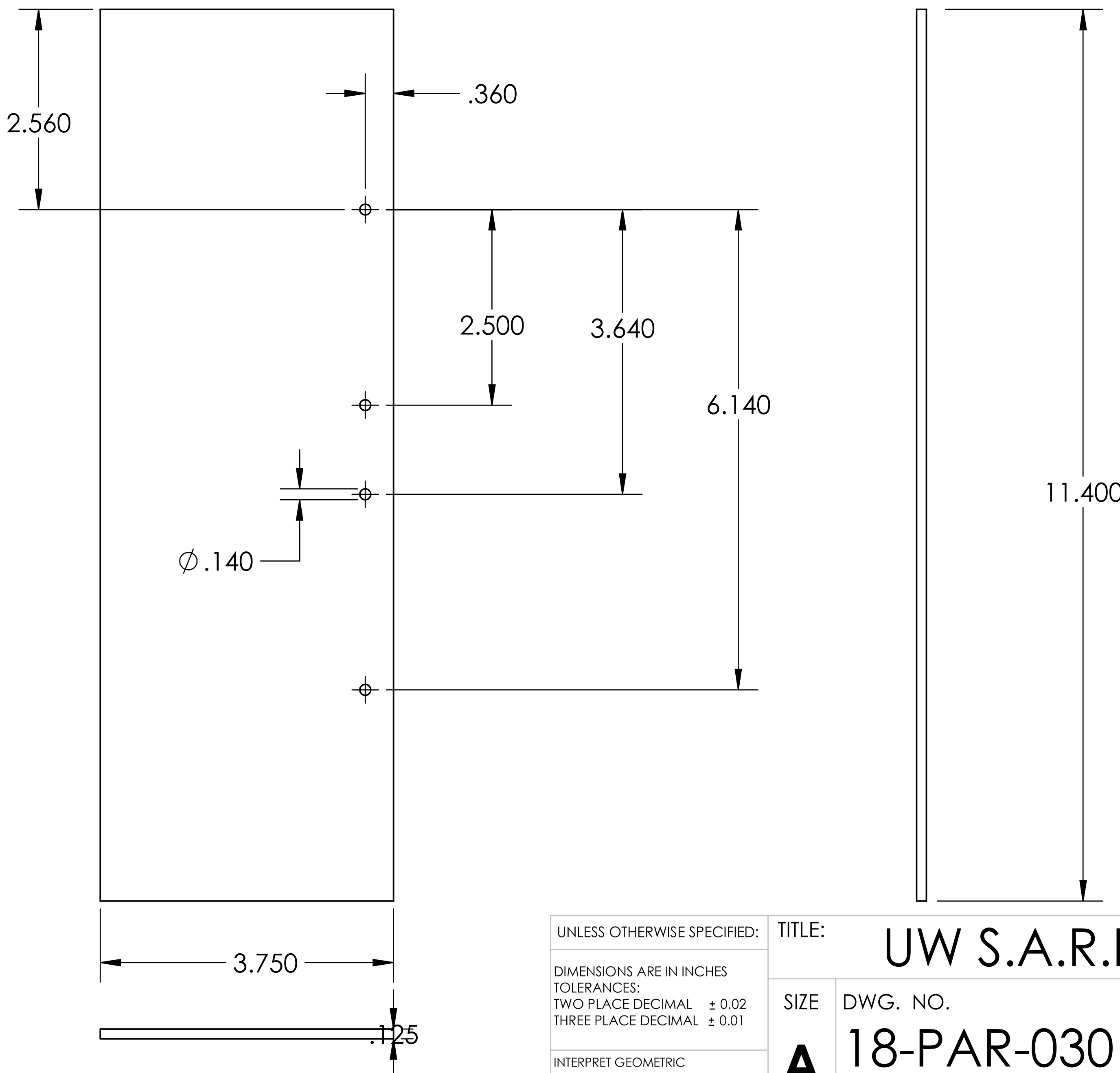
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR05003- Pyro Housing	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 2:1	WEIGHT:	SHEET 1 OF 1



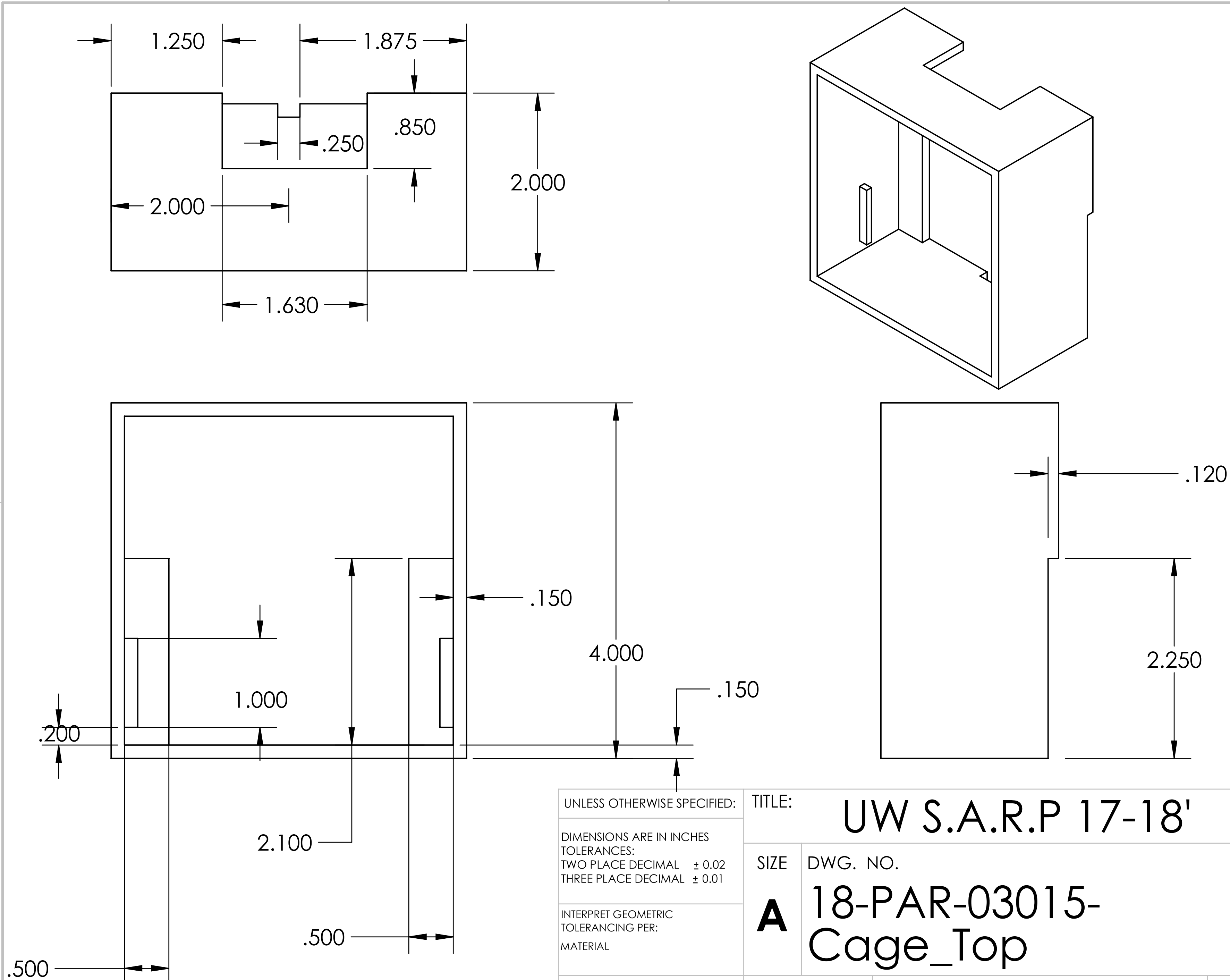
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR05004- Plunger	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 6:1	WEIGHT:	SHEET 1 OF 1



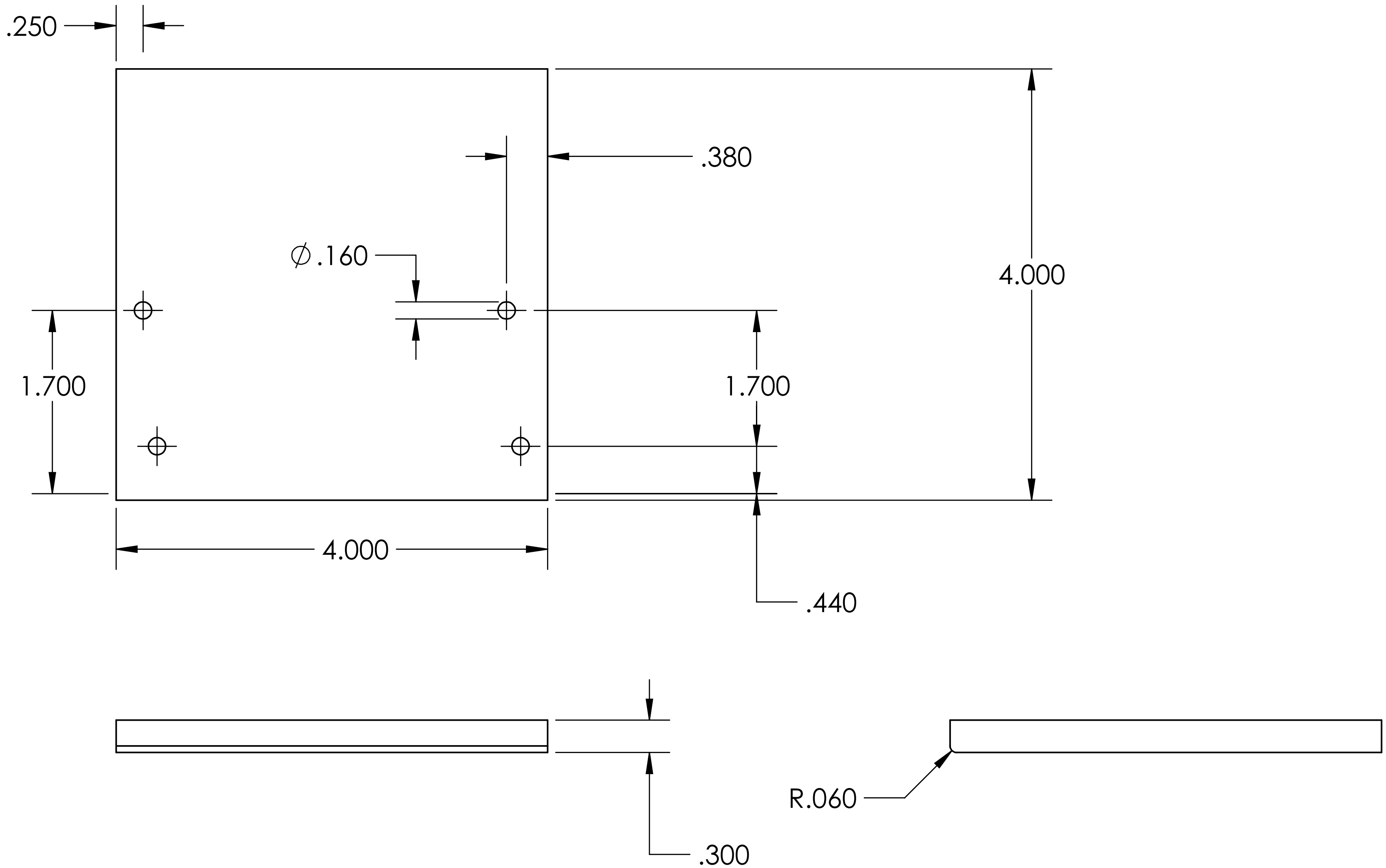
UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-02004- Connector Plate	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT:	SHEET 1 OF 1



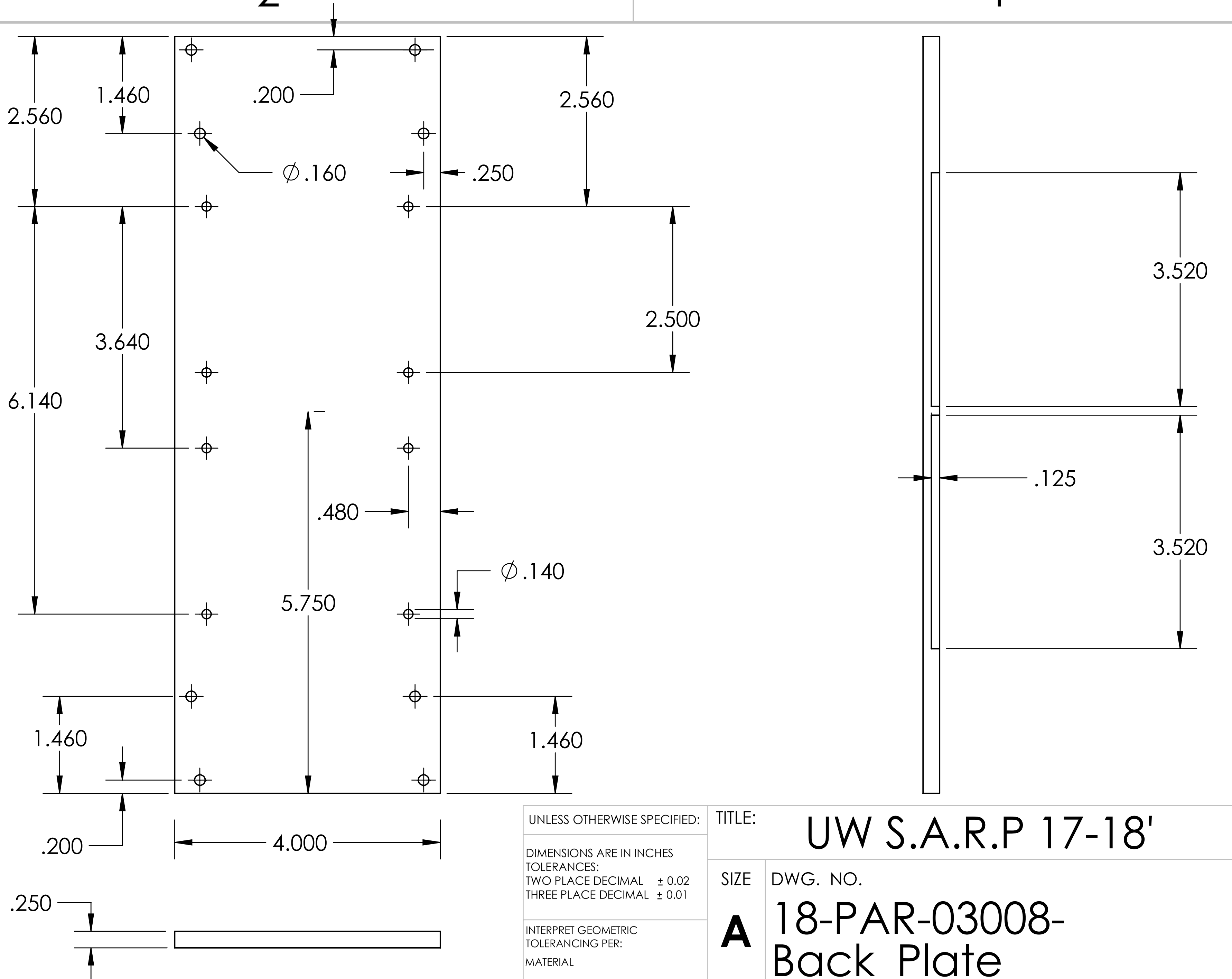
UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-03013-Wooden_Walls
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE:	UW S.A.R.P 17-18'
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-03015-Cage_Top
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 2:3	WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE **A**	DWG. NO. 18-PAR-03009-Base_Plate	
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL			
DO NOT SCALE DRAWING	SCALE: 2:3	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:	TITLE: UW S.A.R.P 17-18'	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.02 THREE PLACE DECIMAL ± 0.01	SIZE A	DWG. NO. 18-PAR-03008-Back_Plate
INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL		
DO NOT SCALE DRAWING	SCALE: 1:2	WEIGHT: SHEET 1 OF 1