Michigan Aeronautical Science Association Liquid Bi-Propellant Rocket

Team 37 Project Technical Report for the 2018 IREC

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The design of an experimental sounding rocket with the purpose of transporting an 8.8-lbm payload to an altitude of 10 000 ft using an SRAD liquid engine is presented. This rocket, named "Laika", has an SRAD wound carbon fiber airframe, and is propelled by an SRAD liquid bi-propellant engine, "Spitfire", with an impulse of 10 800 Ns of impulse and a peak thrust of 850 lbf. The rocket stands 11 ft tall and has a total takeoff mass of 87.5 lbm. It uses a dual bay parachute configuration, which is controlled by dual redundant commercial flight computers. The rocket's primary payload is designed to investigate combustion in high and low acceleration environments. This payload is composed of an accelerometer, ignitor, and cotton balls, and will ignite at set accelerations and will be recorded on camera. The rocket will also carry an experimental SRAD flight computer, which will log flight data.

Nomenclature

AGL	=	Above Ground Level
ATLO	=	Assembly, Test, and Launch Operations
I_{sp}	=	Specific Impulse
*L**	=	Characteristic chamber length
OF	=	Oxidizer to Fuel mass ratio
SF	=	Safety Factor

1) Introduction

Laika is an experimental rocket designed and built by the Michigan Aeronautical Science Association (MASA), a high powered student rocketry club based out of the University of Michigan in Ann Arbor. MASA has competed in IREC for the last five years. The team is composed of approximately 45 undergraduate students and is split into four main sub teams: propulsion, production, airframe, and avionics. Propulsion is responsible for developing and testing of our SRAD liquid engine. Production is responsible for reviewing engineering drawings and machining components. Airframe is responsible for designing, building, and testing the rocket's airframe and parachutes. Avionics is responsible for the data collection instrumentation used during static fire testing and for developing flight electronics.

The team's leadership is split into two main divisions: administrative and technical. Administrative leadership is comprised of a president, vice president, business lead, treasurer, and safety officer. The technical leadership includes chief engineer, propulsion lead, airframe lead, avionics lead, ATLO lead, production lead and payload lead.

During the school year, technical leads conduct meetings and design sessions, and keep their respective sub teams on track with short- and long-term goals. For example, the propulsion lead may break his/her team down into a group working on regenerative cooling research and a group on combustion chamber design. Every month, the team is brought together in a general meeting where progress is shared between each sub team and group.

Each year, MASA's goal is to design, build, and fly a newly developed rocket. This year, the team has built two rockets; one for the 10 000 ft SRAD category, and one as an exhibition two-stage flight to 240 000 ft. Presented herein is the design, build, and test methodology used for our 10 000 ft SRAD rocket, *Laika.*

2) System Architecture Overview

A. Top Level System Summary

Laika, as shown in figure 1, stands 11ft tall and has an outer diameter of 6.4 in. *Laika's* airframe weighs approximately 17.4 lbs. The body tubes, nosecone, and couplers are made of wound carbon figure, with internal retention components made of fiberglass/wood composite plates, and nosecone pieces machined from 6061 aluminum. Carbon fiber components were wound using an X-Winder filament winding machine. Structural components of the engine, which include tanks, tank endcaps, injector and injector manifold, aluminum ribs and the nozzle retention ring, were machined by students on manual and CNC lathes and mills, which were made available through University of Michigan's Wilson Student Project Team Center.

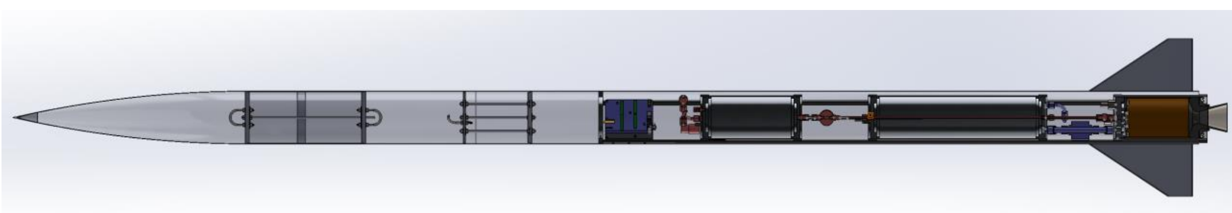

Figure 1. Laika, SRAD 10 000 ft Liquid Bipropellant Rocket *This shows a cut away of the vehicle with bays for the experimental payload, avionics, and details of the engine assembly.*

Laika employs a student-designed and built liquid bi-propellant engine, called Spitfire. It uses nitrous oxide as the oxidizer and 95% ethanol as the fuel. The engine produces 10 800 N-s of total impulse, with 3 780 N of nominal thrust, and burns for five seconds. The engine has propellant tanks for both fuel and oxidizer, a combustion chamber, motorized ball valves, a differential pressure transducer for nitrous oxide liquid level sensing, two linear-actuated quick-disconnect fittings, as well as numerous vent solenoids and pressure transducers. The engine's I_{sp} is calculated to be 215 seconds.

Table 1. Performance Summary.

I_{sp}	215 s
Max. Thrust	3 780 N
Total Impulse	10 800 kN-s
C*	1 450 m/s

B. Propulsion

1. *Performance*

The vehicle is propelled by a nitrous oxide and ethanol liquid bi-propellant engine which produces a maximum thrust of 850 lbf. Engine performance was characterized by a series of three static hot fire tests. An extensive characterization is provided in Appendix A and a summary of performance metrics is given in Table 1. Figure 2 shows thrust data collected during a five-second burn at a student built test site at the University of Michigan.

2. *Propellant Systems*

The fuel tank, oxidizer tank, and propellant plumbing sections sit above the combustion chamber in a rigid assembly bolted together with aluminum ribs. Between the chamber, oxidizer tank, and fuel tank, there are two 8-inch tall plumbing bays which house the propellant feed lines, motorized main propellant valves, pressure transducers, and vent valves. The fuel tank sits above the oxidizer tank, with a continuous, unbroken fuel tube running into and through the oxidizer tank. The tank tubes are made of Al 6061-T6, and the four tank end caps are made of Al 7075. These components are student machined and are designed to operate at 800 psi, with a 2.0 design SF, and have been hydrostatic tested to a 1.5 SF.

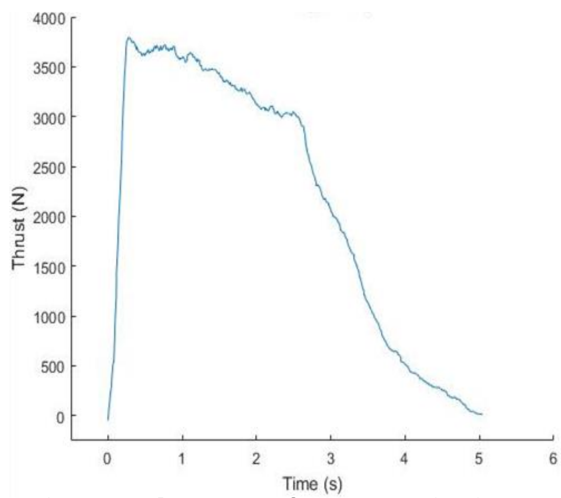

Figure 2: Thrust Data from 3 s Static Fire

Nitrous oxide was selected as an oxidizer due to its relative safety and high vapor pressure at typical ambient temperatures, permitting self-pressurization. The engine was designed to use 5.8 L of nitrous oxide in a 6.4 L tank, for a mass of 4.4 kg. The oxidizer temperature was chosen as a balance between oxidizer density at colder temperatures and higher vapor pressure at higher temperatures. At the goal temperature of 70˚ F, the nitrous oxide generates 750 psi of vapor pressure.

Ethyl alcohol (ethanol) was chosen as the fuel due to high I_{sp}, accessibility, and its documented performance in other liquid propulsion systems. The fuel tank contains 1.43 L of 95% denatured ethanol and 2.16 L of nitrogen gas at a nominal pressure of 750 psi. The N_2 serves to force the fuel through the main fuel line to the injector.

3. *Combustion Chamber*

The combustion chamber is made from Al 6061-T6 and has a phenolic impregnated cardboard liner to serve as an ablative. The nominal operating pressure of the combustion chamber is 400 psi and the aluminum wall was designed for a SF of 4 under room temperature conditions. This high SF was used due to the temperature dependence of yield strength and has been experimentally proven to be reliable. An L* of 85 was chosen to avoid combustion related efficiency losses.

The nozzle consists of a superfine graphite converging section and throat with a 304-stainless steel diverging section. Graphite was selected due to its superior thermal properties and relative ease of manufacturing when compared to similar materials. The steel diverging section is used to hold the graphite in place and was designed using experimental thermal results from the previous year's hybrid engine nozzle. A 3D cross section of the nozzle assembly is provided in Figure 3.

Figure 3: 3D Cross Section of Nozzle Assembly

4. *Injector*

The injector is composed of two element styles with 16 unlike-impinging elements and 8 like-impinging oxidizer elements. This combination of element styles was used to achieve the desired OF ratio of 4. The hole geometry for the oxidizer elements is based off experimental data from the previous year's hybrid engine and the methods discussed in Ref. 1 to avoid feed-coupled instability and provide adequate mass distribution and mixing. Redundant

Viton O-rings separate the fuel and oxidizer sections of the injector manifold to avoid inter-propellant mixing. In the event that these seals fail, vent holes are in place to allow the leak to escape to ambient pressure. Figure 4 shows a cross section of the injector manifold assembly.

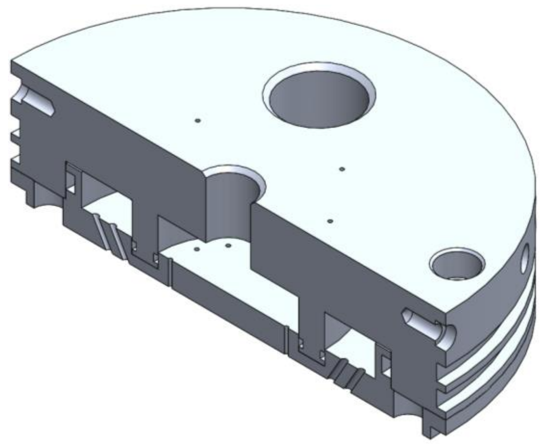

Figure 4. Injector Manifold Assembly. *This cutaway shows the fuel orifices (center) and oxidizer orifices (outer). Two o-rings separate the two flow paths of the manifold. Vent holes can be seen on the top face.*

5. Fill and Ignition System

The fill system was designed to permit remote fill and abort of the nitrous oxide tank. See the Project Test Reports Appendix for a full diagram of this system. One solenoid valve actuates the flow of nitrous oxide through the lines external to the rocket and one solenoid valve opens flow from a vent in the oxidizer tank. Ethanol is loaded into the rocket with a low-pressure fill tank that uses regulated nitrogen gas to force the ethanol up into the fuel tank. Each propellant enters from the bottom of the rocket through a quick-disconnect fitting, then through a tube routed around the combustion chamber up to the respective propellant tank. The quick-disconnect fittings are fixed to linear actuators, which are operated remotely to disconnect the rocket from the fill system before flight.

Ignition occurs by igniting a small APCP grain positioned in the middle of the combustion chamber, then the motorized propellant valves are opened, which starts combustion.

6. Preliminary Testing

Prior to full-scale testing of the engine and propellant systems, all structural components are tested to 1.5 times the nominal operating pressure. Additionally, the APCP ignitor is remotely tested with e-matches.

Static firing is conducted in three phases. The first test is a short-duration static fire of the combustion chamber assembly to mitigate failure modes such as a hard-start or ignition failure. Next, a full-duration test of the combustion chamber is conducted to gather performance data and to ensure adequate performance of the phenolic ablative. The first two tests are conducted using heavy-weight engine components and ground-configuration plumbing. Lastly, full-duration test fires are conducted using flight components, with the tanks and plumbing in a flight-ready configuration.

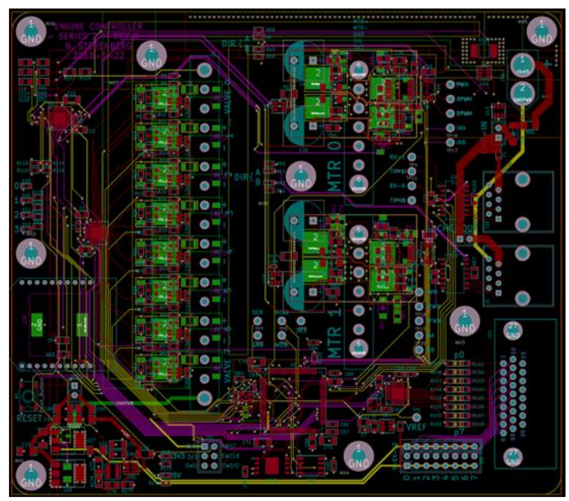

Figure 5. Engine Controller

C. Avionics

1. Engine Control System

The engine control system was designed to allow control of solenoids, valves, and other motors and to read data from various sensors on the engine and fill system from a single interface (computer). The engine controller (Fig. 5) is a circuit board designed entirely by the team and operates with software written by the team. The system features an engine controller onboard the rocket as well as an engine controller groundside to operate the rocket's fill system. Each board independently supports up to 8 12V valves/solenoids, 2 motorized valves, and 8 pressure sensors. The positions of the motorized valves are measured with potentiometers and are controlled by a PID loop. The interface, written in Python, remotely sends addressable packets to the engine controller boards via wireless modems.

2. Live Telemetry System

Besides using two COTS flight computers (EasyMini and StratoLogger) for altitude measurement and parachute deployment, the avionics bay in the rocket boasts a system for live telemetry data streaming. The system consists of two circuit boards designed by the team. The board within the rocket has the following sensors: a barometer, an accelerometer, 6 gyroscopes, and GPS. The board transmits telemetry data from these sensors to a receiving board on the ground, which in turn displays the data to a connected computer. The onboard flight computer simultaneously saves the flight data at a higher frequency to onboard flash. For redundancy, the avionics bay also holds a COTS BigRedBee BeeLine GPS, which transmits the rocket's coordinates.

D. Airframe

1. Performance

Performance simulations were run using Open Rocket, a free software by Sampo Niskanen. The simulations were run using Spaceport America launch conditions, including an ambient temperature of 80°F, an altitude of 4596 ft MSL, and wind speeds of 8 mph.[1] Simulation results are shown in figures 4 and 5. Key performance characteristics are as follows:

Altitude at Apogee: 8959 ft
Off-the rail velocity: 96.3 ft/s (Assuming 17 ft launch rail)
Maximum Mach number: 0.66
Thrust-to-weight ratio: 9.8
Max Q: 29.3 kPa (3.77s after ignition at 1650 ft AGL)

2. Nosecone Design

Laika uses an ogive nosecone profile with a fineness ratio of 3.9. An ogive nosecone was chosen since it is easier to manufacture precisely than other slightly more optimal designs. The fineness ratio was optimized by running multiple Open Rocket simulations to find the ratio that maximized altitude. Internally, the nosecone integrates an adjustable ballast system and the drogue parachute bay. The removable nosecone tip is held on by a 3/8 -16 threaded rod, which threads into the the aluminum nosecone tip and nosecone bulkhead. Various amounts of cast iron plates can be threaded into any location on the rod and retained using nuts, which allows adjustment of Laika's CG location to set an appropriate stability margin as well as fine tune the rockets apogee. The nosecone is retained on the avionics coupler with 4 4-40 shear pins, which shear at apogee to deploy the drogue.

3. Body Design

Laika's body tubes are built from five layers of filament wound 12K carbon fiber tow and Huntsman Araldite LY 1568 / Aradur 3492 epoxy, an aerospace-grade heat cure epoxy. The body tubes have an inner diameter of 6.25 in, and an outer diameter of 6.45 in, resulting from an approximately 0.1 in thickness of five layers of carbon fiber. External aerodynamics of the body tubes are optimized by maintaining the smoothest surface finish possible, achieved through sanding, painting, and polishing. The body tubes are broken into four sections: nosecone/drogue parachute bay, main parachute recovery section, upper motor section, and lower motor section. The main recovery section contains the rocket's main parachutes, and is connected using the payload coupler to the motor section. The motor section holds the motor and the fins. Laika's couplers are built using 5 layers of filament wound carbon fiber, with an outer diameter of 6.25 in. This allows them to slide snugly inside the body tubes. The payload coupler is approximately 12 in long (two body diameters) to minimize bending, and are held to the body tubes using 4 8-32 screws. The avionics coupler is mounted with the same hardware, and is 16 in long with a 4 in vent band through which the flight computers measure barometric pressure to track altitude.

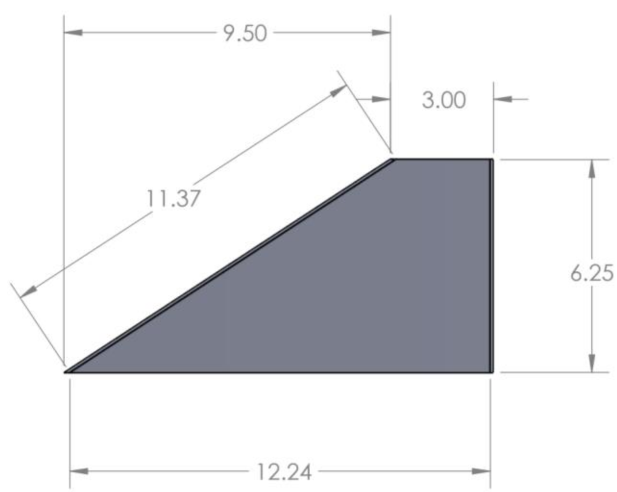

Figure 6. Fiberglass Fin Dimensions

4. Fin Design

The fins on Laika were designed to provide sufficient statics stability while minimizing drag. In order to archive the desired static stability the fins had to be large enough to pull the rockets center of pressure (Cp) to at least one and a half body tube diameters behind the center of gravity. The fins were designed as clipped deltas to ease construction and reduce the risk of a fin hitting first on recovery and breaking. Figure 6 shows the dimensions of the fins. The fins were made from ⅛ inch G10 fiberglass sheet and attached to the body with structural fillets made from filled epoxy. Two layers of fiberglass cloth were laminated over the fins in a process known as tip-to-tip to further reinforce them.

Flutter analysis was performed on the fins using the Barrowman 3D method. The divergence velocity was found to be 1.58 Mach and the flutter velocity was found to be 2.15 Mach, both values are significantly above the rocket velocity.

5. Structural Integration

Structural integration of Laika was designed in several sections - drogue recovery section/nosecone, avionics bay, main recovery section, payload bay, and motor integration. The drogue recovery section is contained within the nosecone and houses Laika's drogue parachute and associated shock cords and chute nomex parachute protectors. There is a bulkhead at the top of the nosecone that secures the nosecone tip. The shock cord attaches to a U-bolt mounted to this bulkhead. The other end attaches to a forward bulkhead attached to the avionics coupler. The nosecone is attached to the avionics coupler with 4 4-40 nylon shear pins, allowing the nosecone to separate and the parachute to deploy at apogee.

The avionics bay is a coupler with bulkheads on both ends, allowing it to conveniently connect the main recovery section and the nosecone. Both bulkheads are connected by a pair of 3/8 -16 aluminum threaded rods, which support the shock load of parachute deployment and hold the rocket body to the parachutes. A plywood board is mounted on these threaded rods with metal brackets, and secured with nuts on both ends. The avionics components are mounted to this board using appropriate screws.

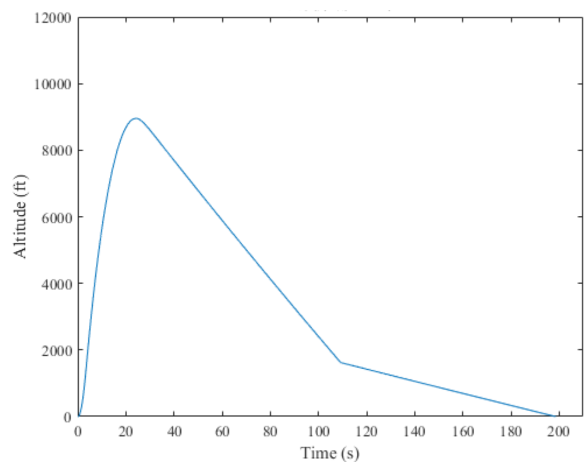

Figure 7. Simulated Altitude Over Time *The above result was obtained using OpenRocket*

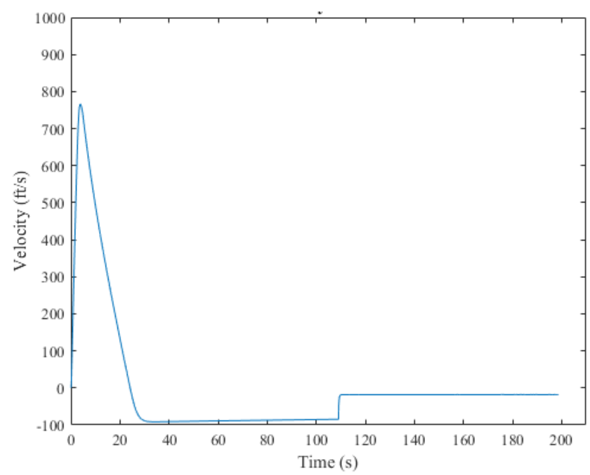

Figure 8. Simulated Velocity Over Time *The above result was obtained using OpenRocket*

The main recovery section is an empty tube containing Laika's main parachute and associated shock cords and chute nomex parachute protectors. There are bulkheads on both ends of the recovery bay, attached to the bottom of the avionics coupler and the top of the payload coupler, to take recovery loads. The top of the recovery tube is attached to the avionics coupler with 4 4-40 nylon shear pins allowing the rocket to separate and the parachute deploy at apogee.

The payload, an 8.8 lb rectangular prism, is contained in the payload bay which also acts as a coupler joining the main recovery section to the motor section using 8-32 screws.

Motor retention is based on secure hard-points along ribs running along the motor and thrust plates at the base. There are three T - shaped thrust plates at the base of the rocket which transfer the thrust to the airframe. The motor is attached to 6061 Aluminum ribs that run along the sides, and secured to these ribs are threaded bumpers that align with holes in the airframe. The bumpers ensure the motor is centered throughout the airframe, and provide negative retention for the motor stack. The motor is secured to the airframe with 3 8-32 screws in 4 locations along the length of the motor section.

6. Rail Guides

1515 rail guides were placed midway between fins to avoid interference with the rail. One rail pin is placed 2 in from the base of the rocket and the other was placed 7 ft above that forward of the center of mass. Both rail guides are fastened to the body using manufacturer-supplied screws and nuts.

E. Recovery

1. Drogue Parachute Design

The drogue parachute is released at apogee to limit rocket descent velocity to comply with IREC regulations, maintain a reasonable descent velocity while minimizing drift, and orient the main rocket body for main parachute deployment. It is constructed using 1.2 oz ripstop nylon, a material chosen due to its relatively low cost, high tensile strength, high melting point, and optimal permeability. The drogue parachute is circular, and has a diameter of 4 ft with a spill hole diameter of 4 in. Using OpenRocket simulations and the dry mass of Laika, a descent velocity of approximately 85 ft/s was calculated. The body tube and nosecone are suspended from the drogue parachute through a network of shroud lines and shock cords. There are 8 Kevlar shroud lines, connected by a quick link to a 50 ft length of 1 in tubular nylon shock cord that attaches to 3/8 in U-bolts attached to the nosecone bulkhead and forward avionics bulkhead. Line connections are made using quick links to streamline assembly and replacement of damaged lines.

2. Main Parachute Design

The main parachute will be deployed at an altitude of 1000 ft AGL. Like the drogue, it is built from 1.2 oz ripstop nylon. The main parachute suspends the rocket using 8 shroud lines, each 14 ft in length, along with 50 ft of 1 in nylon shock cord. Laika's main parachute is conical, with a diameter of 17 ft. It is built using 10 gores. This design was chosen for its relative manufacturing simplicity and sized to provide enough drag to slow the rocket down to 19.6 ft/s to comply with IREC regulations and minimize damage to the rocket upon impact. While in the bay, the main parachute is protected from damage by the ejection charges using a 2 ft square nomex sheet. When ejected, the main parachute is expected to exert up to 1600 lbf of shock load to the rocket. This force is transmitted through shock cords tied to quick links on a U-bolt, which is screwed into a bulkhead at the top of the avionics bay. This bulkhead and U-bolt sustain all recovery loads for both parachutes and hold the rocket body to the shock cords.

F. Payload

1. Flame Propagation Experiment

The payload will observe the effects of high and very low acceleration have on flame propagation. The payload consists of two separate acrylic chambers that will each contain a cotton ball coated in petroleum jelly and an e-match. These chambers will be watched upon by two cameras mounted on the opposite wall and the top of the payload. As soon as the rocket the launches, one of the e-match will ignite and light the cotton ball from one of the chambers. What the two cameras record at this point will be flame propagation under high acceleration. As the rocket approaches apogee, the e-match in the second chamber will ignite and what the cameras record at this point will be flame propagation under very low acceleration. By analyzing the video, we will be able to observe how flames react to varying degrees of acceleration.

This payload was designed and fabricated by Plymouth-Canton Education Park students with the assistance of MASA members. These students and MASA team members met after school once a week and developed the payload over the course of the 2017-2018 academic year.

3) Mission Concept of Operations Overview

This section outlines the mission phases of a nominal flight. Subsystem performance during each of these phases are also provided. A designation of N/A implies that the subsystem is either inactive during this period.

A. Assembly

Propulsion: N/A
Avionics: N/A
Airframe: N/A
Payload: N/A

Transition Event: Rocket construction and inspection are complete and *Laika* is ready to be carried to the pad.

B. Pad Setup

Propulsion: Support systems will be assembled and connected to the fill system. Rocket will be loaded onto the rail.
Avionics: Pad systems will be set up. Wireless link to flight computer and engine controller will be established. Avionics will be safed at this stage.
Airframe: *Laika's* weight will be fully supported by the lowest rail guide.
Payload: Cameras will be turned on at the point recording data

Transition Event: Rocket is set up on the pad and all non-essential personnel are outside the safety perimeter.

C. Fuel Fill

Propulsion: Unpressurized ethanol will be loaded into the rocket by ground crew.
Avionics: N/A
Airframe: N/A
Payload: Will continue to collect data from a camera. No ignition inside of the payload has occurred yet.

Transition Event: Rocket is filled with fuel and all personnel are outside the safety perimeter.

D. Oxidizer Fill

Propulsion: Rocket will be loaded with nitrous oxide and fuel tank will be pressurized to flight pressure with nitrogen. Fill lines will be decoupled and separation will be tested. This process is controlled by ground crew outside the safety perimeter.
Avionics: Ground avionics will facilitate nitrous oxide loading.
Airframe: Airframe will bare increased weight.
Payload: N/A

Transition Event: Rocket is fully fueled and ready for flight.

E. Ignition

Propulsion: Ignition command will be sent to the custom ignition device and main valves will be commanded to open, which will trigger the engine's startup. Chamber pressure and thrust climb to nominal values.
Avionics: Avionics will control igniter and valves.
Airframe: Will begin to bear thrust loads.
Payload: N/A

Transition Event: Engine thrust overcomes a thrust to weight ratio of 1 and the airframe begins to lift off the rail.

F. Liftoff

Propulsion: Engine will continue to build thrust.
Avionics: COTS flight computers will detect liftoff and begin logging data.
Airframe: Airframe will begin lifting off it's support block and will be guided by the launch rail. At the point the lowest guide leaves the rail, the *Laika* will be traveling at 107 ft/s.

Payload: Will detect liftoff and will start the ignition of the first flame. Cameras will be collecting data.

Transition Event: Rocket's lowest guide leaves the launch rail.

G. Ascent Under Power

Propulsion: Engine will continue to produce thrust and accelerate the rocket.
Avionics: Avionics will continue to transmit live telemetry to ground station and will log flight data internally.
Airframe: Airframe will travel through "Max Q" and sustain its largest loads
Payload: N/A

Transition Event: Engine cutoff.

H. Ascent Coast

Propulsion: N/A
Avionics: Avionics will continue to transmit live telemetry to ground station and will log flight data internally.
Airframe: Airframe will continue to coast to apogee.
Payload: Will start the ignition of the second flame propagation and will continue to record data.

Transition Event: Flight computers detect apogee and ignite drogue deployment charges.

I. Descent Under Drogue

Propulsion: N/A
Avionics: Avionics will monitor altitude for 1,000 ft AGL and continue to transmit telemetry to ground station.
Airframe: Nose cone will separate from the airframe, which will pull out the drogue parachute. The drogue will slow the rocket's descent to 90 ft/s.
Payload: At this point, the samples should have burned out.

Transition Event: Flight computers detect 1,000 ft AGL and ignite main deployment charges.

J. Descent Under Main

Propulsion: N/A
Avionics: Avionics will establish GPS link with secondary locator device and continue to receive live telemetry from flight computer. They will begin broadcasting the rocket's location to ground recovery team.
Airframe: Avionics bay/coupler will separate from the airframe, which will pull out the main parachute. The main will slow the rocket's descent to 16 ft/s.
Payload: Will continue to record data on the payload.

Transition Event: Rocket lands on the ground.

K. Recovery

Propulsion: N/A
Avionics: Avionics will continue to transmit GPS location and produce noise, which will aid in recovery.
Airframe: Ground recovery team will safe unexploded charges.
Payload: N/A

Transition Event: Rocket is returned to base camp.

4) Conclusions and Lessons Learned

Over the past year, MASA has undergone many changes in both its organizational and technological focus. We switched our focus to the production of a liquid bi-propellant engine from a hybrid motor and in doing so required us to identify bottlenecks in our workflow and address them.

One major change was investing more into our workspace layout and hardware. We completely revamped the space to be more open and set higher standards for organization. The result was that we could have more people work faster and more effectively thus allowing us to meet our strict deadlines. We invested in new tools that allowed us to produce higher quality and higher complexity parts.

From a technical standpoint, we learned a significant amount about plumbing and how to reduce its complexity for assembly. The major change that was required to successfully build the liquid engine was switching to a nearly NPT fitting free system. Almost all plumbing is done using 37 deg flare fittings or compression nuts. This allowed assembly to be much more straightforward and allowed us to mate parts properly.

A consistent source of problems in our system was the development and operation of motorized valves. There were eight iterations of the motorized valve before we created a well-functioning system. We started with prototype 3D printed mounts and a gear assembly where the three main parts (motor, potentiometer, and valve) did not share an axis of rotation. The final design placed the three parts coaxial to each other and used a motor from a seemingly unrelated application. Rapid design cycles were key to making this part work in both hardware and software.

Laika, an SRAD liquid bipropellant rocket, was developed at the University of Michigan by the Michigan Aeronautical Science Association (MASA). It will fly to approximately 10 000ft at 2018 IREC. It uses in-house electronics for both engine controller and live telemetry. The airframe is composed of carbon fiber body tubes and a fiberglass nosecone which were designed and manufactured entirely by students. The motor, Spitfire, is an ethanol-nitrous oxide liquid bipropellant engine. It produces 850 lbs of thrust for three seconds during flight.

Appendix A: System Weights, Measures and Performance Data

See attached progress report.

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: 3/23/2017 [1]

Team ID: 37

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

Country: United States

State or Province: Michigan [2]

State or Province is for US and Canada

Team Information

Rocket/Project Name:	Laika [3]
Student Organization Name	MASA - Michigan Aeronautical Science Association [4]
College or University Name:	University of Michigan [5]
Preferred Informal Name:	MASA [6]
Organization Type:	Club/Group
Project Start Date	7/1/2017 [7]
Category:	10k – SRAD – Hybrid/Liquid & Other

Projects are not limited on how many years they take

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For Mailing Awards:

Payable To:	MASA
Address Line 1:	2606 Draper Drive
Address Line 2:	Ann Arbor, MI 48109
Address Line 3:	
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
Undergrad	31
Masters	2
PhD	0

Male	29
Female	4
Veterans	no
NAR or Tripoli	1

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

MASA provides various benefits to the the community through outreach programs such as Aerospace Day where members build and launch Estes rockets with elementary and middle school students, Design Immersion where members work with hundreds of Engineering freshmen in the first week of the year, along with participating at afterschool events and Math/Science nights at local schools. Our outreach efforts also include partnering with high school students at Plymouth Canton Educational Park to design and build a payload to be flown at competition this year.

Rocket Information

Overall rocket parameters:

	Measurement	Additional Comments (Optional)
Airframe Length (inches):	132 [12]	
Airframe Diameter (inches):	6.45 OD [13]	
Fin-span (inches):	19.5 [14]	
Vehicle weight (pounds):	66.5 [15]	
Propellent weight (pounds):	12.2 [16]	
Payload weight (pounds):	8.8 [17]	
Liftoff weight (pounds):	87.5 [18]	
Number of stages:	1 [19]	
Strap-on Booster Cluster:	No [20]	
Propulsion Type:	Liquid [21]	
Propulsion Manufacturer:	Student-built [22]	
Kinetic Energy Dart:	No [23]	

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

SRAD Format - [Stage]: [Motor/Engine Type], [Propellant mixture], [Letter Class], [Total Impulse]
1st Stage: SRAD Liquid, 2.5 lbs of 95% liquid ethanol and 9.7 lbs of liquid nitrous oxide, N Class, 10,800 Ns [24]

Total Impulse of all Motors: 10,800 [25] (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:	ESRA Provide Rail [26]	
Rail Length (feet):	17 [27]	
Liftoff Thrust-Weight Ratio:	9.8	~850 lbs of thrust, ~87 lbs launch mass
Launch Rail Departure Velocity (feet/second):	96	
Minimum Static Margin During Boost:	3.72	*Between rail departure and burnout
Maximum Acceleration (G):	8.83	Maximum thrust is ~0.1 seconds after liftoff
Maximum Velocity (feet/second):	768	
Target Apogee (feet AGL):	10K [28]	
Predicted Apogee (feet AGL):	8,952	

Payload Information

Payload Description:

The Payload will attempt to observe the effects of combustion under both high and low acceleration by using high speed cameras to catch the events. We plan to compare our results with the same test run on the ground under nominal conditions. We will be lighting two seperate cotton balls in their own compartments at takeoff where the combustion will experience high acceleration. We also will be lighting another two seperate cotton balls in their own compartments at apogee where the combustion will experience microgravity.

Recovery Information

The rocket recovers in three sections attached by nylon cords. These sections are the nose cone, avonics bay, and main body tube. The drouge chute is made from ripsto nylon, has a diameter of 24in inches, and is deployed by barometric detection of apogee. The main chute is made from ripsto nylon, has a diameter of 6.5 feet, and is deployed by barometric detection of 1000ft using the stratologger and easymini flight computers. All events have a primary and back-up charge

Planned Tests

* Please keep brief

Date	Type	Description	Status	Comments
10/28/17	Ground	Partial-duration liquid engine test	Successful	Tanks and plumbing not in flight config.
11/12/17	Ground	Full-duration liquid engine test	Successful	Tanks and plumbing not in flight config.
3/17/18	Ground	Full-duration test w/ flight tanks	Successful	Tanks and plumbing IN flight config.
5/12/18	Ground	Final pre-flight engine test	Successful	Engine and tanks ready for flight

5/16/18	Ground	Engine-to-airframe integration test	TBD	Physical fit between engine and airframe
5/29/18	Ground	Engine fill and drain, full rocket assembly	TBD	Fill/drain tanks with nitrous and water in a fully assembled rocket
	Ground	Seperation Tests	TBD	standard deployment test
4/7/18	In-Flight	of recovery and avionics using solid test platf	TBD	Testing live telemetry downlink from custom

Any other pertinent information:

The liquid engine, tanks, and all associated plumbing is in its final configuration for flight. This configuration was tested in a successful hotfire on 3/17/18. We plan to hotfire at least once more after modifications are made to the nitrous and ethanol fill system.

End of File

Appendix B: Project Tests Reports

A. SRAD Propulsion System Testing

Throughout the 2017-2018 school year, Spitfire was static fired a total of 3 times, in addition to 2 static fires with a smaller development engine. These tests provided valuable data regarding the performance of the engine and potential problems with procedures involving setup, propellant fill, and avionics. The first 3 static fires were conducted in the fall of 2017 with a smaller proof-of-concept engine. These tests validated the combustion chamber, injector, ignition, fill procedure, and motorized valve design. Preliminary problems such as unreliable motorized valves and ignition were identified and subsequently fixed in the 2 static fires of this small engine.

Shortly after the successful development engine tests, the team progressed to developing flight hardware and ground support equipment. This hardware was tested in 3 static fires, with the last static fire being an engine stack test comprised of flight propellant tanks, motorized valves, fill system, quick disconnect actuators, and fill procedures.

Below is a picture of our most recent static fire setup. It is a full engine stack test to collect data for final flight simulations. Below the engine stack is the thrust stand, which is comprised of an assembly to bolt onto the combustion chamber, a flame trench which redirects exhaust horizontally, and water cooling to prevent the flame trench from burning through. There are numerous sensors attached to the engine during a normal test. There are 5 pressure transducers monitoring the pressure of the propellant tanks, fuel and oxidizer injector manifolds, and combustion chamber. To collect thrust data, 4 load cells are placed under the combustion chamber. These sensors connect to a DAQ, which sits directly outside the bunker, in addition to the engine controller which collects low speed data. Attached next are the performance metrics of the 3 static fires of the liquid engine.

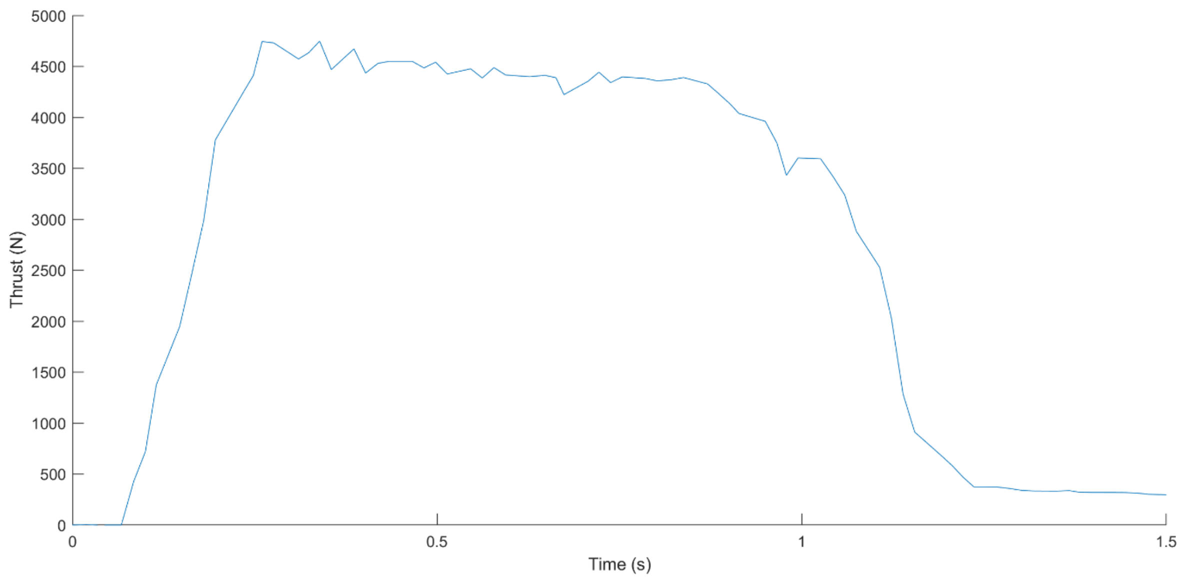
Figure 9. Static Fire Test Setup

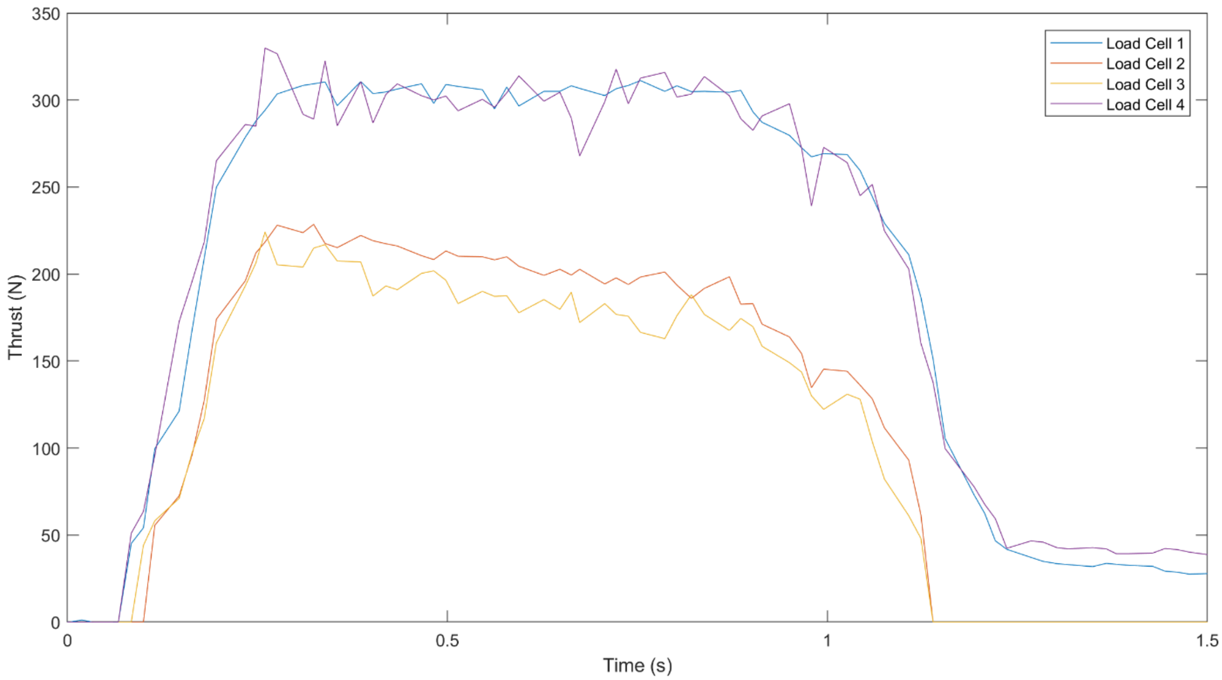
Below is the test data from the 3 most recent static fires of Spitfire, an SRAD liquid engine. The figures, in this order, describe the overall thrust, individual thrust recorded from load cells, pressures in pressure vessels and important components, pressure drop across the injector orifices normalized by the injector manifold pressure and chamber pressure for both oxidizer and fuel, and pressure drop across the feedlines from tank to injector in both oxidizer and fuel lines

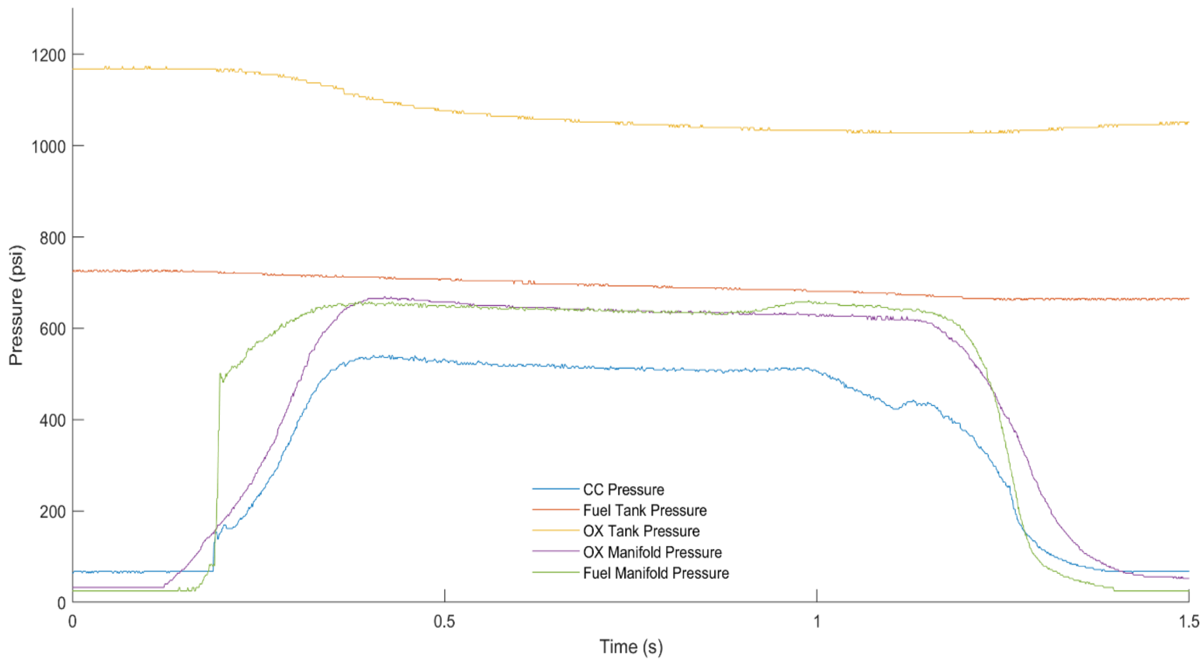
10/28/17 Hotfire Test
Data Analysis

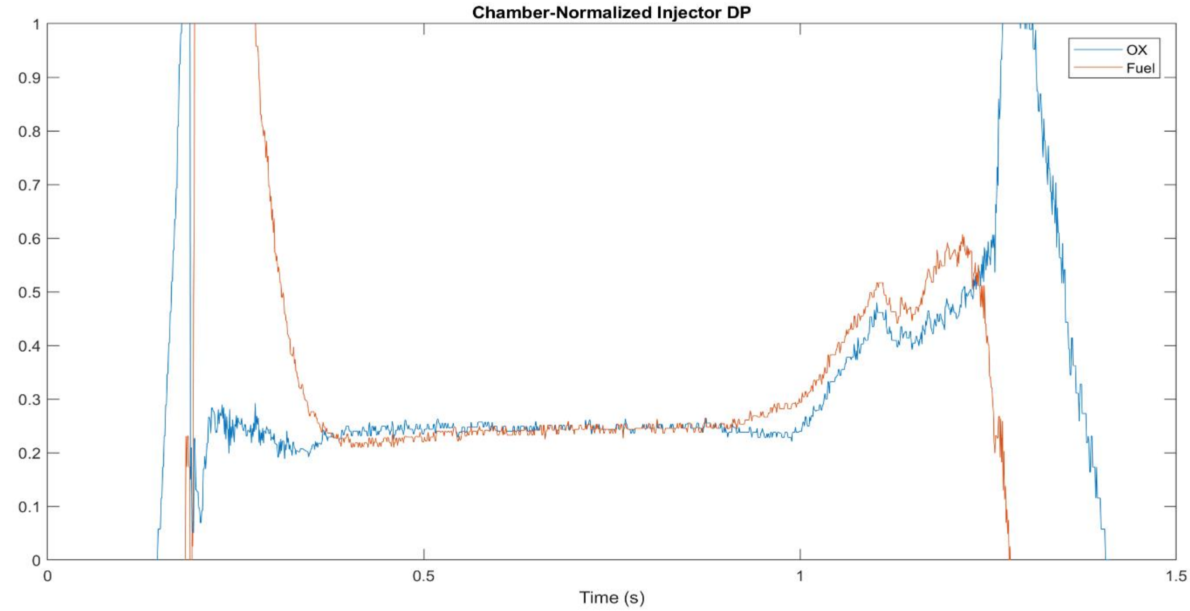
Input	Oxidizer Mass Burned (kg)	Fuel Mass Burned (kg)
Value	1.48	0.37

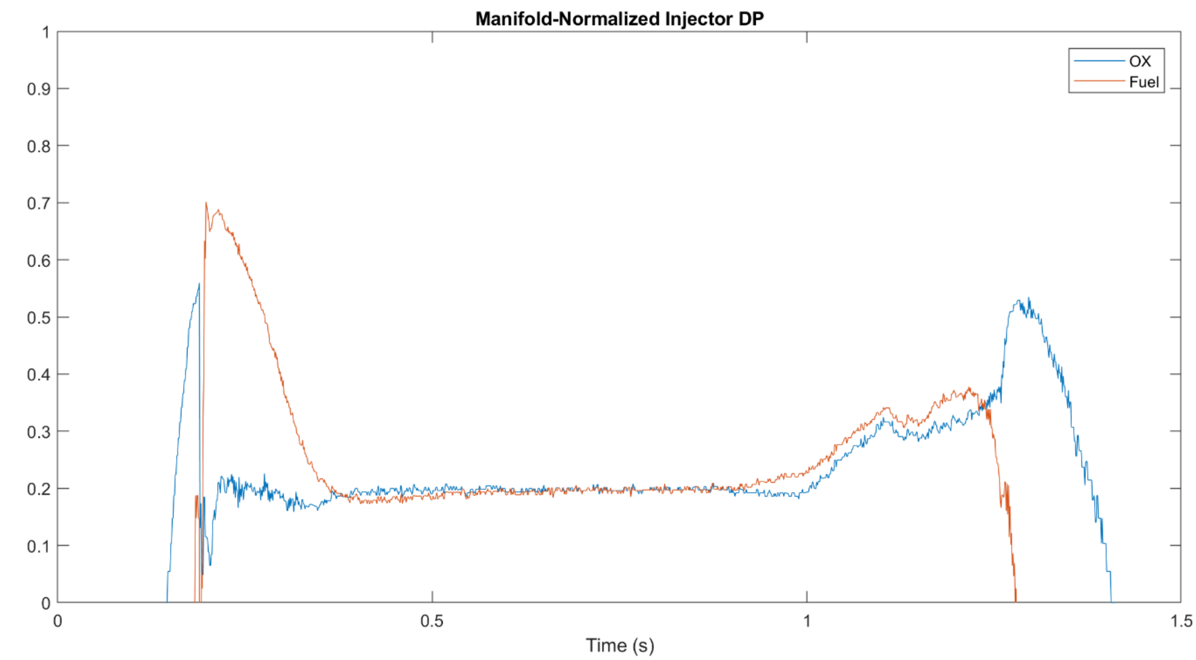
Input	I_{sp} (s)	Impulse (N*s)	C_t	C* (m/s)	Av. Thrust (N)	Max Thrust (N)
Value	218		0.98	2049	3986	4285

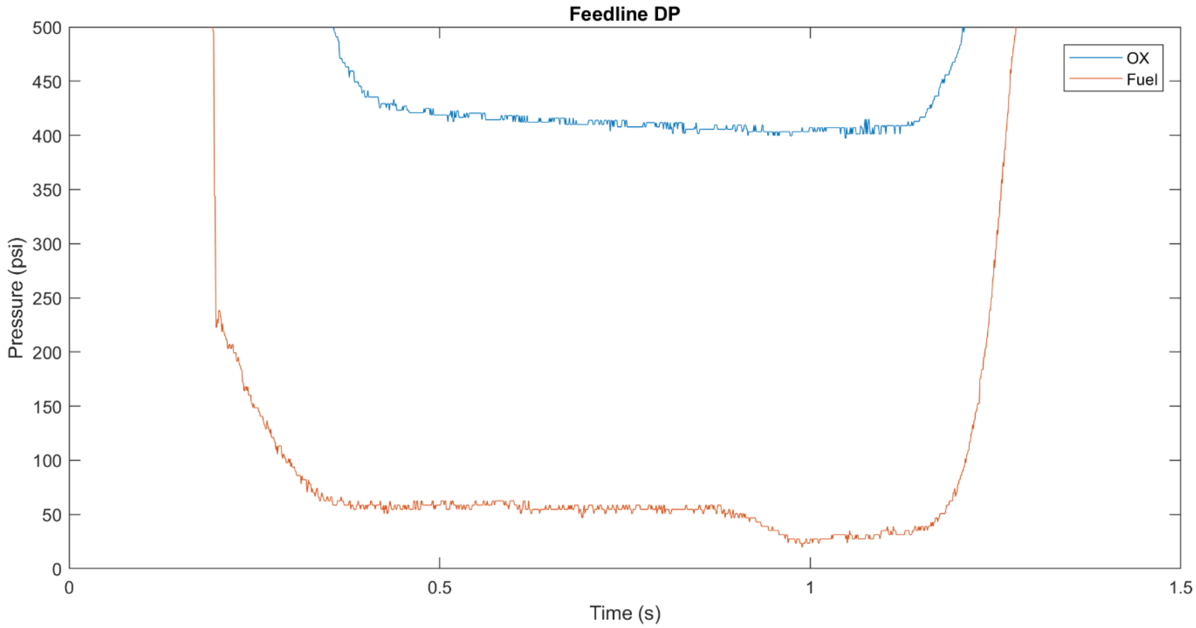



Load Cell 1
Load Cell 2
Load Cell 3
Load Cell 4
Thrust (N)
Time (s)
350
300
250
200
150
100
50
0
0
0.5
1
1.5


CC Pressure
Fuel Tank Pressure
OX Tank Pressure
OX Manifold Pressure
Fuel Manifold Pressure
Pressure (psi)
Time (s)
1200
1000
800
600
400
200
0
0
0.5
1
1.5


Chamber-Normalized Injector DP
OX
Fuel
Time (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5

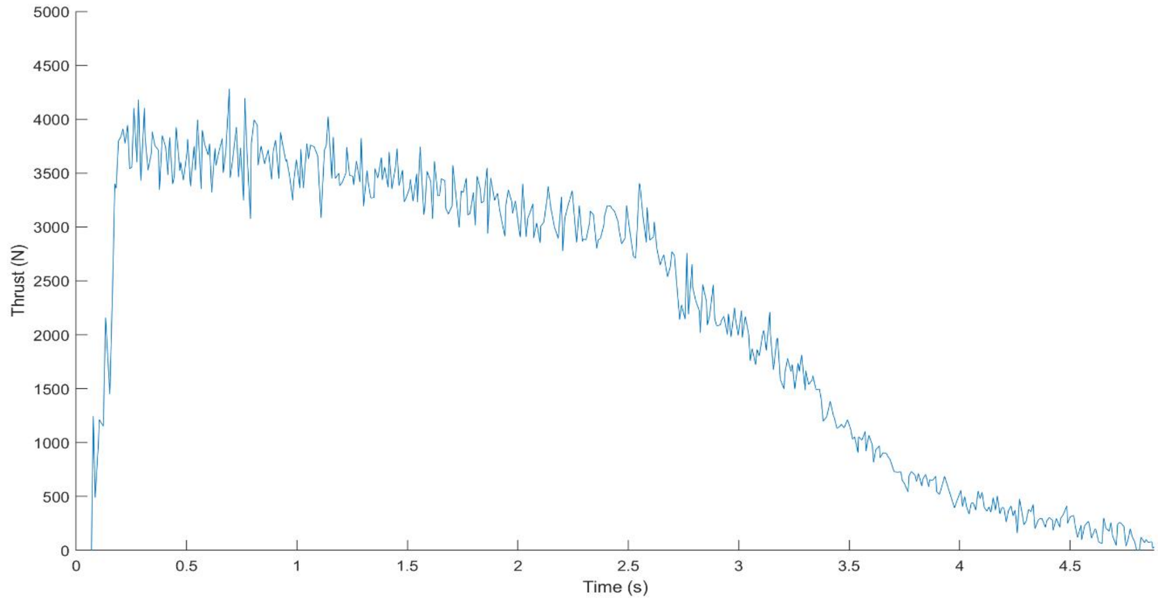

Manifold-Normalized Injector DP
OX
Fuel
Time (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5

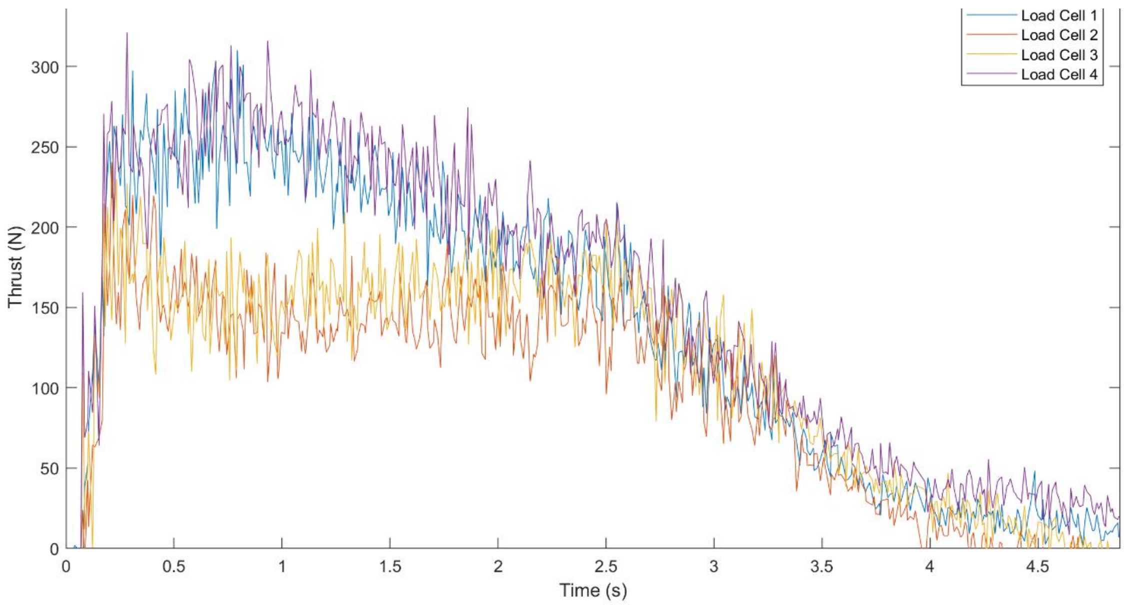

Feedline DP
Pressure (psi)
Time (s)
OX
Fuel
500
450
400
350
300
250
200
150
100
50
0
0
0.5
1
1.5

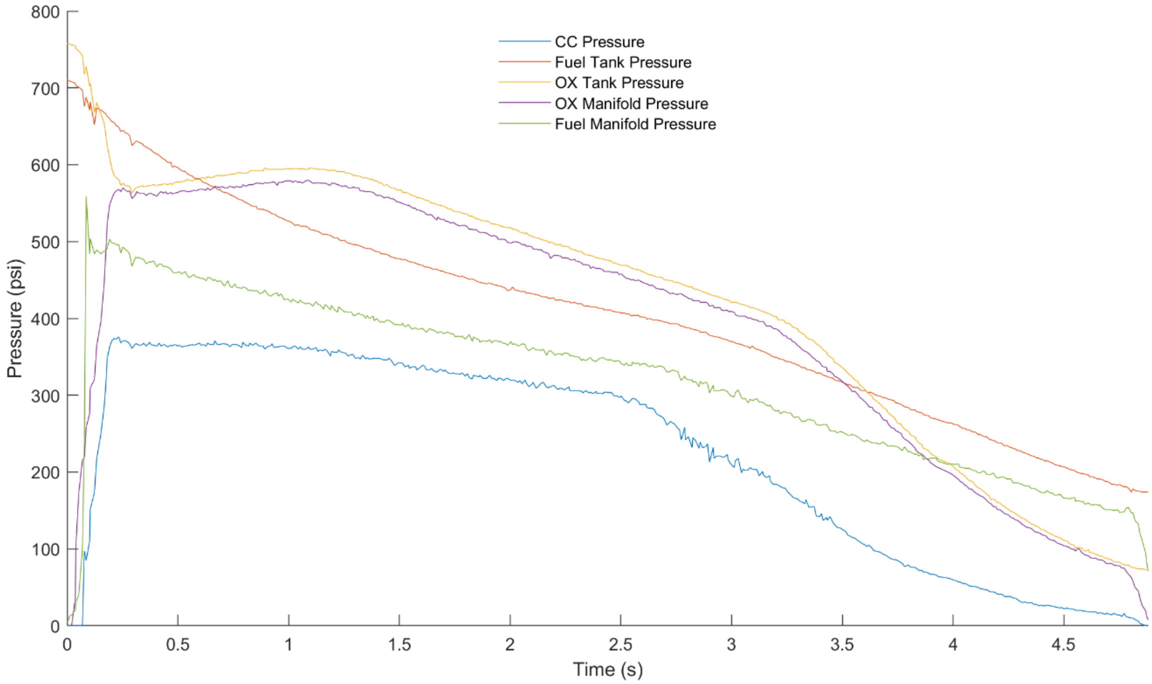
11/12/17 Hotfire Test
Data Analysis

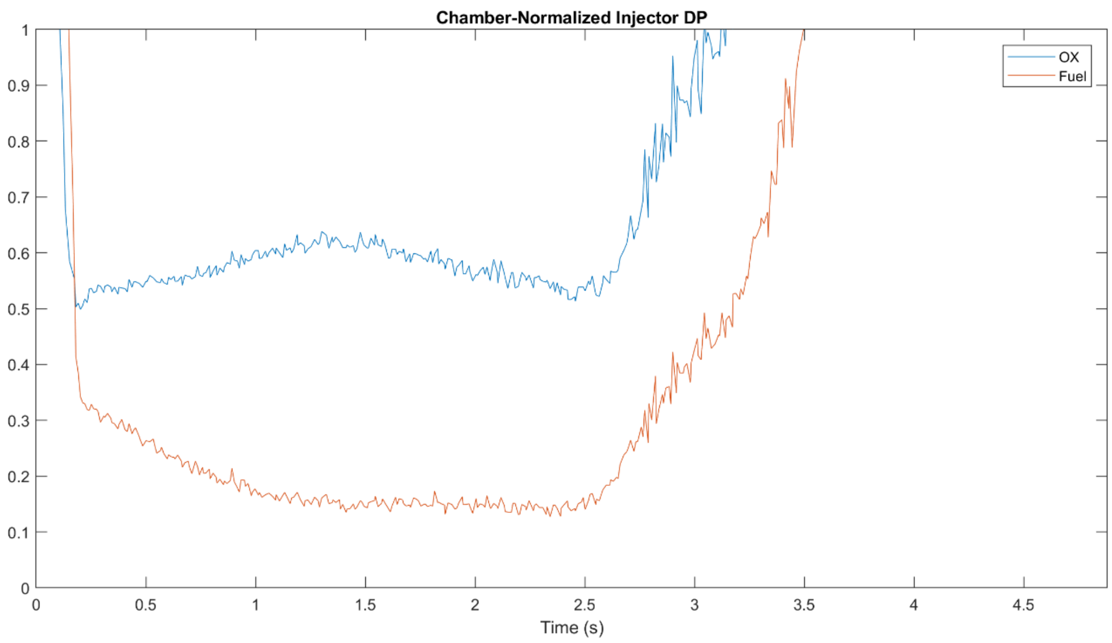
Input	Oxidizer Mass Burned (kg)	Fuel Mass Burned (kg)
Value	5.96	1.49

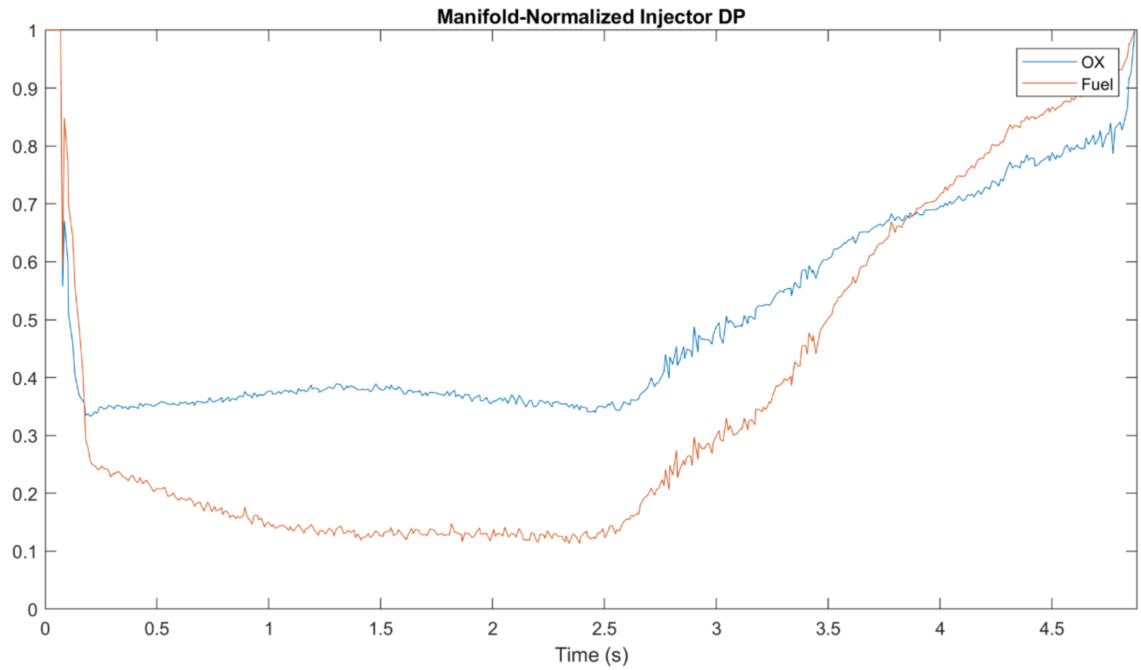
Input	I_{sp} (s)	Impulse (N*s)	C_t	C* (m/s)	Av. Thrust (N)	Max Thrust (N)
Value	192		0.92	2036	3511	4882

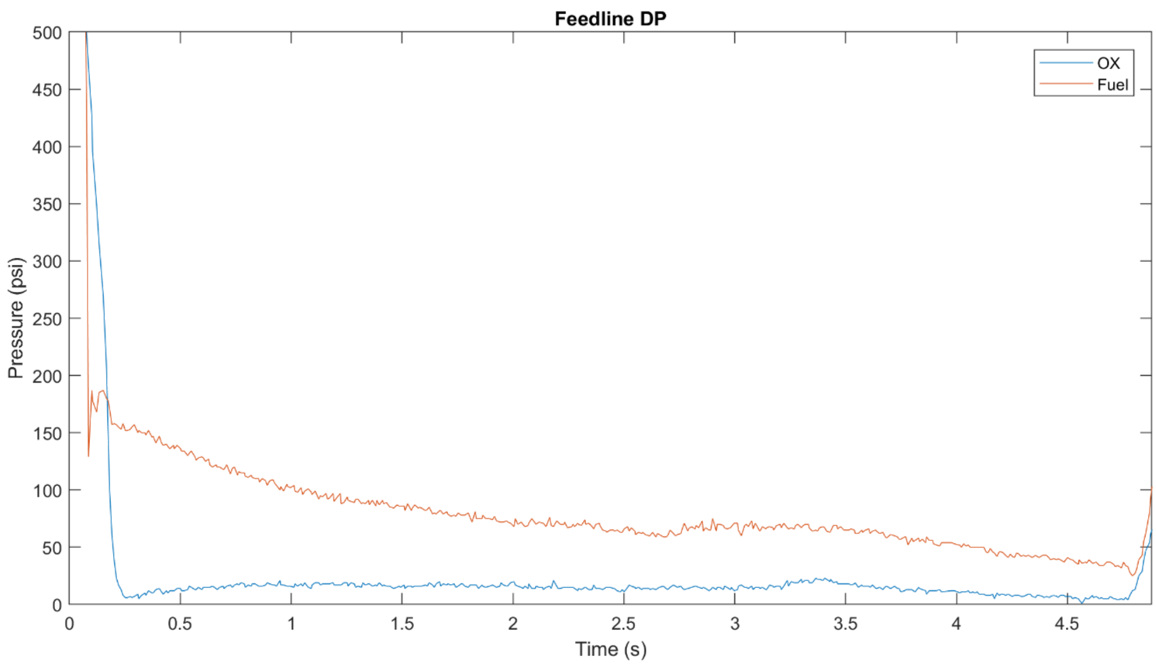





CC Pressure
Fuel Tank Pressure
OX Tank Pressure
OX Manifold Pressure
Fuel Manifold Pressure
Pressure (psi)
Time (s)


Chamber-Normalized Injector DP
OX
Fuel
Time (s)

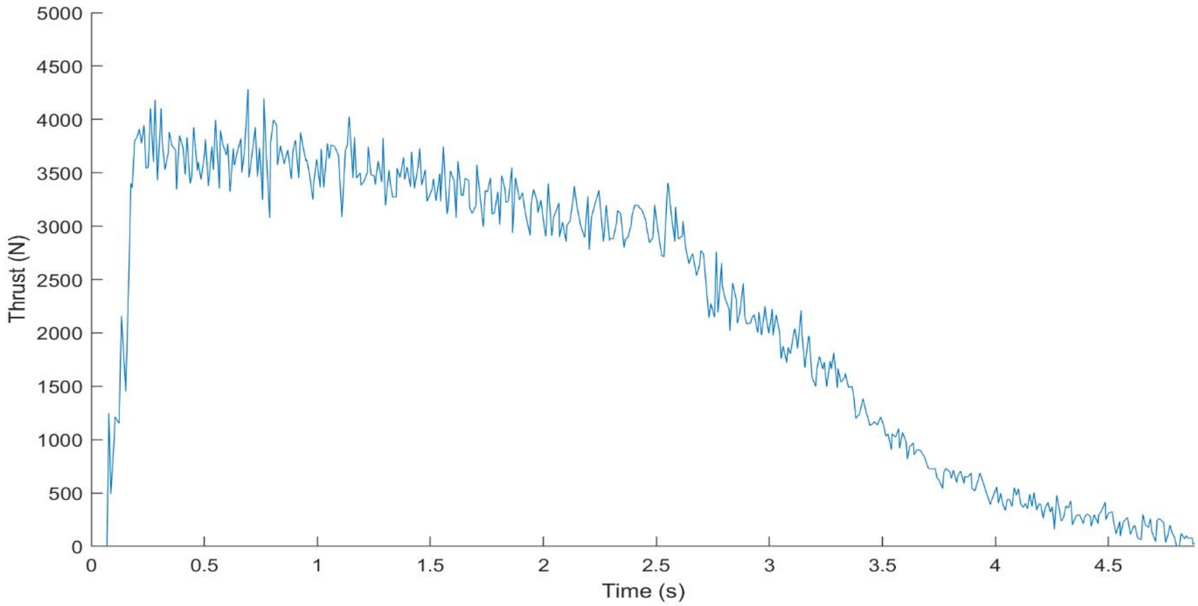

Manifold-Normalized Injector DP
OX
Fuel
Time (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1
1.5
2
2.5
3
3.5
4
4.5

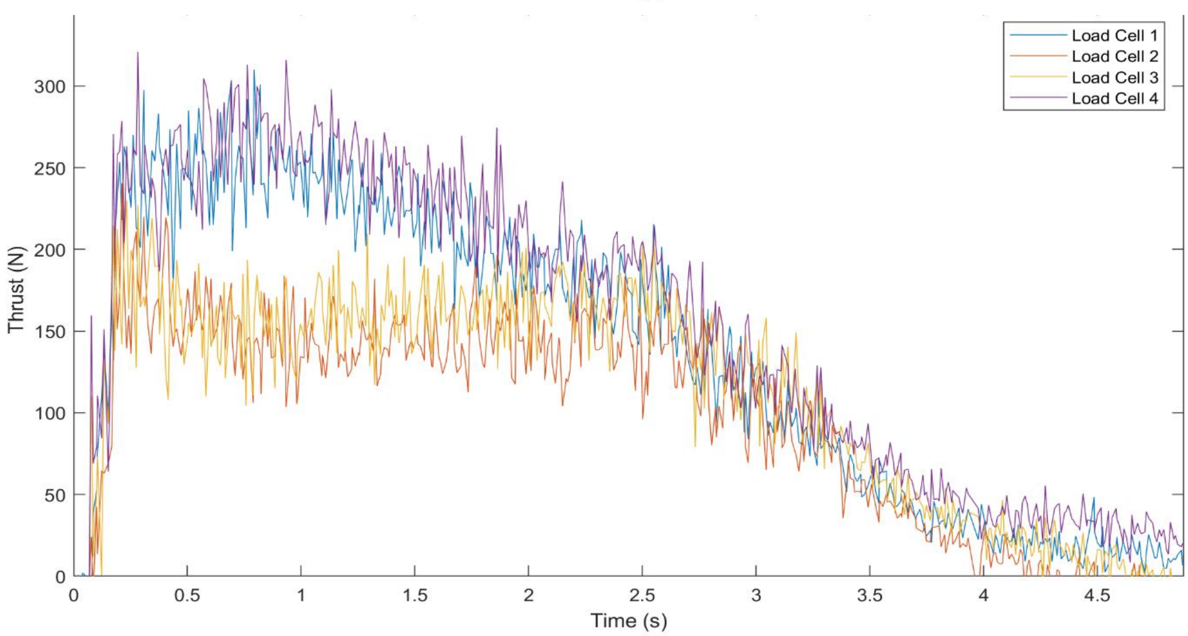

Feedline DP
OX
Fuel
Pressure (psi)
Time (s)
0
50
100
150
200
250
300
350
400
450
500
0.5
1
1.5
2
2.5
3
3.5
4
4.5

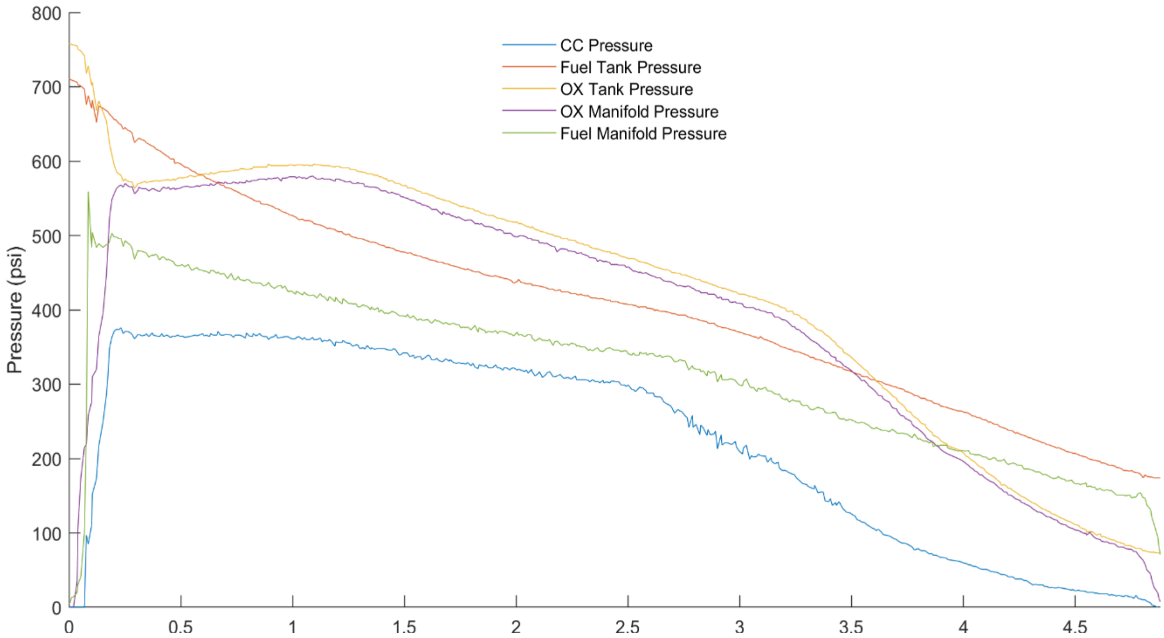
3/17/18 Hotfire Test
Data Analysis

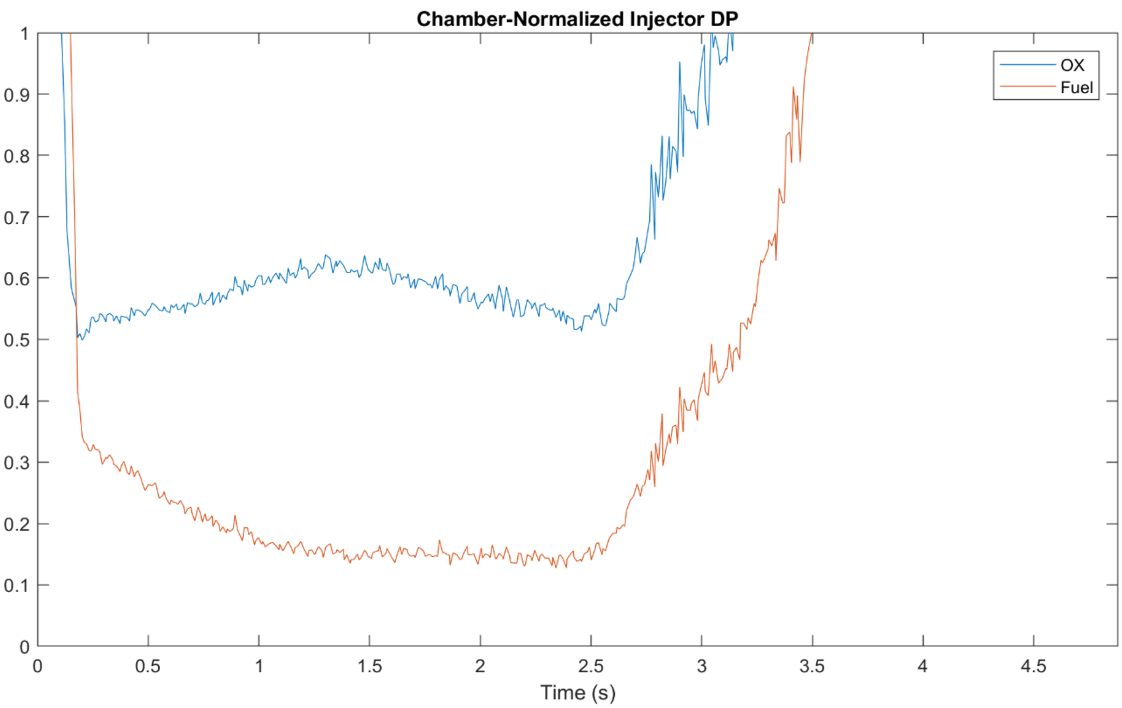
Input	Oxidizer Mass Burned (kg)	Fuel Mass Burned (kg)
Value	4.48	1.12

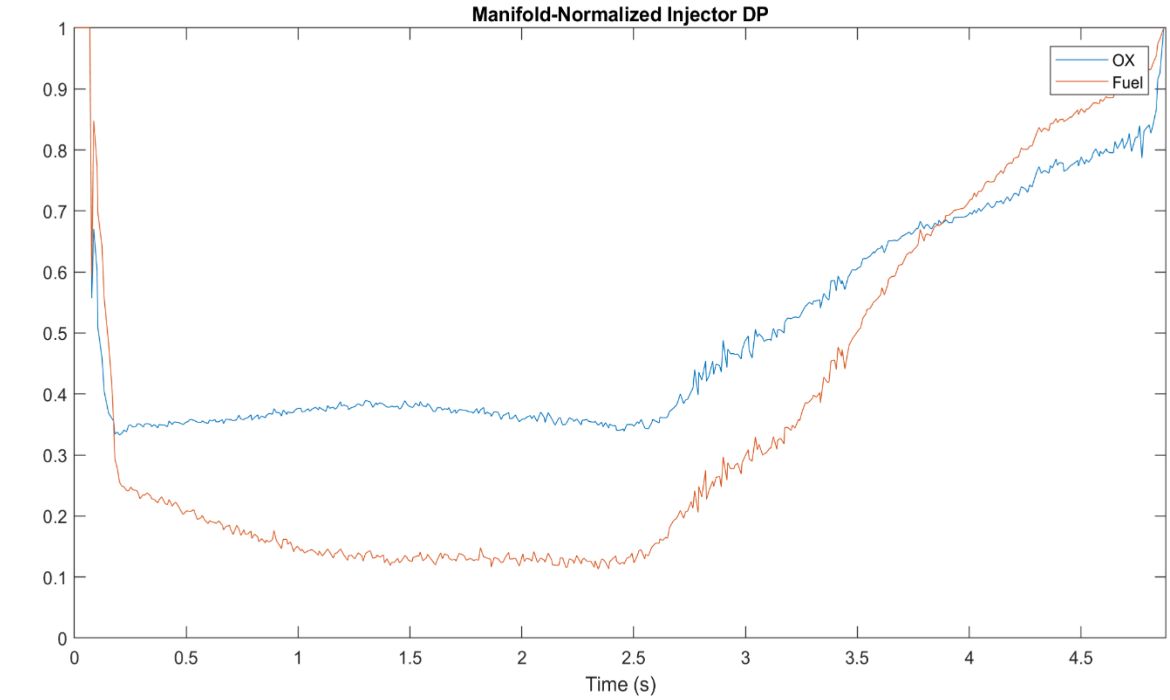
Input	I_{sp} (s)	Impulse (N*s)	C_t	C* (m/s)	Av.Thrust (N)	MaxThrust (N)
Value	215	10800	1.5	1541	2787	4285

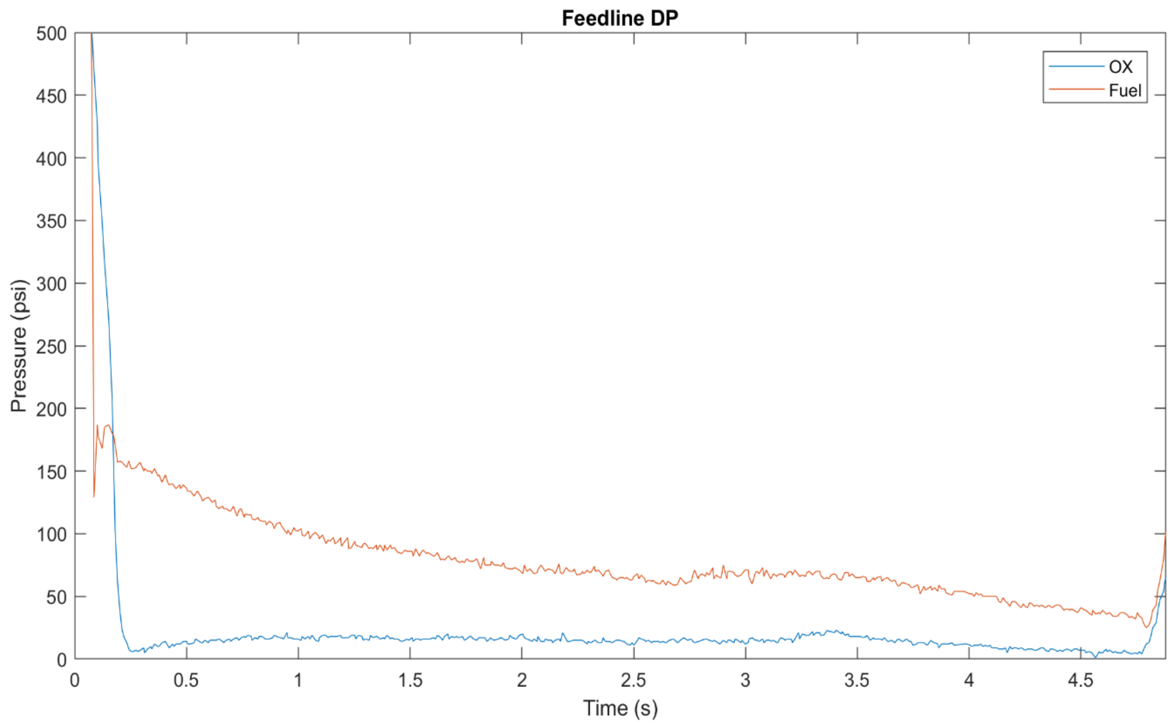





CC Pressure
Fuel Tank Pressure
OX Tank Pressure
OX Manifold Pressure
Fuel Manifold Pressure
Pressure (psi)


Chamber-Normalized Injector DP
OX
Fuel
Time (s)


Manifold-Normalized Injector DP
OX
Fuel
Time (s)


Feedline DP
OX
Fuel
Pressure (psi)
Time (s)

B. SRAD Pressure Vessel Testing

All systems which will operate at an elevated pressure are hydro-statically pressure tested to at least 1.5x MEOP. For the oxidizer tank, fuel tank, this value is 1200 psi. The chamber was pressure tested to 1200 psi. Pressure testing is accomplished using a Rice Hydro hand pump, which has a maximum operating pressure of 2000 psi. Below is the P&ID diagram of Laika.

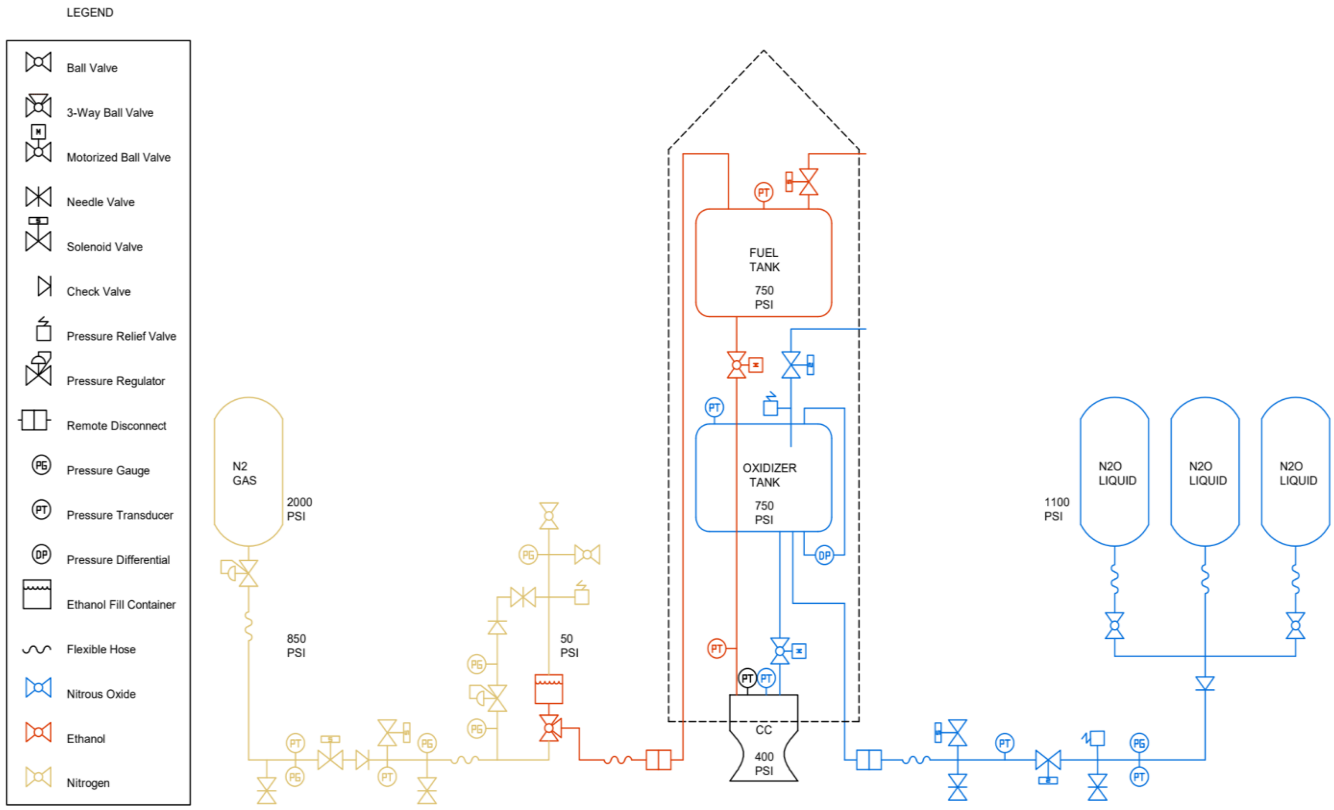


Figure 10. Plumbing and Instrumentation Diagram

C. Recovery Testing

Laika's recovery system was tested by ground separation tests. This method is used to determine the size of the blackpowder charges required to consistently separate the nosecone and release the drogue parachute. These tests yielded a charge size of 5 g of 4F black powder for the main parachute, excluding the mass of the e-match and charge packaging. A secondary charge with 6.5 grams of black powder will also be flown as backup incase the first charge fails to separate the rocket. The drogue bay will use a 3.5-gram black powder charge with a 4.5-gram redundant charge.

1. Flight Avionics

Two flight computers will be used for redundancy, both of which are mounted in the avionics bay. The primary flight computer is a Easy-Mini, and the secondary flight computer is a PerfectFlite Stratologger CF. Two different flight computers were specifically chosen to avoid any failure mode that may be specific to a certain flight computer. The primary flight computer is set to fire its separation charge at apogee, and its main parachute charge at 1 000 ft AGL. The secondary flight computer is set to fire its separation charge at delay of 2 seconds after apogee, and its main parachute charge at 800 ft AGL. These delays ensure that sufficient time has passed so that charges in too quick succession do not damage any recovery components, but are close enough together to minimize any harmful effects to the recovery sequence.

Also, onboard the rocket is a custom board flight computer for high speed data logging. This PCB was designed by MASA's avionics team to help characterize the forces incurred during parachute deployment. Commercial flight computers generally record acceleration at too low a rate to resolve the impulsive forces of parachute deployment. This custom flight computer will record accelerometer data at close to 1 KHz. The flight computer was also designed to be able to deploy the rocket's parachutes, however, minimal testing has been done on this system and it will not be used in the 2018 Spaceport America Cup flight. All the commercial flight computer circuits and procedures are designed to minimize the chances of a premature charge detonation. Until installation in the rocket, ejection charges will have their leads shorted. After installation, the flight computer power lines are passed through a magnetic switch. Until the rocket is on the pad, the switches remain off, preventing any potential power spikes that could set off the charges. When on the pad and ready for launch, the flight computers are armed by passing a magnet near the magnetic switches, turning on the power to the flight computers.

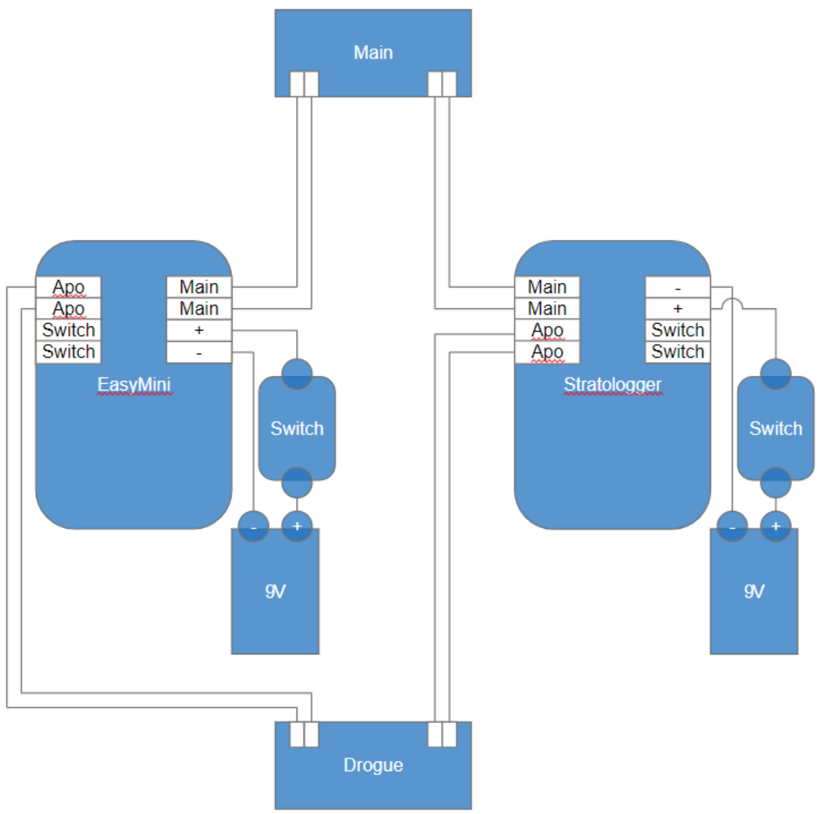


Figure 11. Redundant Recovery Avionics Wiring Diagram

D. Live Telemetry Testing

The live telemetry system built by the team utilizes two printed circuit boards. The first board, which flies on the rocket, has a barometer, accelerometer, 6 gyroscopes, and GPS. During flight, this board simultaneously records data to onboard flash and transmits to another board on the ground. The ground-side board transmits data to a laptop to be displayed.

To test this system, it was flown on a rocket powered by a M motor to an altitude of 10,000+ feet. The two boards remained in radio contact throughout the entire flight and descent. The team was able to see the rocket's maximum altitude live, use the system's transmitted position to recover the rocket, and recover the saved data from the circuit board within the rocket. This flight was essential to validate that the system would perform optimally under the circumstances of high velocity and high altitude. The only major change to the system post-test was to add a switch between rocket-side circuit board and its battery, so that the battery wouldn't be depleted during rocket integration.

Appendix C: Hazard Analysis

See attached hazard analysis.

Hazard Analysis Appendix

Intercollegiate Rocket Engineering Competition 2018

Michigan Aeronautical Science Association

Team 37

Introduction

Safety is the primary concern of the Michigan Aeronautical Science Association. From transportation to handling, we have taken every precaution to ensure hazards and their consequences have been minimized. This appendix addresses, as applicable, hazardous material handling, transportation and storage procedures of propellants, and any other aspects of the design which pose potential hazards to operating personnel.

Summary of Potential Hazards

- Nitrous oxide transportation, storage and handling
- Ethanol transportation, storage and handling
- APCP transportation and storage/safety precautions
- Gunpowder ejection charge transportation
- Lithium Polymer Battery transportation

Material	Potential Hazard	Mitigation Approach with Regards to Handling, Transportation, and Storage	Risk Level
Pressurized Nitrous Oxide Containers	Risk of fire or explosion. On physical contact with liquid: frostbite. Inhalation may cause unconsciousness.	Handle with care, using PPE including appropriate gloves and safety goggles. Transport in vehicles with trunks isolated from cabin. Keep nozzle facing driver so the tank flies outward and away from driver. Use dolly on land to reduce risk of dropping.	Low
Ethanol Containers	Risk of fire. Harmful if swallowed.	Handle using PPE including disposable gloves and safety goggles. Transport while isolated in sealed plastic containers. Keep far from other chemical and electrical sources. Avoid heat and shocks.	Low
APCP (Ammonium Perchlorate Composite Propellant) Grains	Highly combustible, risk of explosion. On physical contact may cause redness and pain.	Handle using PPE including disposable gloves and safety goggles. Transport while isolated in sealed plastic containers. Keep far from other chemical and electrical sources. Avoid heat and shocks.	Medium
Gunpowder Ejection Charges	Highly combustible, risk of explosion. On	Handle using PPE including disposable gloves and safety goggles. Transport while	Low

	physical contact may cause redness and pain.	isolated in sealed plastic containers. Keep far from other chemical and electrical sources. Avoid heat and shocks.	
Lithium Polymer Battery	On physical contact may cause redness and pain.	Store in dark, cool location in Lithium Polymer safe transport bag. Avoid heat.	Low

Appendix D: Risk Assessment

See attached risk assessment matrix.

IREC 2018 - Liquid 10k Category, Risk Analysis/Mitigation
Michigan Aeronautical Science Association

Phase of Flight	System	Hazard	Possible Cause	Preventative Measures	Mitigation Approach	Risk of Mishap and Rationale	Likelihood of Injury After Mitigation
Assembly	Avionics	Recovery system deploys on the ground	Flight computer malfunction; Ejection charge wire malfunction	Do not arm flight computers until on the pad; Shunt all ejection charges and frequently check for continuity	Handle ejection charges with proper PPE; Evacuate the vicinity and contact the proper launch site personnel	Low, recovery system avionics are tested extensively before integrated with ejection charges	Medium
Pad Setup	Propulsion	Propellant Leak	Improper sealing of plumbing	Snoop tests, air pressure testing	If large leak, drain and retighten all joints.	High, small leaks tend to occasionally happen	Low
		Main Valve Opening Failure	Engine controller malfunction, unresponsive motor	Redundant mechanical system, multiple tests	Use redundant mechanical system	Low, has been repeatedly tested	
		Solenoid Opening Failure	Unresponsive solenoid	Redundant mechanical system, multiple tests	Use redundant mechanical system	Low, commercial solenoid	Low
		Quick disconnect failed to detatch	Mechanical failure, unresponsive linear actuator	Redundant mechanical system, multiple tests	Use redundant mechanical system	Low, extensive testing of system	Low
		On pad pressure failure	Extremely high pressure in tanks	Hydrostatic testing and air pressure testing. Designed with a safety factor of 2. Safe distance from rocket required.	Drain nitrous, do not approach.	Low, all hardware has been tested extensively	Medium
	Airframe	Rocket falls from rail	Improper integration with launch rail; Rail pin breaks from rocket	Roles are defined for who attaches rocket to rail, as to avoid confusion and mishaps; Conduct structural tests to ensure rail pins can withstand the weight of the entire rocket	With roles preventing confusion, everyone can focus on the rocket and not be distracted; Have everyone back up from the rocket and inspect area for hazardous debris; Carefully approach rocket with permission from the RSO	Low, the team has practice loading rockets onto rails and testing rail pins	Low
Ignition	Propulsion	Hang fire	Ignition wires separating from e-matches or short circuit	Continuity checks of ignition system; Use COTS motor and ignition system	Ensure all personnel are a safe distance from the pad, as specified by the RSO; Follow all range safety protocol before approaching the rocket; Wear proper PPE	Low, system has been tested repeatedly without failure	Low

Ascent Under Power	Propulsion	In flight pressure failure	Extremely high pressure in tanks	Hydrostatic testing and air pressure testing. Designed with a safety factor of 2. Safe distance from rocket required. Rocket fired at angle away from people.	Drain nitrous, do not approach.	Low, all hardware has been tested extensively	Low
		Engine retention fails	Incorrect simulation; Errors in production or relevant parts	Simulate the structure and build with a safety factor (1.5)	Have all personnel far from the launch site; Follow all RSO rules; Alert proper personnel is problem is spotted	Low, the team has experience making engine retention parts and none have failed	Medium
	Airframe	Rocket does not follow expected trajectory	Incorrect simulation; Powerful wind gusts; Rocket instability; Airframe structural failures	Designed with stability margins in mind	Maintain line of sight watch on rocket and alert all personnel onsite.	Medium, rocket deviated from path somewhat on previous IREC launch	Medium
		Body tube undergoes structural failure	Incorrect calculations; High wind forces/bending forces	Computational analysis of components	Alert all personnel onsite to the presence of an incoming ballistic projectiles. Maintain line of sight watch on rocket.	Low, all body tube components were designed with at least a safety factor of two.	Low
		Rocket Instability	Motor doesn't burn evenly; Miscalculation in fin sizing; Fin failure; Airframe structure failure	Double checking stability margins; measuring center of mass before launch, ballast adjustments.	Rocket may veer off course or fly in an unexpected direction. Alert personnel onsite and maintain line of sight watch on rocket.	Medium, stability is difficult to test, but stability analyses has been examined through software	Medium
		Flight computer dies	Battery connected backwards; Static electricity; Short circuit	Verify things are plugged in correctly before connecting power; Wrap electrical components with electrical tape/insulation to prevent static buildup or short circuits	If parachutes do not deploy, alert all personnel onsite to the presence of an incoming ballistic projectile. Maintain line of sight watch on rocket.	Low, there is a possibility of a battery failure due to overheating in a New Mexico summer.	Low

	Avionics	Ejection charges fail to detonate	Open Circuit; dead flight computer/battery	Verify computer operation preflight; Ensure 9V battery voltage is at least 8V before launch; Continuity check E-charge circuits before and after crimping	If parachutes do not deploy, the rocket will come down ballistic. Alert all personnel onsite and maintain line of sight watch on rocket. Parachute bays are designed and tested to withstand expected pressures.	Low, multiple separation tests have verified ejection charge detonations and flight computers are commercial	Low
		Ejection charges detonate too early	Flight computer failure; Electrical surge	Verify computer operation pre-launch; insulate all electrical components to minimize odds of any surges	Parachute(s) will deploy early, and rocket will quickly reach apogee and begin descent. If the cords are tangled, the rocket may come down ballistic and all personnel will be alerted. Alternatively, the rocket may normally descend without reaching full altitude. Mitigation will include careful wrapping of the parachutes.	Medium, the flight computers sensors may not be accurate.	Low
		E-charges detonate too late	Faulty e-matches	Conduct separation tests with e-charges; Continuity check e-matches prior to launch	Rocket will come down ballistic and appropriate warnings will have been made. Personnel will be wearing PPE (safety glasses/face masks) while disassembling the rocket and removing unspent charges	Medium, the flight computers sensors may not be accurate	Low
Decent under drogue/main		Wire Connections breaking	Weak crimps; stressed wires	Pull-test on all crimps; Using flight computers to check if charges have been connected; Use wire clamps to reduce stress on wires; All wires are designed to have slack	Parachute(s) may not deploy and rocket will come down ballistic. Alert all personnel onsite and maintain line of sight watch on rocket	Medium, wires are weak and the electronics will experience shaking as the rocket launches	Low

	Airframe	Drogue separation or main deployment fails	Any avionics issues/ejection charge issues (see avionics); Too strong connection on separation couplers; Inadequate gunpowder in ejection charge	Conducted separation tests	Rocket will come down ballistic and appropriate warnings will have been made. Maintain line of sight watch on rocket.	Medium, inability to test actual conditions of separation	Low
		Seam failure on main parachute or drogue	Excessive loads on parachute; flawed stitches on parachute	Drogue deployment test; Calculation maximum load on parachute with safety factor of at least 2	If either parachute fails, rocket may come down ballistic. Alert all personnel onsite and maintain line of sight watch on rocket	Low, the load on the parachute is being spread out over all of the seams and each seam was designed with a safety factor of at least 2.	Low
		Main parachute fails to unfurl	Parachute snags inside tube; Poor separation	Parachute wrapped inside deployment bag to help prevent snagging; Parachute properly folded and packed prior to launch, validated through ground tests.	Rocket may come down ballistic. Alert all personnel onsite and maintain line of sight watch on rocket	Low, ground test has validated this	Low
		Main parachute tangles after deployment	Parachute folded improperly	Parachute is carefully folded prior to launch, validated through ground tests	Rocket may come down ballistic. Alert all personnel onsite and maintain line of sight watch on rocket	Medium, high number of lines leads to higher probability of tangling	Low
		Main parachute deploys at apogee and drifts	Flight computer malfunction with early ejection charge ignition; Recovery system structural failure	Ground recovery tests	Ensure launch is permitted at safe time by RSO. Maintain line of sight of rocket	Medium, recovery systems can be difficult to fully test in flight conditions on the ground	Low

Appendix E: Assembly, Preflight, and Launch Checklists

See attached checklists.

***Laika* Launch SOP**
Michigan Aeronautical Science Association
IREC 2018, June 19-23
10K SRAD Liquid Launch
Last Update: 5/18/2018

NOTE: RSO HAS FINAL SAY ON ALL MATTERS

Purpose: Ground crew procedures at pad, fill, launch, and recovery

Avionics Ground Station Set-Up

- ❏

Pad GSE Set-up

- ❏ Bring pad toolbox. Double check that you have arming keys (3/32 allen key) and adjustable wrenches.
- ❏ Place fuel tower and tank stand near the rail. Use flex hoses to judge distances.
- ❏ Make the following hose connections and turn valves to the following positions:
    - ❏ Connect the fuel QD hose to the fuel tower
    - ❏ Connect the tank stand nitrogen hose to the fuel tower
    - ❏ Close all four needle valves on the tank stand panel (A,N, I, and K)
    - ❏ Close the two ball valves on the tank stand panel (O and P)
    - ❏ Fully open the pressure regulator on the fuel tower by turning clockwise (W)
    - ❏ Close the 3-way ball valve on the fuel tower by turning the arrow to the “left” position (Y)
    - ❏ Close the needle valve on the fuel fill tower (U)
    - ❏ Close the funnel ball valve on the top of the fuel fill tower (R)
    - ❏ Close the vent ball valve on the top of the fuel fill tower (T)
- ❏ Place the closed nitrous oxide and nitrogen gas tanks into the following positions:
    - ❏ One nitrous oxide tank into the middle slot and chain it down
    - ❏ One nitrogen gas tank into the left slot and chain it down
- ❏ Make the following hose connections:
    - ❏ Connect the nitrous tank GCA fitting to the middle CGA hose, *do NOT open the tank valve*
    - ❏ Connect the nitrogen gas tank GCA fitting to the tank stand CGA hose, *do NOT open the tank valve*
- ❏ Connect transducer and valve harnesses to ground engine controller.
- ❏ Plug in and boot up engine controller.
- ❏ Set up wireless system and establish connection with mission control.

- ❏ Test all solenoids and transducers on fill system via engine controller.
- ❏ Turn valves to the following positions:
    - ❏ Fully open the nitrogen gas tank valve, confirm that the high-side gauge reads between 1400 and 2200 psi
    - ❏ Tighten the nitrogen gas tank pressure regulator T-handle until the low-side gauge reads between 200 and 250 psi -- *this will pressurize the hose and a section of the fill panel*
    - ❏ Check that the fill panel nitrogen gauge also reads between 200 and 250 psi (B)
    - ❏ Fully open the nitrous oxide tank valve -- *this will pressurize the hose and a section of the fill panel*
- ❏ Check the nitrous oxide system pressure (G and L):
    - ❏ If pressure is below 900 psi, wrap tank heaters around nitrous oxide tank until pressure reaches 1,000 psi
    - ❏ If pressure is above 1,000 psi, pack ice around the nitrous oxide tank until pressure decreases to 1,000 psi

Rocket on Rail

- ❏ Lower the rail to horizontal position
- ❏ Line up the guides on the rocket with the rail and slowly slide the rocket onto rail
- ❏ Once the lowest guide is resting on the block, raise the rail into the launch orientation and lock into place
- ❏ Connect avionics connector to port on rocket and verify system health
- ❏ Plug in quick disconnect actuators to engine controller ground board

Manual Ethanol Loading

- ❏ Get ESRA official permission to begin ethanol loading
- ❏ Connect the fuel fill system to the rocket: join the orange-keyed quick disconnect. *Do NOT connect the green-keyed QD for nitrous oxide.*
- ❏ Open the two ball valves at the top of the fuel fill tower (R and T)
- ❏ Pour the pre-measured bottle of 1,430 mL of 95% ethanol through the funnel into the fuel fill tank
- ❏ Close the two ball valves at the top of the fuel fill tower (R and T)
- ❏ Turn the three-way ball valve to the “up” position (Y)
- ❏ Actuate the nitrogen fill solenoid for three seconds to pressurize the nitrogen hose to 200 psi (D)
- ❏ Confirm that the high-side fuel tower pressure gauge (X) reads ~200 psi and the low-side fuel tower pressure gauge (V) reads ~50 psi
- ❏ Fill ethanol into the rocket:
    - ❏ Open the fuel-fill tower needle valve (U)
    - ❏ Cycle the rocket-fuel-vent solenoid on/off for 15 seconds
    - ❏ Confirm that the rocket fuel tank pressure transducer reads zero
    - ❏ Confirm that the fuel-fill tank pressure gauge reads zero (S)

- ❑ Open the top ball valve (R) and insert a wooden dowel to confirm that there is no ethanol left in the fuel fill tank, then close the ball valve.
- ❑ Safe the fuel fill system and configure for remote fuel pressurization:
    - ❑ Vent nitrogen from the fill hose by opening, then closing, the vent needle valve (N)
    - ❑ Confirm that the nitrogen fill hose pressure gauge reads zero (H)
    - ❑ Close the fuel tower needle valve (U)
    - ❑ Turn the fuel tower 3-way ball valve to the “down” position (Y) to configure for fuel tank pressurization.
    - ❑ Increase the nitrogen mother tank regulator pressure to between 800 and 850 psi.

Final Pad Preparations

- ❑ Connect the oxidizer fill system to the rocket: join the green-keyed quick disconnect.
- ❑ Get ESRA official permission to insert igniter
- ❑ Ensure area is clear of non essential personnel
- ❑ Turn arming switches on av bay
    - ❑ Turn on BRB and ensure gps lock and signal
    - ❑ Turn on masa flight computer and verify telemetry
    - ❑ Turn on stratologger and listen for beeps to ensure functionality
    - ❑ Turn on easy mini and listen for beeps to ensure functionality
- ❑ Turn on payload (if not boilerplate)
- ❑ Turn on all cameras and double check that they are rolling
- ❑ Insert igniter into the chamber and clamp into place on nozzle
- ❑ Check voltage on ignition leads is not 12 V and there is continuity
- ❑ Connect igniter to ignition line
- ❑ Retreat from pad

Remote Nitrous Oxide Loading

- ❑ Target pressure: 750 psi
- ❑ Wait until the mother tanks are between 900-1000 psi and then start cycling the fill solenoid (F)
- ❑ If the mother tanks drop below 800 psi (L), pause filling and wait for them to heat back up to 900-1000 psi.
- ❑ Track the progress of the oxidizer liquid level by comparing the DP transducer readout and rocket oxidizer tank pressure, look for sudden spikes during and after fill and vent, meaning that the tank is likely full. Refer to Figure 1 for examples of these spikes in data.
- ❑ Confirm oxidizer liquid level by venting and looking for the puff of white nitrous oxide vapor from the side of the rocket. However, the lack of a white puff only indicates that the liquid level is at or below the dip tube.
- ❑ Alternate fill and vent cycles until the oxidizer level is full and the rocket oxidizer tank is at or near 750 psi

Remote Fuel Pressurization

- ❑ Target pressure: 750 psi
- ❑ Cycle on/off the nitrogen fill solenoid (D) until the pressure reaches 750 psi.
- ❑ If the pressure is filled above 750 psi, open the fuel tank vent solenoid to decrease pressure.

Terminal Sequence

- ❑ Disconnect QDs (Fuel then Ox)
- ❑ Confirm visually that QDs have separated
- ❑ Confirm by venting that the QDs have been separated:
    - ❑ Actuate the nitrogen fill hose vent solenoid for 5 seconds (M)
    - ❑ The nitrogen fill hose pressure transducer (Q) should read near 0 psi
    - ❑ The rocket fuel tank pressure should read unchanged
    - ❑ Actuate the nitrous oxide fill hose vent solenoid for 5 seconds (E)
    - ❑ The nitrous oxide fill hose pressure transducer (J) should read much lower than 700 psi, but not necessarily zero
    - ❑ The rocket oxidizer tank pressure should read unchanged
- ❑ Set engine controller telemrates
- ❑ Confirm telemetry and GPS lock from Big Red Bee
- ❑ Confirm telemetry link with flight computer and GPS lock
- ❑ Wipe flight computer flash
- ❑ Start logging

Poll for Launch

- ❑ Airframe
- ❑ Avionics
- ❑ Propulsion
- ❑ Safety
- ❑ Chief
- ❑ ATLO

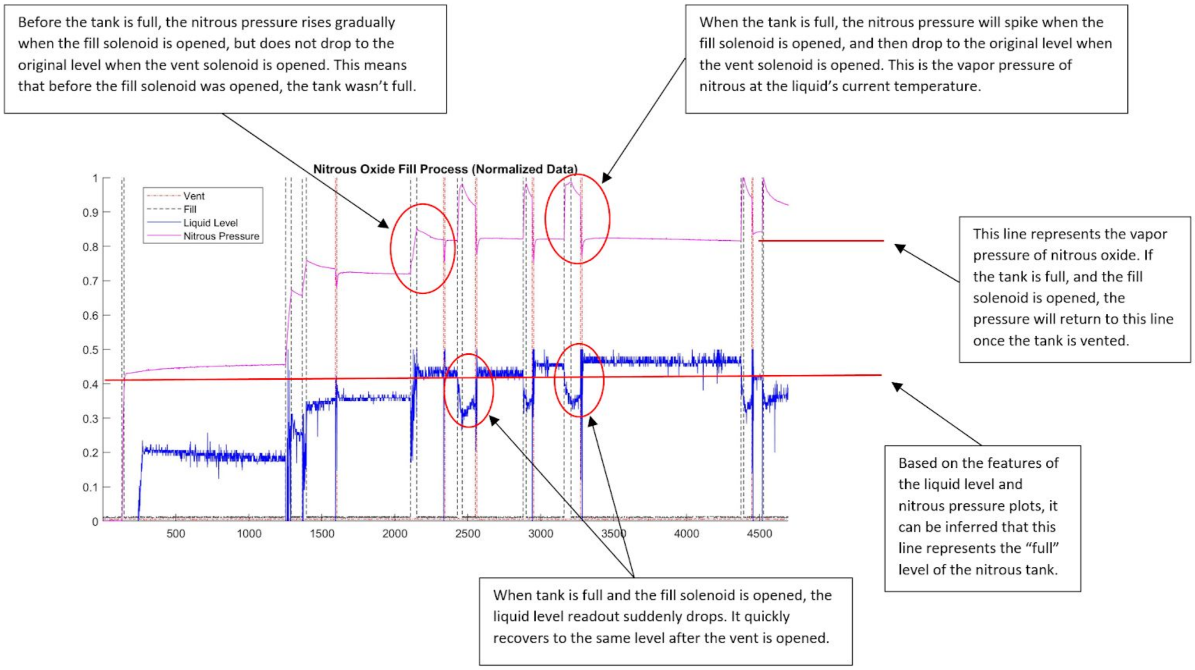
IGNITION

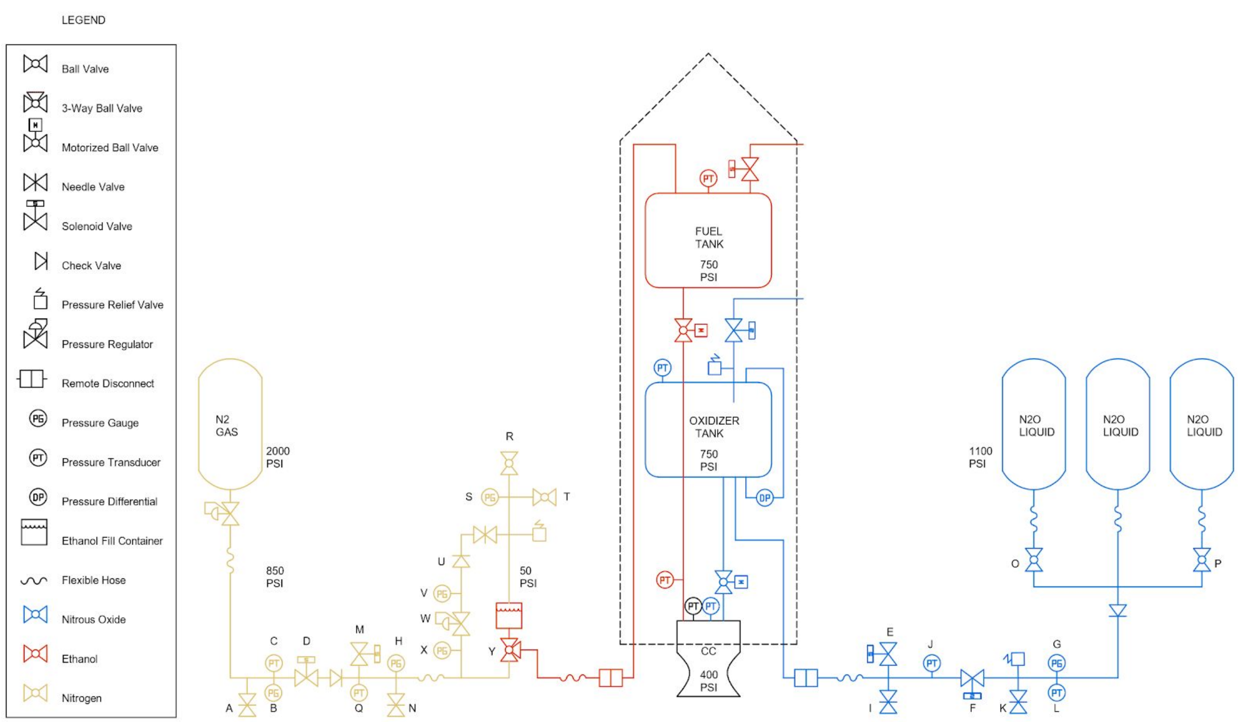
- ❑ RSO Launch Approval
- ❑ Check the sky for aircraft
- ❑ Arm engine controller
- ❑ Begin audible countdown
- ❑ Punch it, Sternie!

Post-Flight/Recovery

- ❑ Following liftoff, disarm engine controller
- ❑ Obtain location of rocket from telemetry and line-of site information
- ❑ Obtain official approval to proceed to landing site

- ❏ Bring cell phones (verizon), water, radios, tracking equipment, PPE (safety glasses, facemask), lipo batteries, arming key (3/32 allen key), ⅛ allen key
- ❏ Approach rocket carefully using appropriate PPE (safety glasses, facemask)
- ❏ Ensure no charges remain in recovery bays
- ❏ Ensure no propellants are left in tanks
- ❏ Carefully return rocket to base camp


Before the tank is full, the nitrous pressure rises gradually when the fill solenoid is opened, but does not drop to the original level when the vent solenoid is opened. This means that before the fill solenoid was opened, the tank wasn't full.
When the tank is full, the nitrous pressure will spike when the fill solenoid is opened, and then drop to the original level when the vent solenoid is opened. This is the vapor pressure of nitrous at the liquid's current temperature.
Nitrous Oxide Fill Process (Normalized Data)
Vent
Fill
Liquid Level
Nitrous Pressure
This line represents the vapor pressure of nitrous oxide. If the tank is full, and the fill solenoid is opened, the pressure will return to this line once the tank is vented.
Based on the features of the liquid level and nitrous pressure plots, it can be inferred that this line represents the "full" level of the nitrous tank.
When tank is full and the fill solenoid is opened, the liquid level readout suddenly drops. It quickly recovers to the same level after the vent is opened.


LEGEND
Ball Valve
3-Way Ball Valve
Motorized Ball Valve
Needle Valve
Solenoid Valve
Check Valve
Pressure Relief Valve
Pressure Regulator
Remote Disconnect
Pressure Gauge
Pressure Transducer
Pressure Differential
Ethanol Fill Container
Flexible Hose
Nitrous Oxide
Ethanol
Nitrogen
N2 GAS
2000 PSI
850 PSI
50 PSI
FUEL TANK
750 PSI
OXIDIZER TANK
750 PSI
CC
400 PSI
1100 PSI
N2O LIQUID
N2O LIQUID
N2O LIQUID

MASA Liquid Engine Assembly SOP

Last Update: 3/9/18

Purpose: Pre-test assembly and post-test disassembly of the liquid engine

Combustion Chamber

- [ ] Insert retention ring into chamber with thick section pointed inward
- [ ] Insert nozzle bolts, aluminum standoffs on inside, and nut, and tighten (leave bolts reserved for connecting nitrous and fuel fill lines)
- [ ] Grease o-ring (039 on flight nozzle) and fit onto graphite insert. Then push insert into steel carrier.
- [ ] Grease two o-rings (247 or 248) and fit onto graphite to chamber o-ring grooves
- [ ] Slide nozzle assembly into chamber and push until seated on retention ring.
- [ ] Cut phenolic liner to length (7.81 in) and grease exterior surface. Slide into chamber. Ensure that phenolic is seated properly in grooves.
- [ ] Grease inner and outer manifold o-rings (030 and 033 respectively) and place into inner sealing grooves. Place o-ring (K238) in outer ox-path groove. Be sure to use krytox grease for this step.
- [ ] Insert injector, tighten with injector bolts. Be careful not to unseat o-rings. Check that transducer hole in endcap and injector are aligned.
- [ ] Grease two o-rings (246) and put onto chamber endcap.
- [ ] Insert injector endcap assembly into chamber, aligning markings on endcap with chamber, insert and tighten chamber bolts, (leave bolts reserved for connecting nitrous and fuel fill lines). The hole where the chamber pressure transducer is connected should be excluded.
- [ ] Double check all bolt tightnesses
- [ ] Attach chamber transducer to standoff then attach standoff to chamber end-cap. Teflon both threads.
- [ ] Attach ox manifold transducer. Be sure to Teflon threads.
- [ ] Attach fuel manifold fitting to endcap using 906 o-ring to seal
- [ ] Attach ox pipe fitting to ox manifold using 910 o-ring to seal

Ox Tank

- [ ] All grease used in these steps must be krytox
- [ ] Grease two o-rings (246) and place over ox tank top endcap.
- [ ] Insert endcap into tank while being careful not to knick o-rings. Use 24 shoulder bolts to secure endcap.
- [ ] Grease two o-rings (248) and place over ox tank bottom endcap.
- [ ] Insert endcap into tank while being careful not to knick o-rings. Use 24 shoulder bolts to secure endcap. Start with bolts closest to ⅞ in port.
- [ ] Double check tightness on all bolts

- ❏ Attach center fuel pipe pass through to top and bottom endcaps. Ensure fittings are tefloned.
- ❏ Tighten down pass through fuel pipe fittings on both ends
- ❏ Attach ox pipe fitting to bottom of endcap using 910 o-rings
- ❏ Attach ox fill pipe and DP fittings to bottom endcap with 906 o-rings

Fuel Tank

- ❏ Grease two o-rings (246) and place over fuel tank top endcap
- ❏ Insert endcap into tank while being careful not to knick o-rings. Use 24 shoulder bolts to secure endcap.
- ❏ Grease two o-rings (246) and place over fuel tank bottom endcap
- ❏ Insert endcap into tank while being careful not to knick o-rings. Use 24 shoulder bolts to secure endcap.
- ❏ Double check tightness on all bolts
- ❏ Attach Swagelok fitting to bottom center hole of fuel tank.
- ❏ Attach fuel tank pressure transducer to top of fuel tank. Use teflon on the threads.
- ❏ Attach a 4 and a 6 AN fitting to two other ports on top of tank. Use 906 o-rings to seal.

Ox Bay

- ❏ Attach t-fitting to fuel manifold fitting. Ensure copper flare seal is used
- ❏ Attach short pipes to ox valve
- ❏ Attach valve assembly to ox tank but only lightly tighten. Ensure copper seal is used
- ❏ Bring through pipe and ox pipe into contact with respective chamber ports ensure both connections have copper flare seals. Do not tighten fully only light hand tightening.
- ❏ Attach all 3 ox bay ribs at 120 degree intervals demarcated by sharpie marks on tanks. Ribs will be numbered to denote position. Ensure ribs align up on ox and fuel bays.
- ❏ Rotate valve into correct orientation and tighten ox tank side fitting fully
- ❏ Tighten down chamber side ox and fuel pipe fittings.
- ❏ Attach 1600 PSI pressure transducer to rotational fitting. Ensure threads are tefloned.
- ❏ Cap rotational fitting. Ensure copper flare seal is used.
- ❏ Attach fuel manifold transducer assembly to t-fitting. Ensure copper flare seal is used. Ensure transducer position is satisfactory.
- ❏ Ensure that wires are run to the correct position; particularly the potentiometer circular connector.
- ❏ Attach NPT to pipe adapters on each side of DP sensor.
- ❏ Attach orientation pipe to dp sensor. And then attach orientation pipe to ox tank dp fitting. Ensure sensor positioning is satisfactory.

Fuel Bay

- ❏ Connect fuel valve to bottom of fuel tank

- ❏ Use ribs to align fuel and ox tanks and keep proper distance. Bring fuel through pipe up to valve and ensure proper length. Use swagelok fitting on valve to connect pipe to valve.
- ❏ Check measurement on dip tube then insert dip tube to appropriate depth in tank and lock it into place in diptube pass through fitting.
- ❏ Attach T-fitting to top of dip tube. One side should be ⅛ NPT, the other should be a swagelok nut.
- ❏ On swagelok side of T-fitting, attached U-shaped pipe for pressure relief valve.
- ❏ Attach the pressure relief valve to the end of the U-shaped pipe
- ❏ Teflon NPT threads on T-fitting and then attach vent solenoid to said fitting. Ensure directionality is correct.

Top Bay

- ❏ Connect npt

External Pipe Runs

- ❏ Dp pipe
- ❏ Fuel pipe
- ❏ Ox pipe

Payload Assembly SOP:

Acrylic Chambers

- ❏ Start with the 3.5”x3.5” piece and the insert the 3.5”x6” into the slots that go across on the length of the 3.5”x3.5” piece.
- ❏ Then take the 1.75”x6” piece and insert it perpendicular to both of the pieces so that its ridges fit into the slots that exist on both of the other pieces.
- ❏ Once the edges are aligned and the pieces are perpendicular to one another, apply the acrylic glue into the gap to secure them in place.
- ❏ Then place the last 3.5”x1.75” piece on top of the pieces, fitting it into place. Make sure the big holes line up with the bottom. Glue as well.

Cameras

- ❏ Screw a 2-56 bolt through both of camera mounts attaching them to one of 2-56 holes in the smallest metal piece and the one of the 2-56 holes in the bigger metal piece.
- ❏ Make sure the cameras are charged and have SD cards and then mount the cameras

Metal Box

- ❏ Assemble the boxes with 5 of the sides, leaving one off one of front pieces (bigger pieces with no tapped holes)
- ❏ Make sure the holes in the top and bottom are aligned with how the acrylic holes will placed (read ahead to see how the holes will be aligned.

Electronics

- ❏ Velcro the electronic breakout board and the batteries to the bottom of the box out of the way of the thru holes (opposite side of the camera mounted on the smaller metal piece) DO NOT CONNECT THE BATTERY YET

Acrylic Chamber

- ❏ Place the acrylic into the box with the chambers facing outwards, on the opposite side of the camera

Metal Box

- ❏ Make sure the holes and on the bottom are aligned with the holes in the acrylic.
- ❏ Place an ematch and a petroleum jelly coated cotton ball in each of the acrylic chambers (DO NOT CONNECT THE E-MATCHES YET)
- ❏ Place the front back onto the box and screw on. DO NOT FORCE THE SCREWS SO YOU DO NOT BREAK THE ACRYLIC.

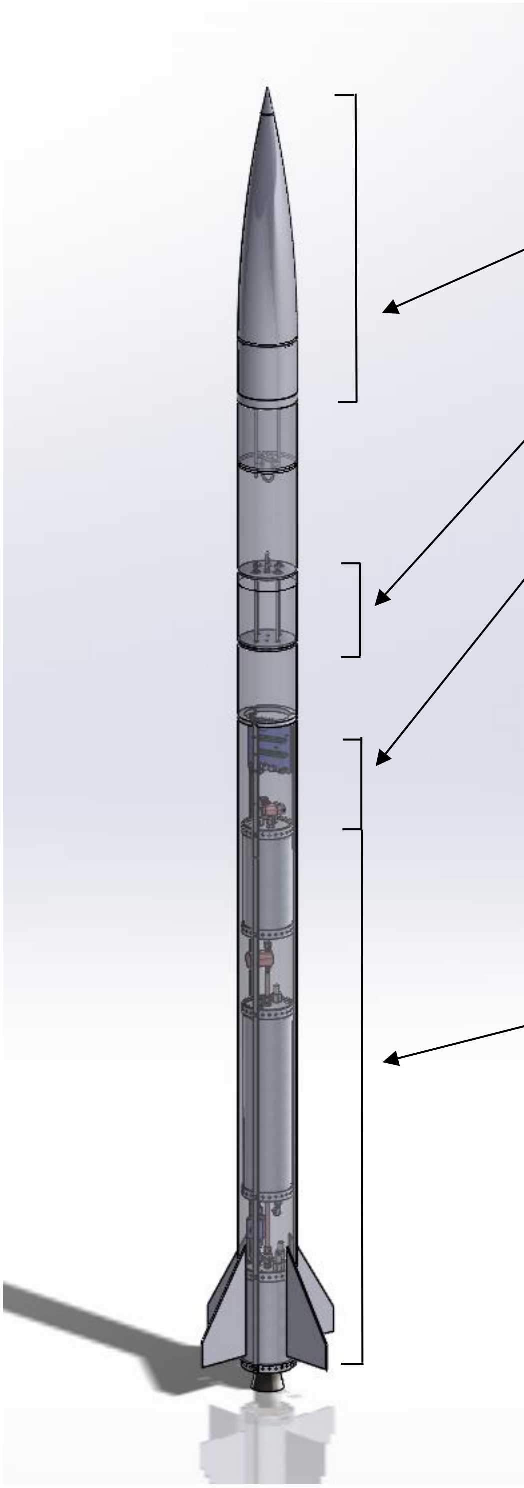
Get the Payload weighted at this time

Metal Box

- ❏ Fit the threaded rods through the box stopping before the acrylic to put a nut on and then a nut on after the acrylic, sandwiching the acrylic at every point where the threaded rod crosses the acrylic.
- ❏ Connect the e-matches to the breakout board and place the heads on top of the cotton balls.
- ❏ Before you finish, lay the box on its side. Turn the cameras on and then plug in the battery. FROM NOW, MAKE SURE THE PAYLOAD STAYS ON ITS SIDE AND MAKE SURE YOU KNOW WHICH SIDE IS UP (THE SIDE WITH CAMERA OPPOSITE OF THE ELECTRONICS)

Appendix F: Engineering Drawings

Attached are the engineering drawings which define the subsections of *Laika*. Below is the organization of the documents and how they relate to the overall assembly. The following list of drawings is the order in which they appear in Appendix F.



Rocket assembly

Fin

Fin can assembly

Nose cone assembly

Payload bay assembly

Payload front

Payload side

Payload bottom

Engine controller schematics

Propulsion stack assembly

Combustion chamber assembly

Injector plate

Oxidizer tank tube

Fuel tank tube

Combustion chamber tube

Oxidizer tank bottom endcap

Oxidizer tank top endcap

Fuel tank top endcap

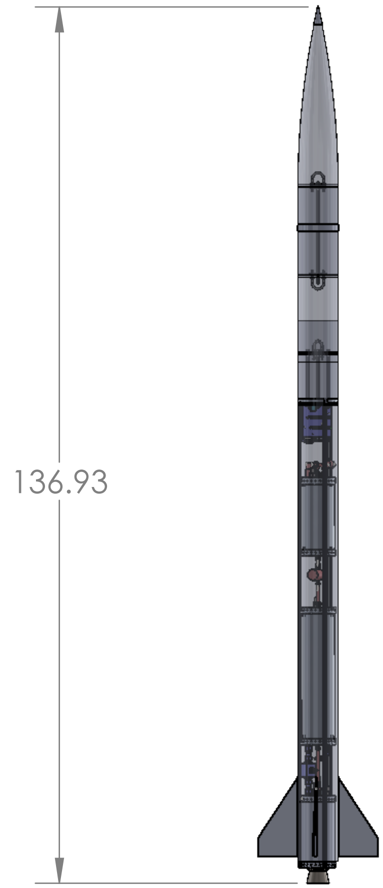
Fuel tank bottom endcap

Chamber endcap manifold

Graphite nozzle section

Steel nozzle section

Nozzle retention ring



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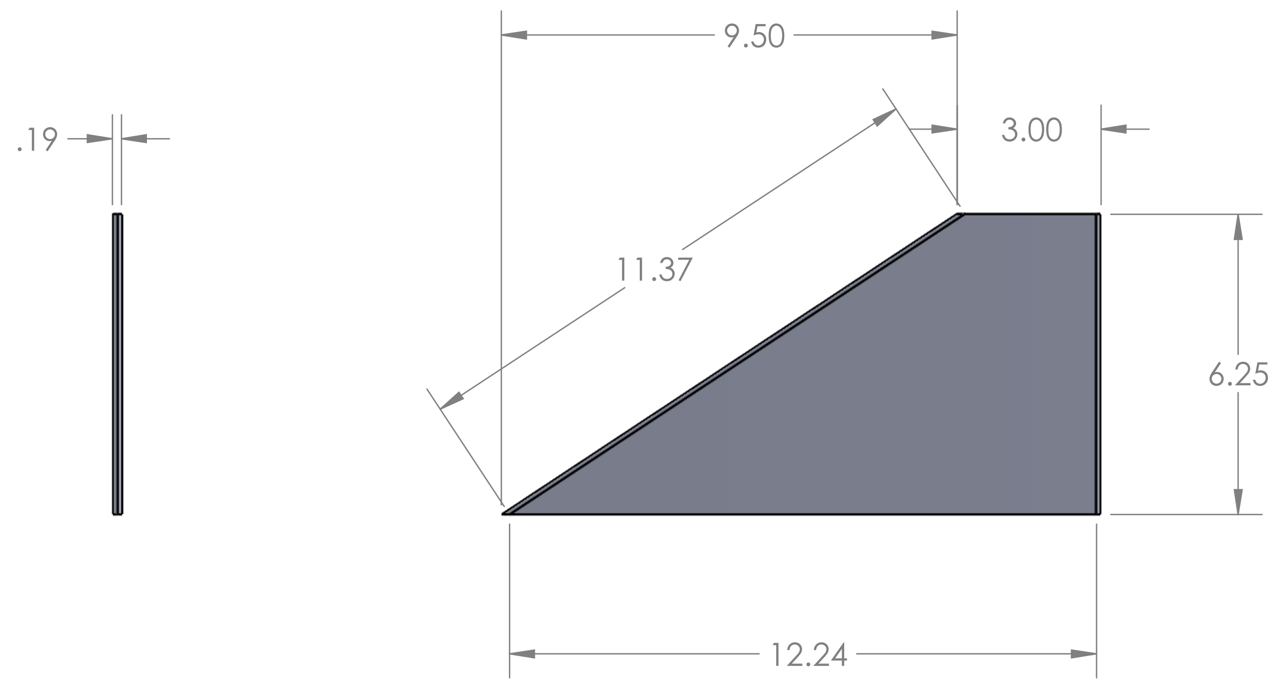

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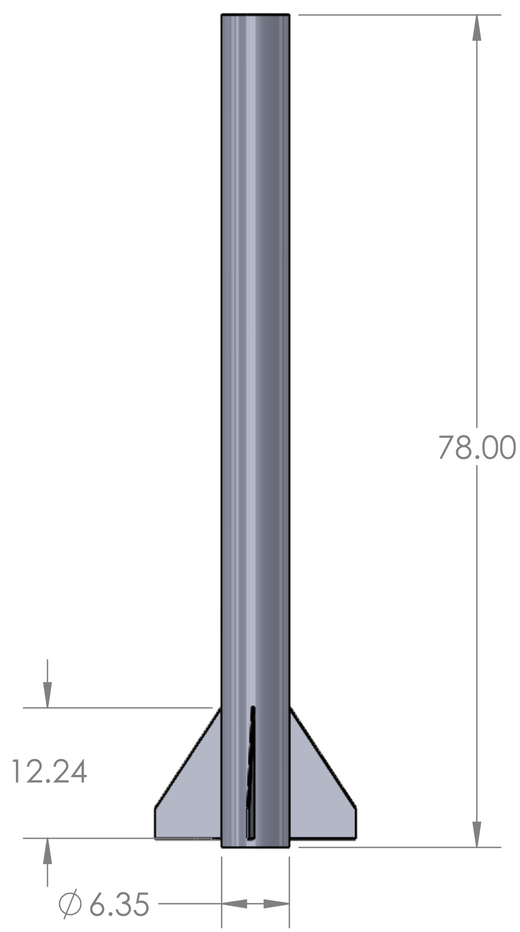

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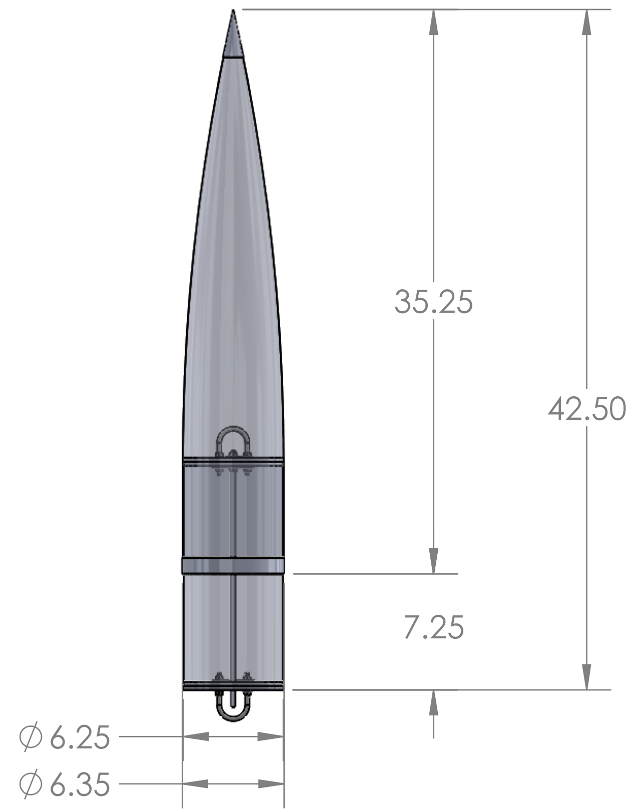

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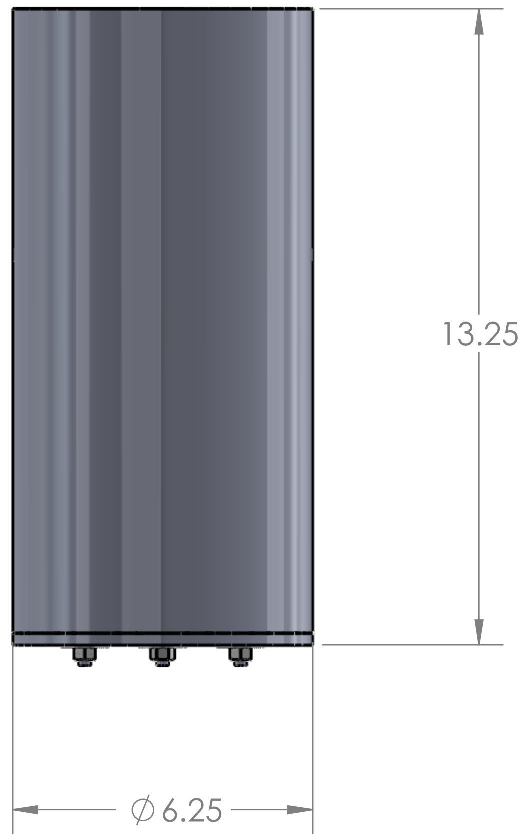

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MFG APPR.		
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A	payload	

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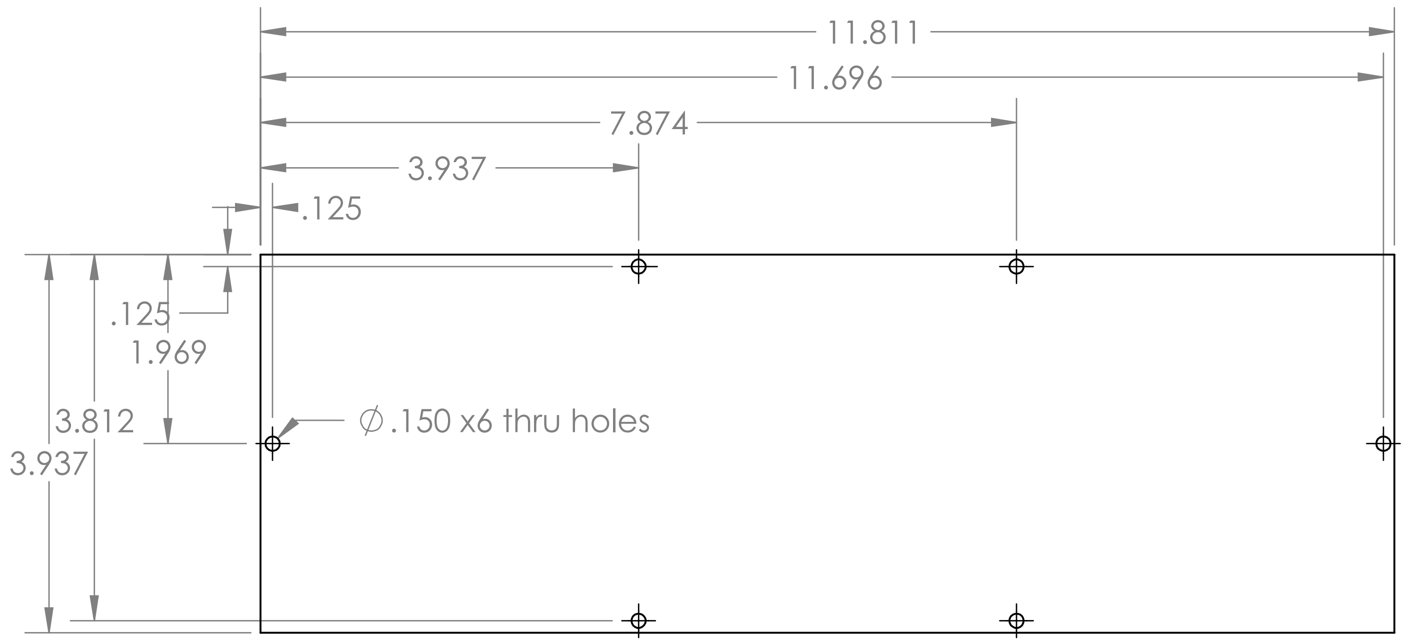

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SIZE	DWG. NO.	REV
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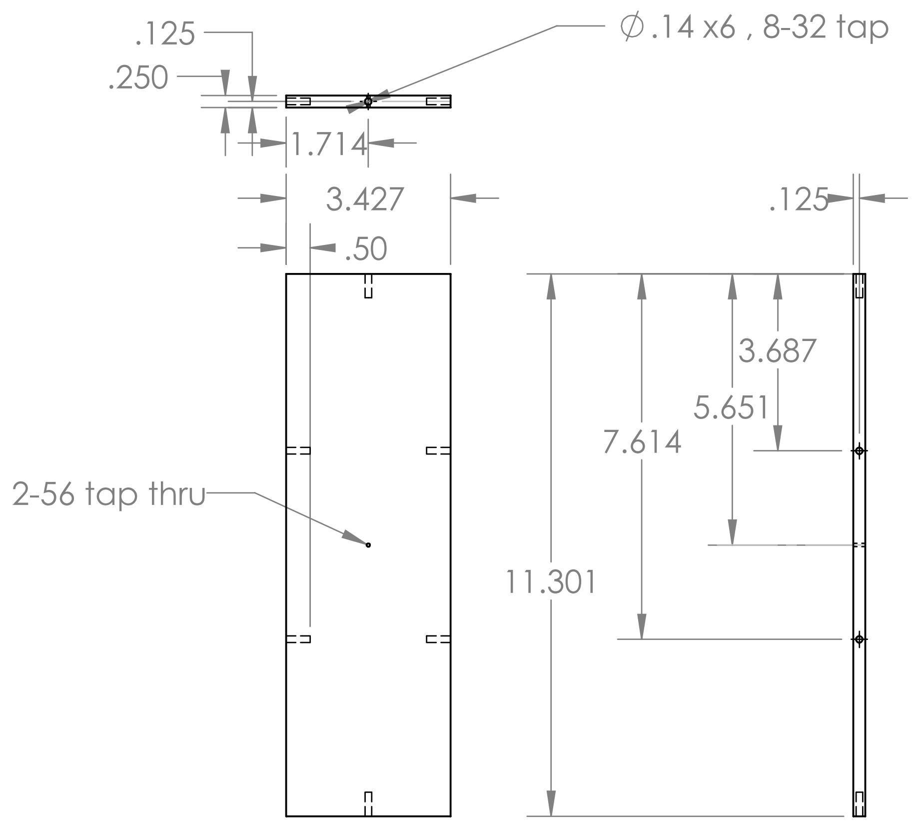
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

2 1



PROPRIETARY AND CONFIDENTIAL

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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

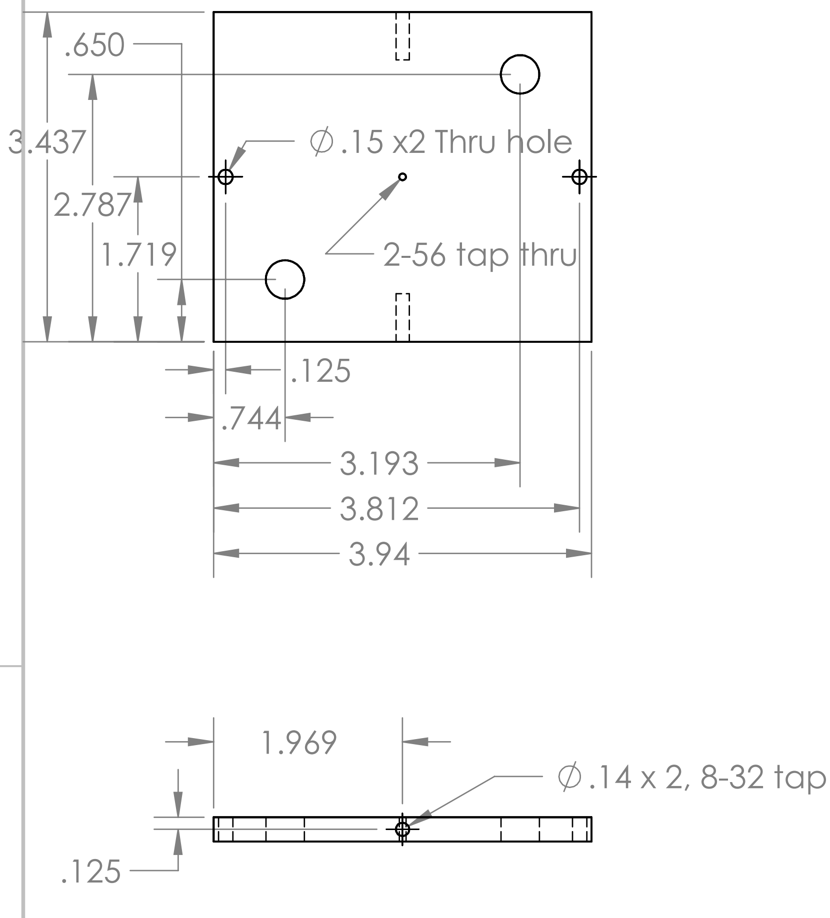
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	Side	

SCALE: 1:4 WEIGHT: SHEET 1 OF 1



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.		

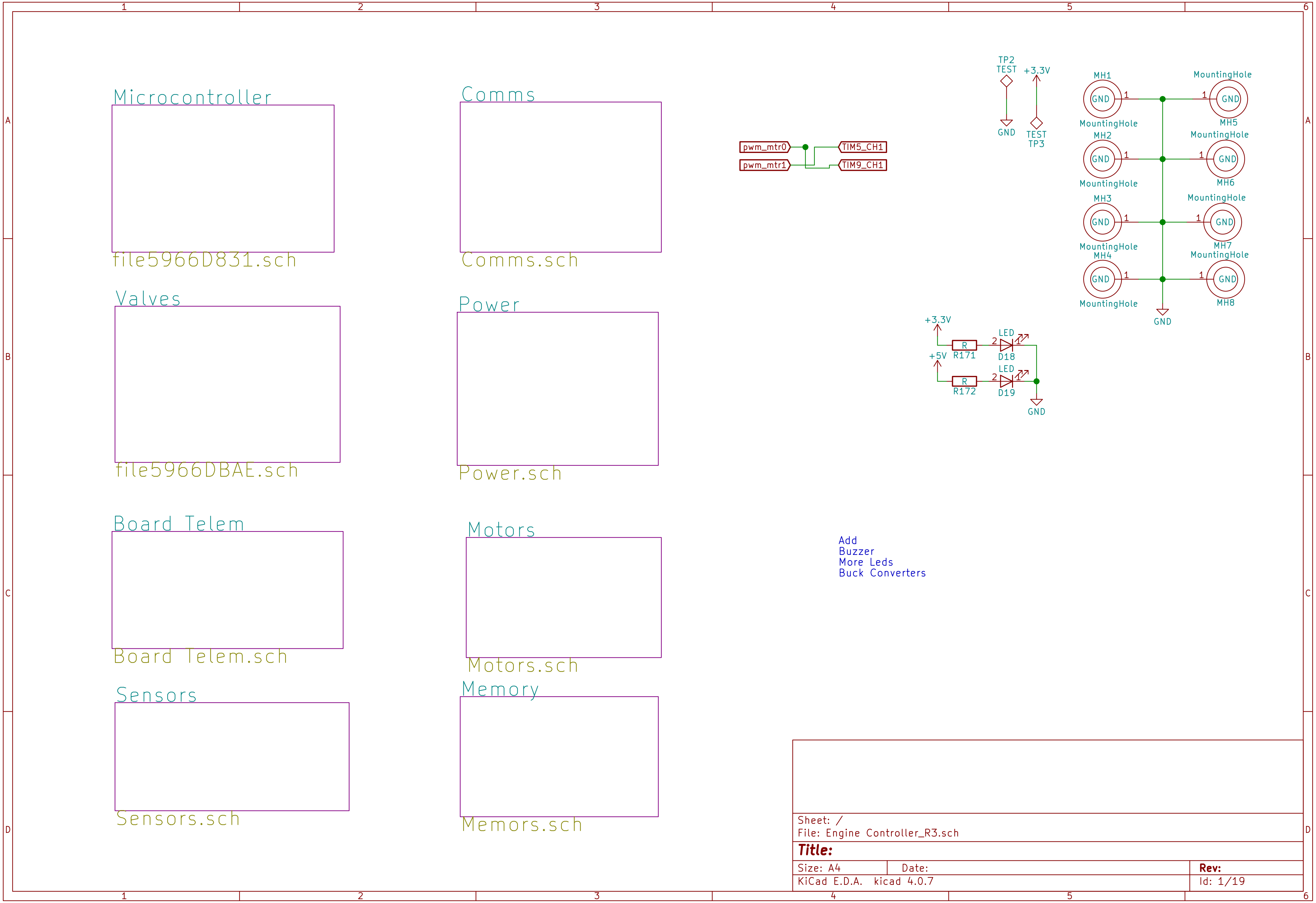
COMMENTS:

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE **A** DWG. NO. topbottom REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1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file5966D831.sch
Comms
Comms.sch
Valves
file5966DBAE.sch
Power
Power.sch
Board Telem
Board Telem.sch
Motors
Motors.sch
Sensors
Sensors.sch
Memory
Memors.sch
pwm_mtr0
pwm_mtr1
TIM5_CH1
TIM9_CH1
TP2
TEST
GND
+3.3V
TEST
TP3
MH1
MountingHole
MH2
MountingHole
MH3
MountingHole
MH4
MountingHole
MH5
MountingHole
MH6
MountingHole
MH7
MountingHole
MH8
GND
+3.3V
R
R171
LED
D18
+5V
R
R172
LED
D19
GND
Add
Buzzer
More Leds
Buck Converters
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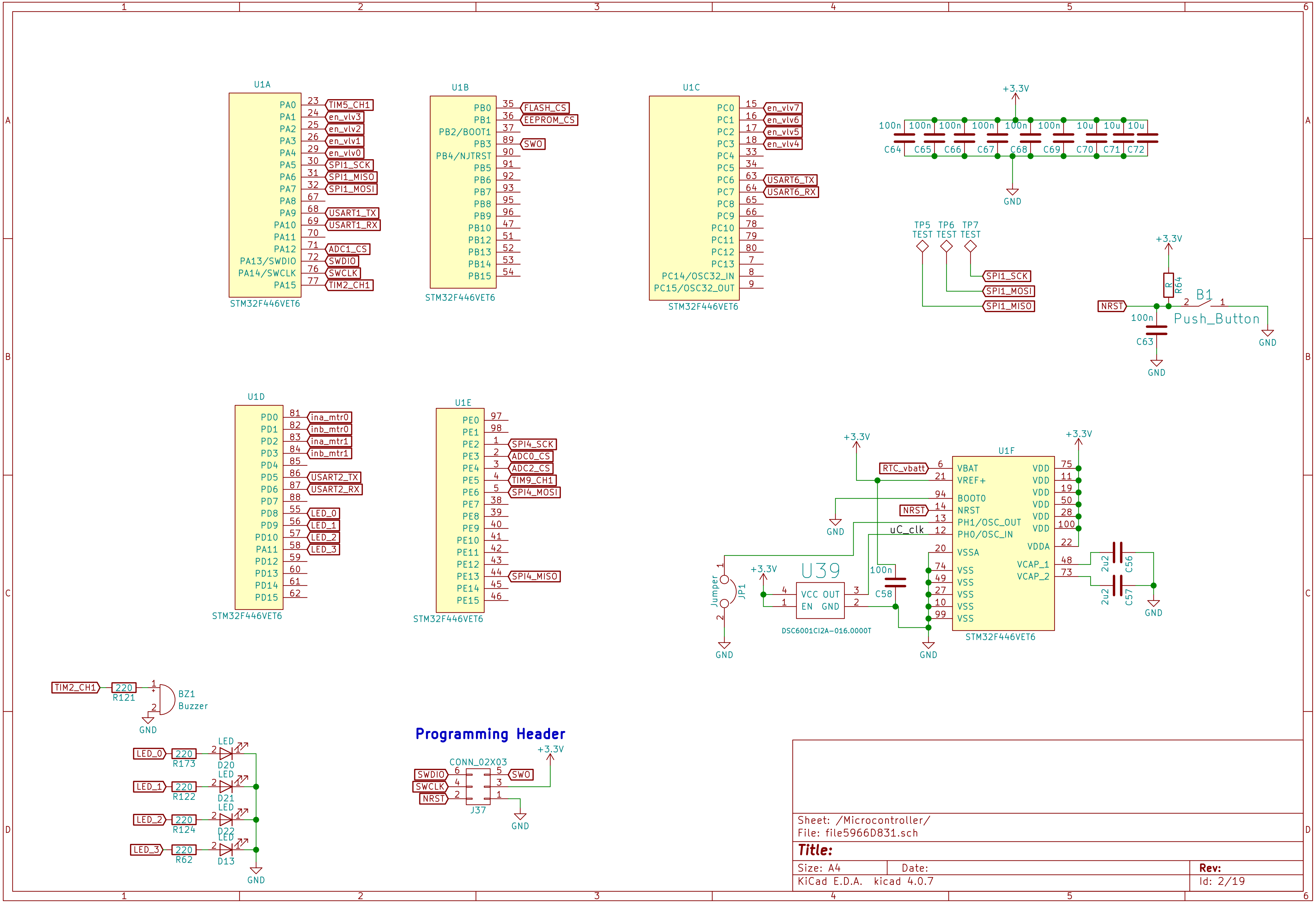
Title:
Size: A4
Date:
Rev:
KiCad E.D.A. kicad 4.0.7
Id: 1/19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PA0 23 TIM5_CH1
PA1 24 en_vlv3
PA2 25 en_vlv2
PA3 26 en_vlv1
PA4 29 en_vlv0
PA5 30 SPI1_SCK
PA6 31 SPI1_MISO
PA7 32 SPI1_MOSI
PA8 67
PA9 68 USART1_TX
PA10 69 USART1_RX
PA11 70
PA12 71 ADC1_CS
PA13/SWDIO 72 SWDIO
PA14/SWCLK 76 SWCLK
PA15 77 TIM2_CH1
STM32F446VET6
U1B
PB0 35 FLASH_CS
PB1 36 EEPROM_CS
PB2/BOOT1 37
PB3 89 SWO
PB4/NJTRST 90
PB5 91
PB6 92
PB7 93
PB8 95
PB9 96
PB10 47
PB12 51
PB13 52
PB14 53
PB15 54
STM32F446VET6
U1C
PC0 15 en_vlv7
PC1 16 en_vlv6
PC2 17 en_vlv5
PC3 18 en_vlv4
PC4 33
PC5 34
PC6 63 USART6_TX
PC7 64 USART6_RX
PC8 65
PC9 66
PC10 78
PC11 79
PC12 80
PC13 7
PC14/OSC32_IN 8
PC15/OSC32_OUT 9
STM32F446VET6
+3.3V
100n 100n 100n 100n 100n 100n 10u 10u 10u
C64 C65 C66 C67 C68 C69 C70 C71 C72
GND
TP5 TP6 TP7
TEST TEST TEST
SPI1_SCK
SPI1_MOSI
SPI1_MISO
+3.3V
R R64
B1
NRST 2 1
100n
Push_Button
C63
GND
GND
U1D
PD0 81 ina_mtr0
PD1 82 inb_mtr0
PD2 83 ina_mtr1
PD3 84 inb_mtr1
PD4 85
PD5 86 USART2_TX
PD6 87 USART2_RX
PD7 88
PD8 55 LED_0
PD9 56 LED_1
PD10 57 LED_2
PA11 58 LED_3
PD12 59
PD13 60
PD14 61
PD15 62
STM32F446VET6
U1E
PE0 97
PE1 98
PE2 1 SPI4_SCK
PE3 2 ADC0_CS
PE4 3 ADC2_CS
PE5 4 TIM9_CH1
PE6 5 SPI4_MOSI
PE7 38
PE8 39
PE9 40
PE10 41
PE11 42
PE12 43
PE13 44 SPI4_MISO
PE14 45
PE15 46
STM32F446VET6
+3.3V
+3.3V
U1F
RTC_vbatt 6 VBAT
21 VREF+
94 BOOT0
NRST 14 NRST
13 PH1/OSC_OUT
uC_clk 12 PH0/OSC_IN
20 VSSA
74 VSS
49 VSS
27 VSS
10 VSS
99 VSS
VDD 75
VDD 11
VDD 19
VDD 50
VDD 28
VDD 100
VDDA 22
VCAP_1 48
VCAP_2 73
2u2 C56
2u2 C57
STM32F446VET6
GND
GND
GND
GND
Jumper JP1
+3.3V
U39
VCC OUT
EN GND
DSC6001CI2A-016.0000T
100n
C58
TIM2_CH1 220 R121
BZ1 Buzzer
GND
LED_0 220 R173 LED D20
LED_1 220 R122 LED D21
LED_2 220 R124 LED D22
LED_3 220 R62 LED D13
GND
Programming Header
CONN_02X03
+3.3V
SWDIO 6 5 SWO
SWCLK 4 3
NRST 2 1
J37
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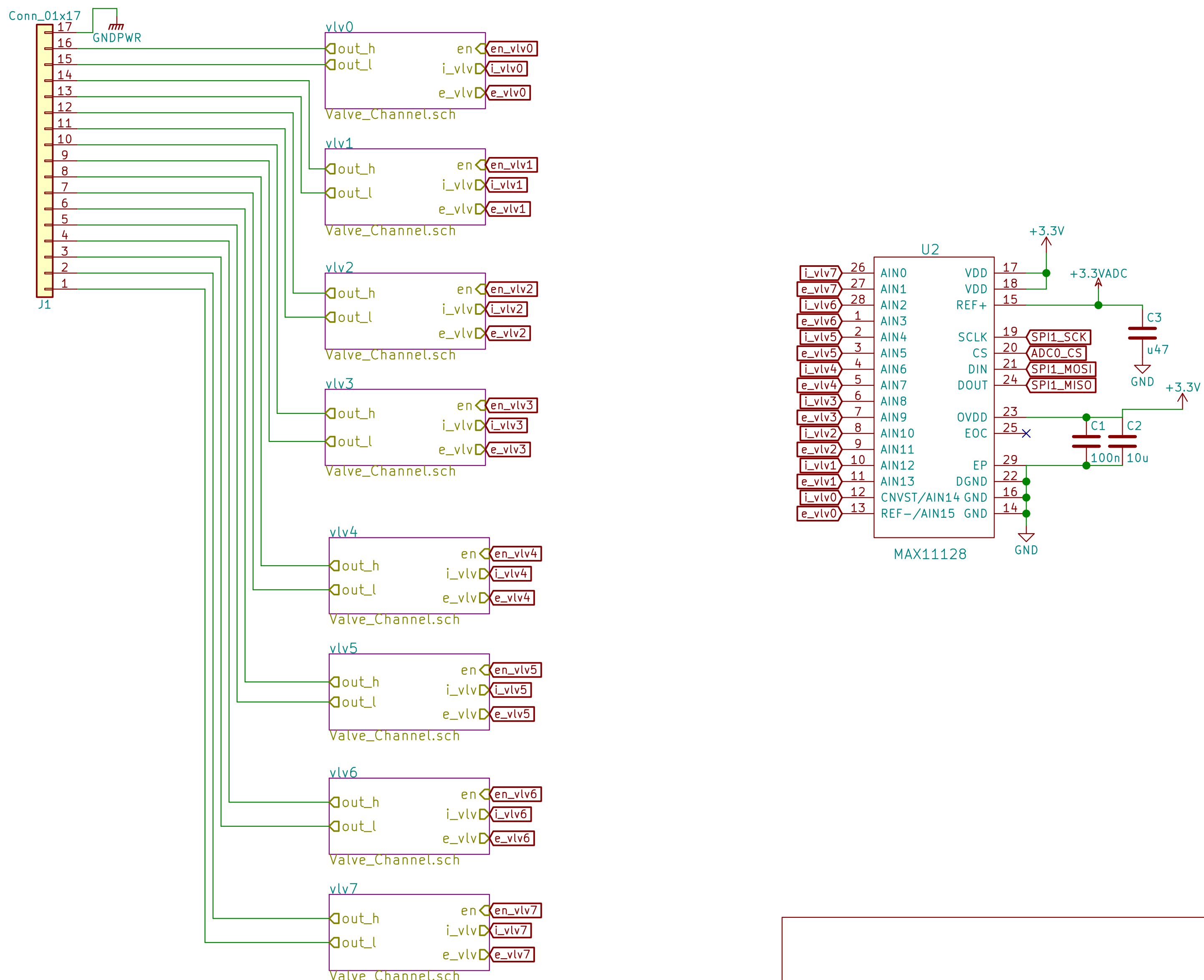
Size: A4 Date: Rev:
KiCad E.D.A. kicad 4.0.7 Id: 2/19



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Size: A	Date:	**Rev:**
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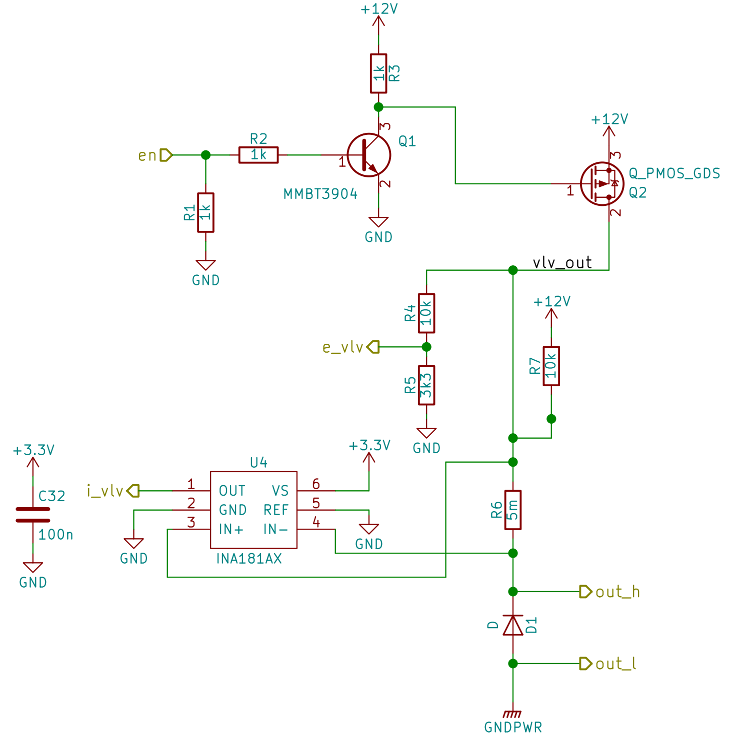

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Size: A4	Date:	**Rev:**
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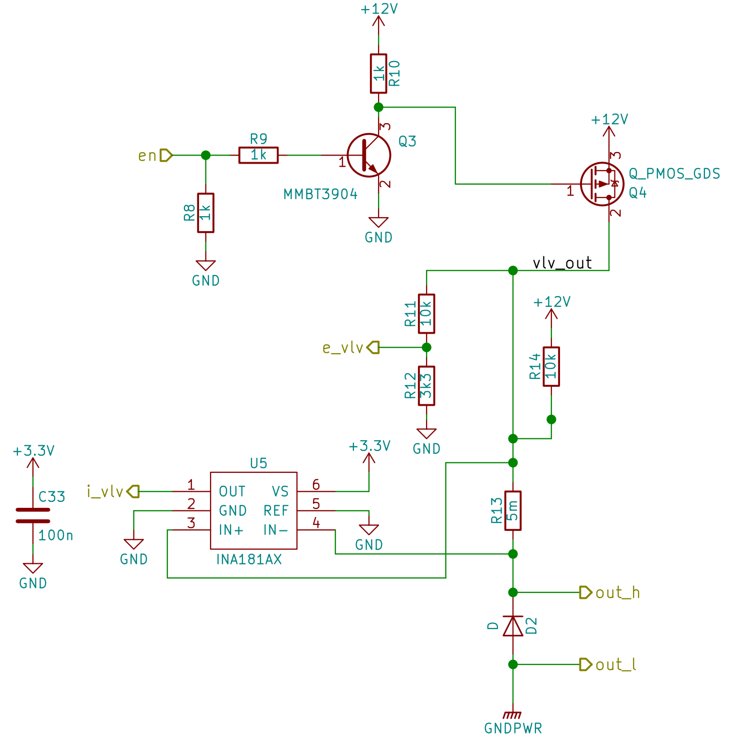

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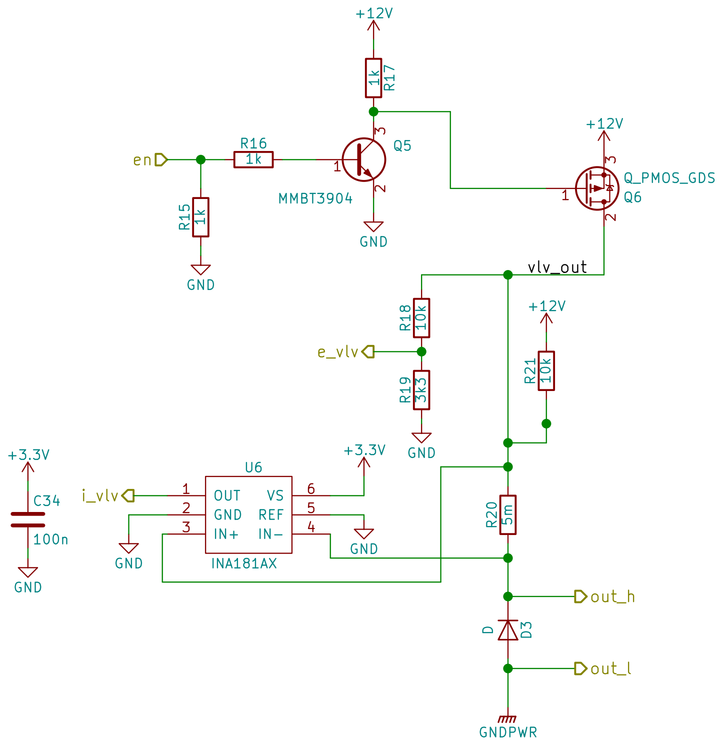

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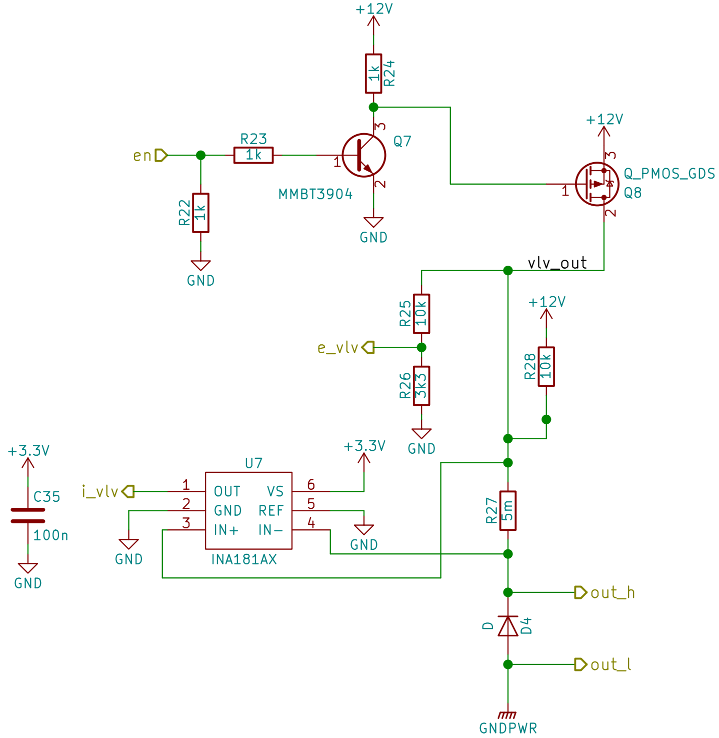

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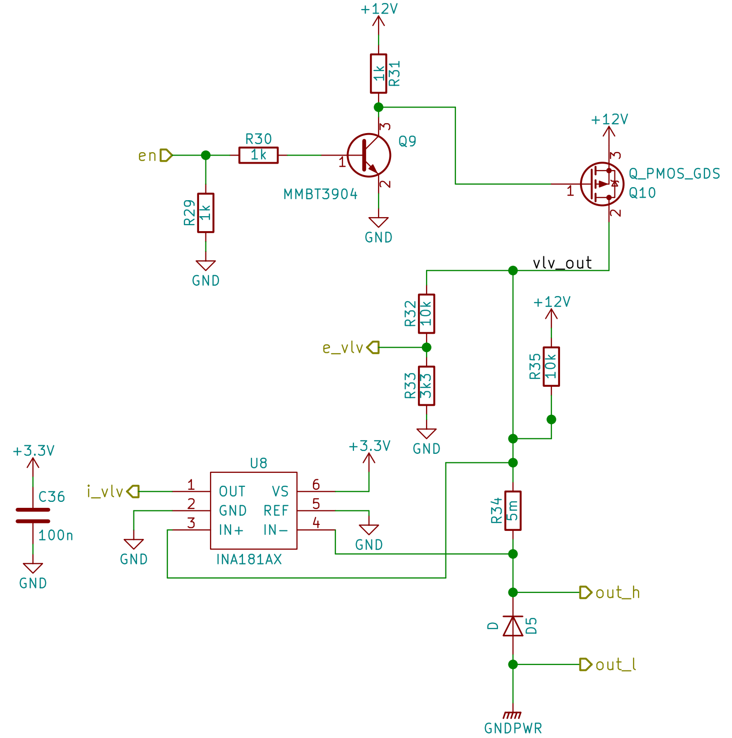

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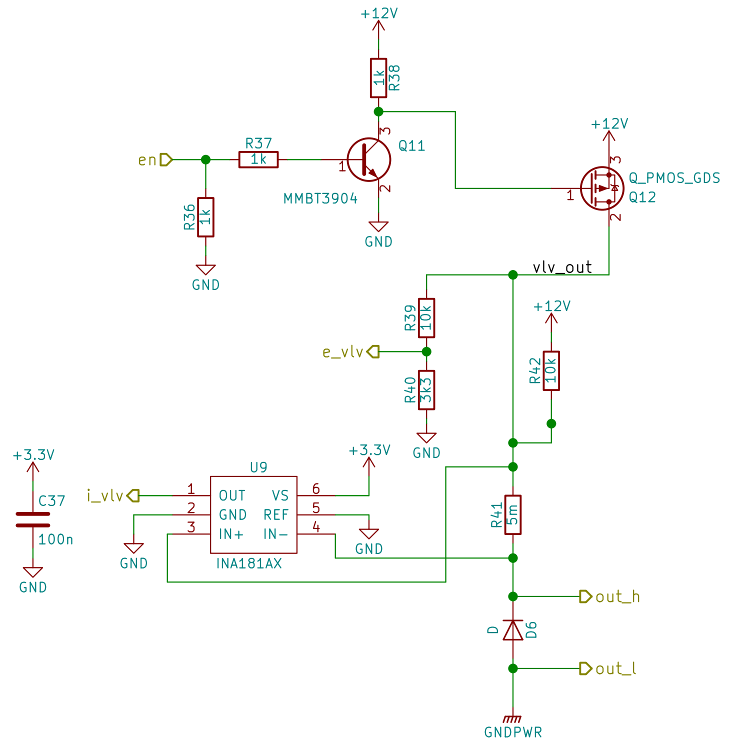

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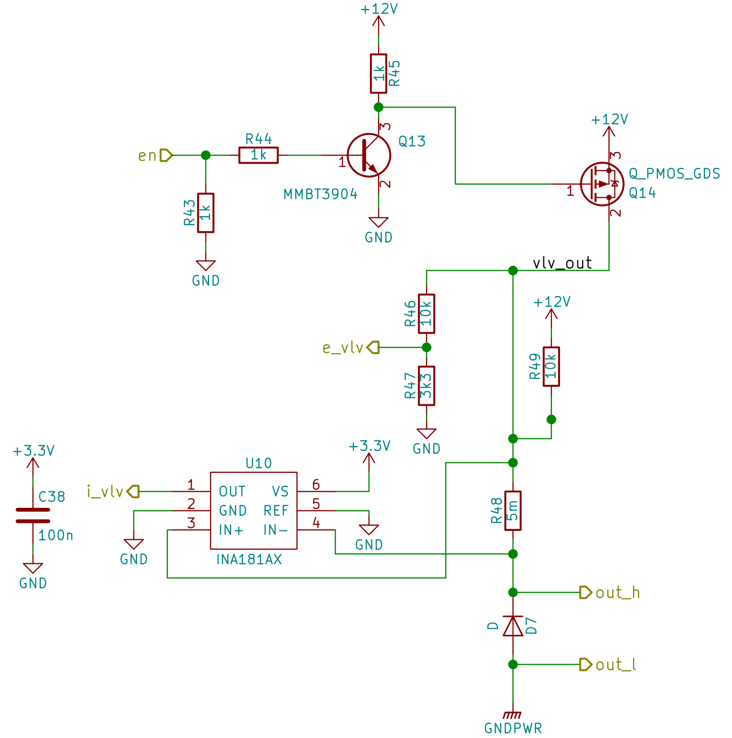

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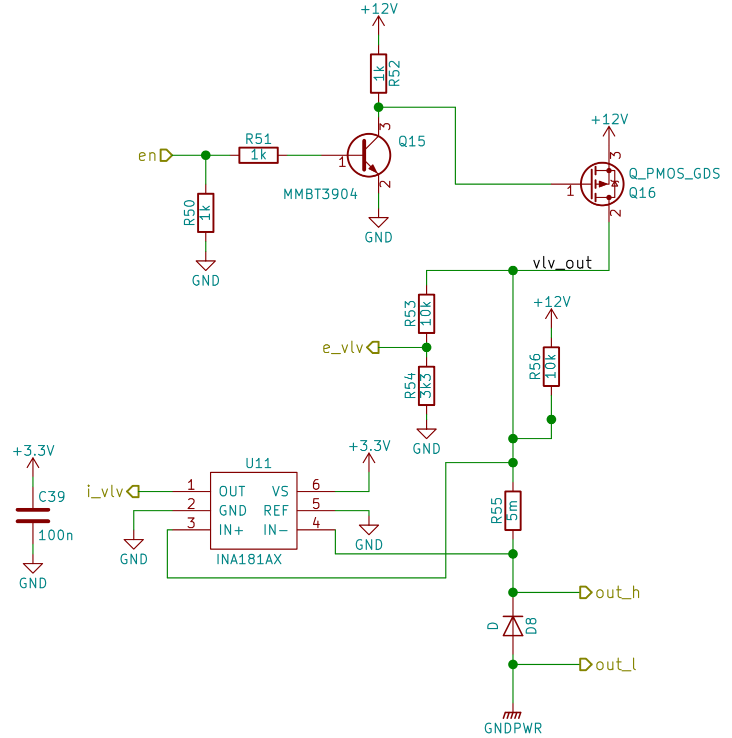

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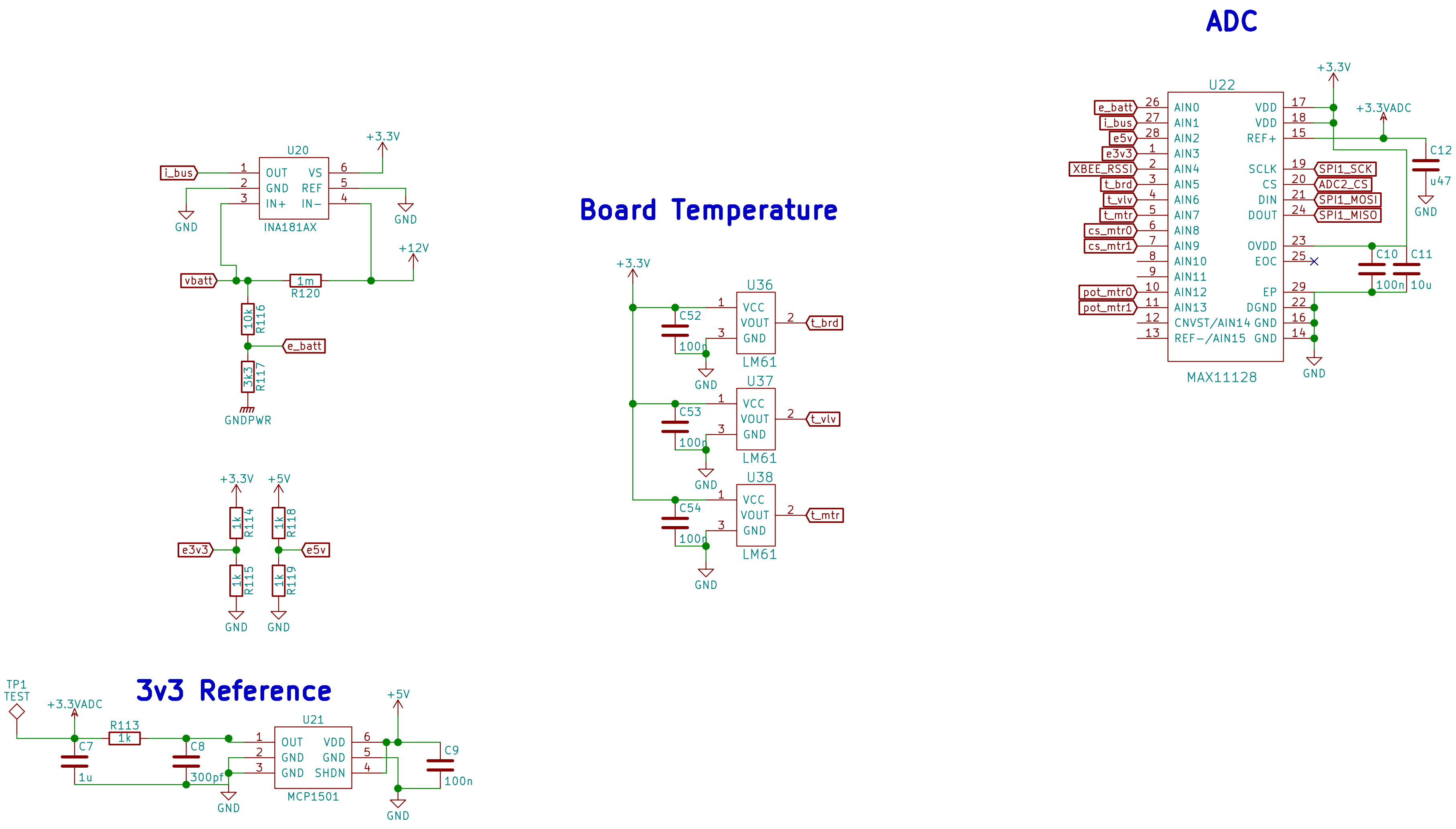

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Size: A4 Date: **Rev:**

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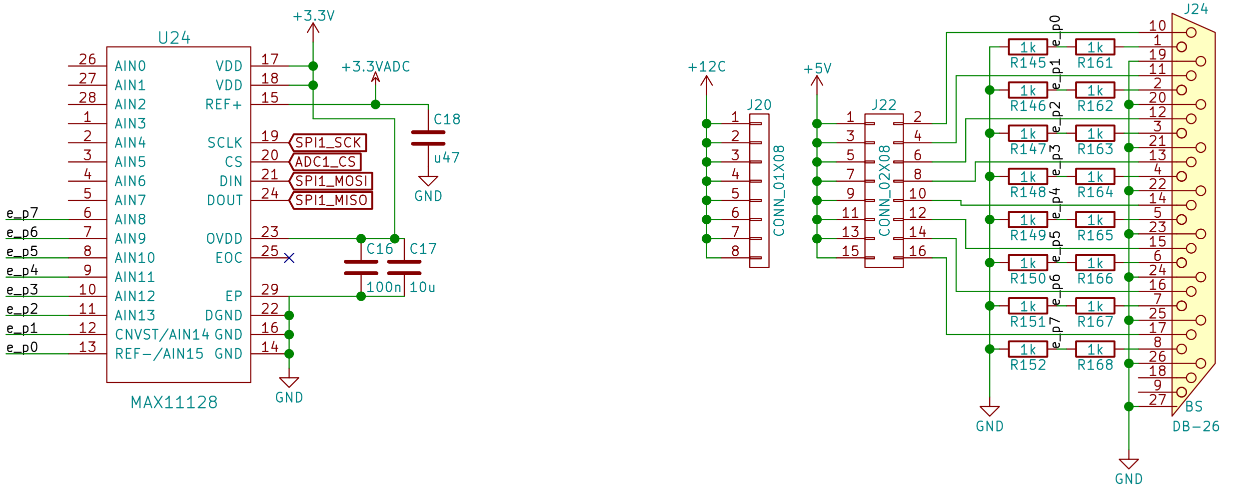

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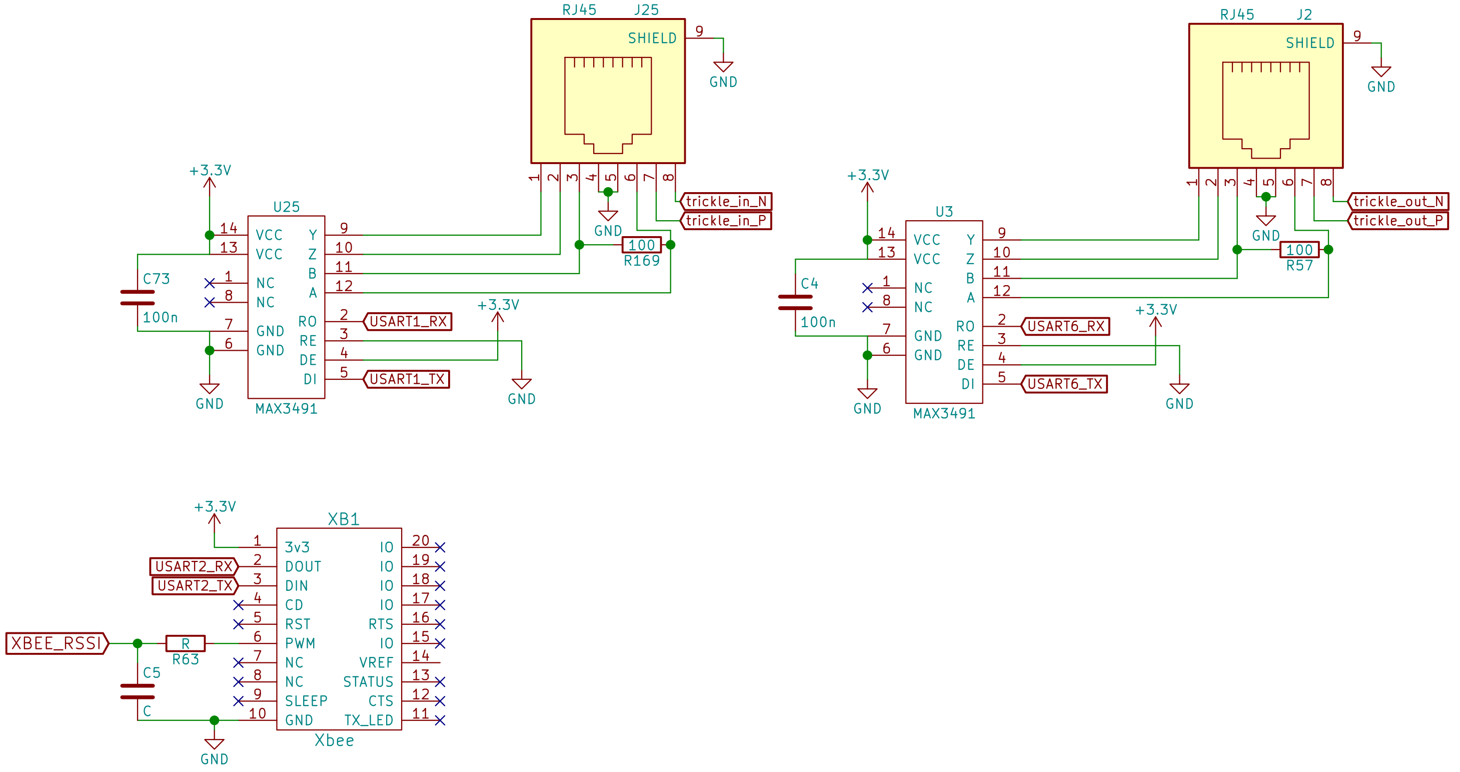

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Size: A4 | Date: | **Rev:**

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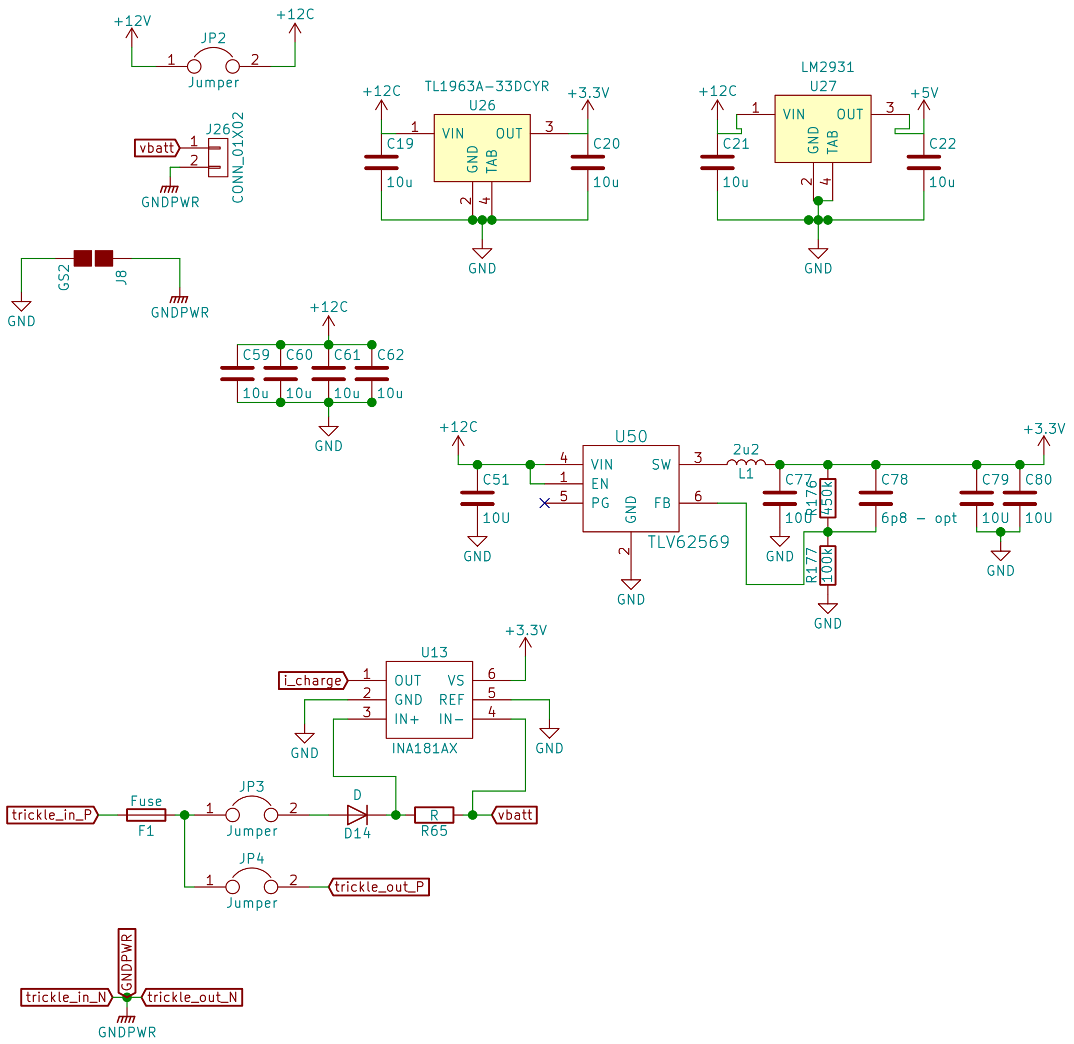

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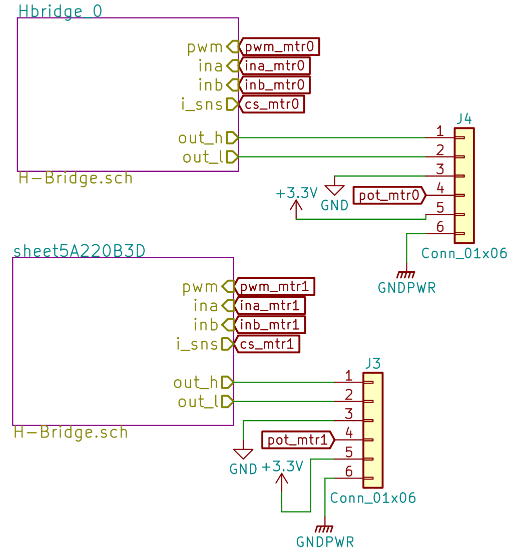
Size: A4 | Date: | **Rev:**

KiCad E.D.A. kicad 4.0.7 | Id: 15/19



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Size: A4 | Date: | **Rev:**

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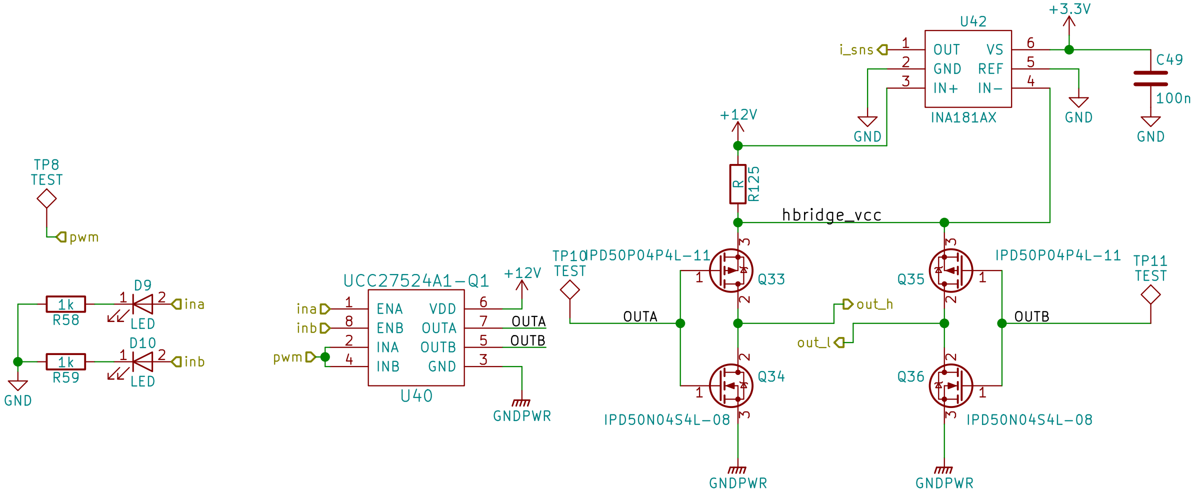

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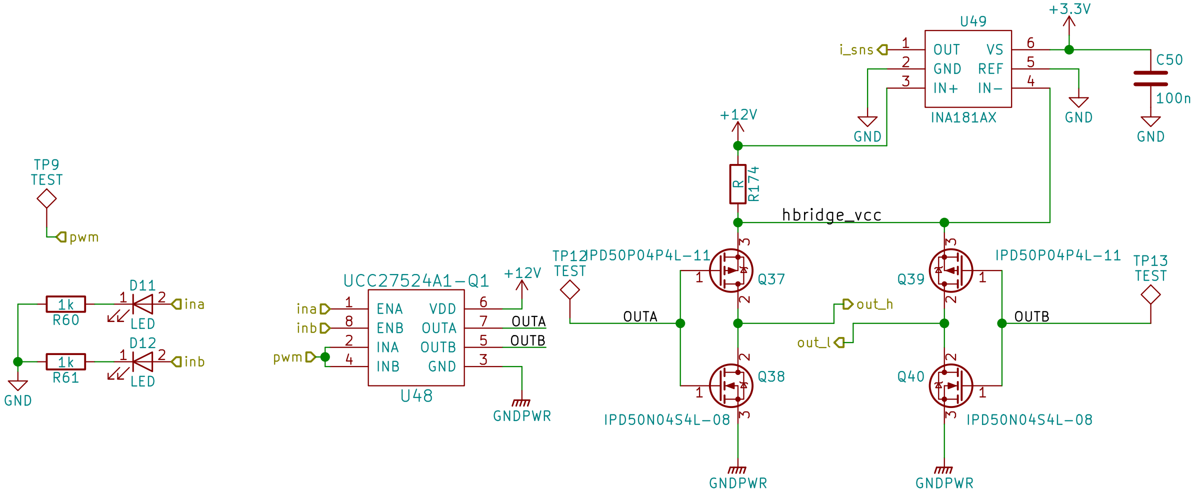

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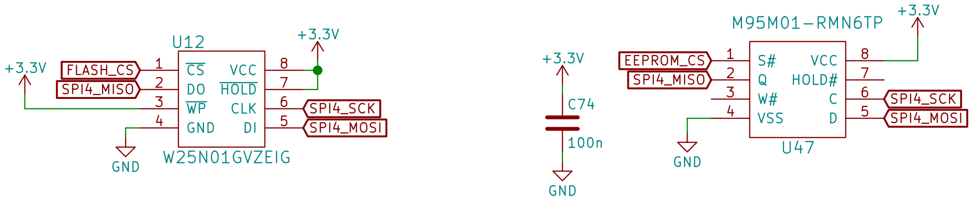

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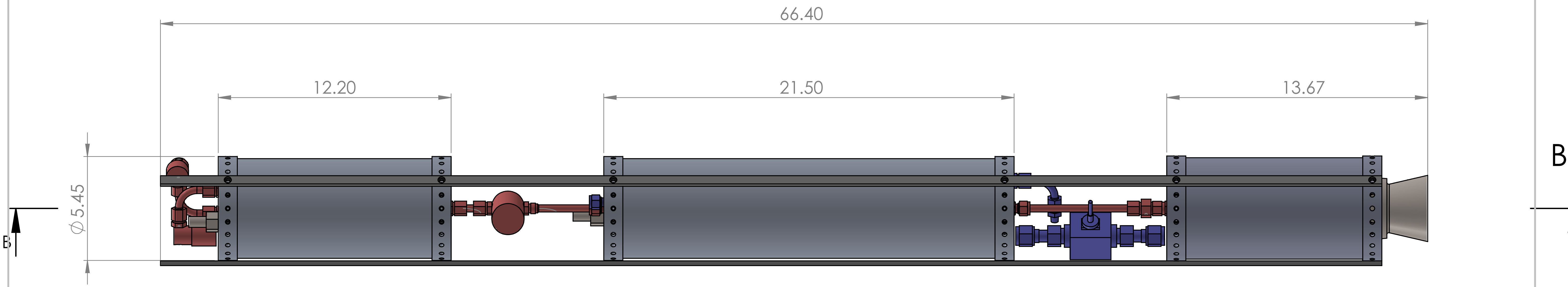
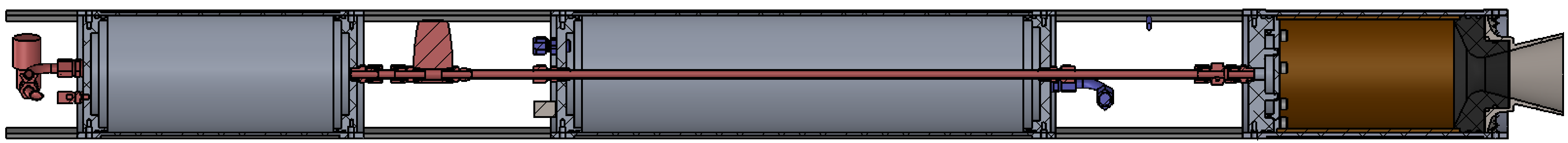
Size: A4 Date: **Rev:**

KiCad E.D.A. kicad 4.0.7 Id: 19/19





SECTION B-B
SCALE 1 : 5

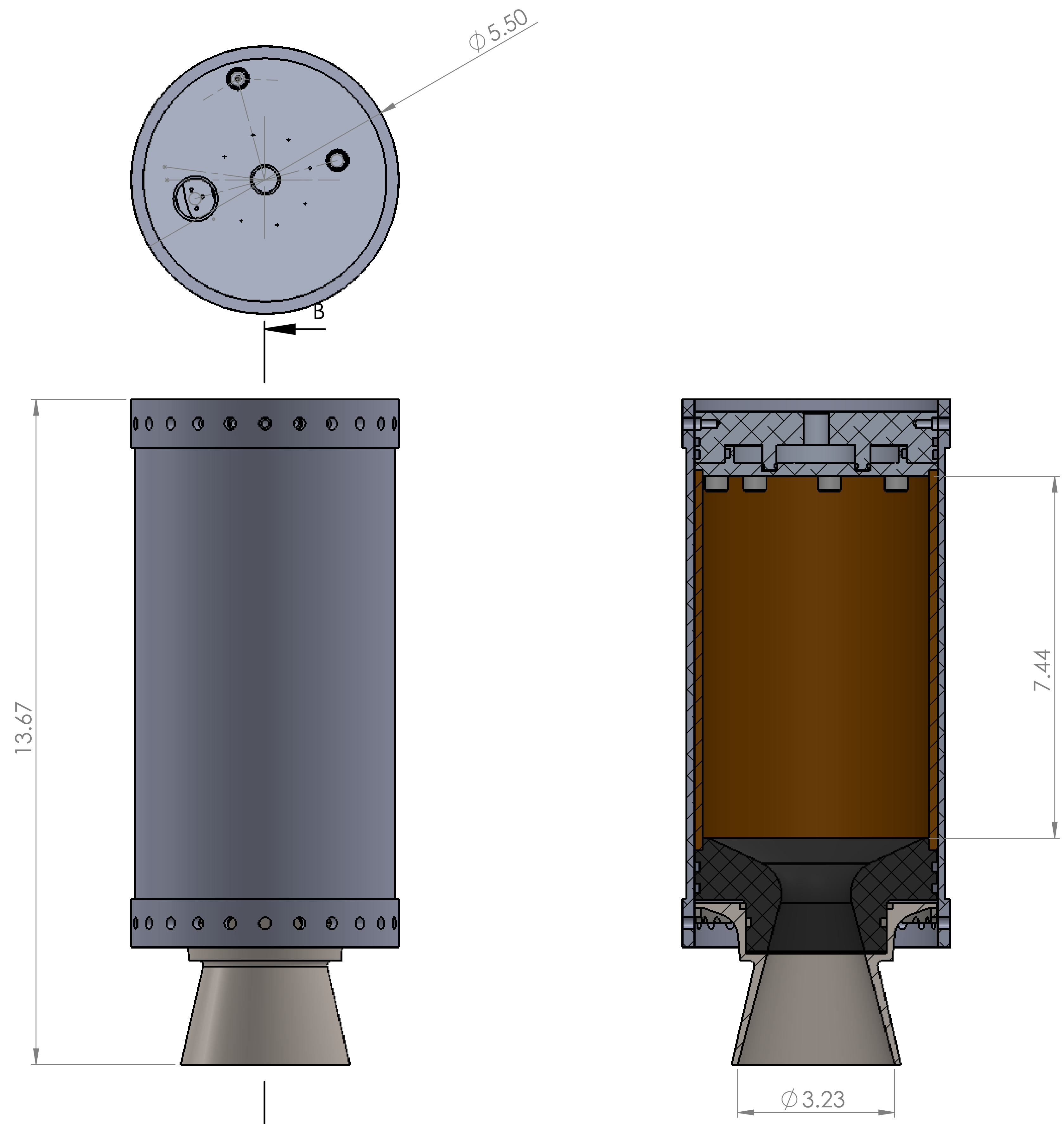
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES:	DRAWN	X.XXX	X.X.XX
	DESIGNER SIGN-OFF	X.XXX	X.X.XX
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX

TITLE:

Propulsion Stack

DWG. NO.	REV
XXX	C

SCALE: 1:20	WEIGHT: XXX	SHEET 1 OF 1



SECTION B-B
SCALE 1 : 2.5

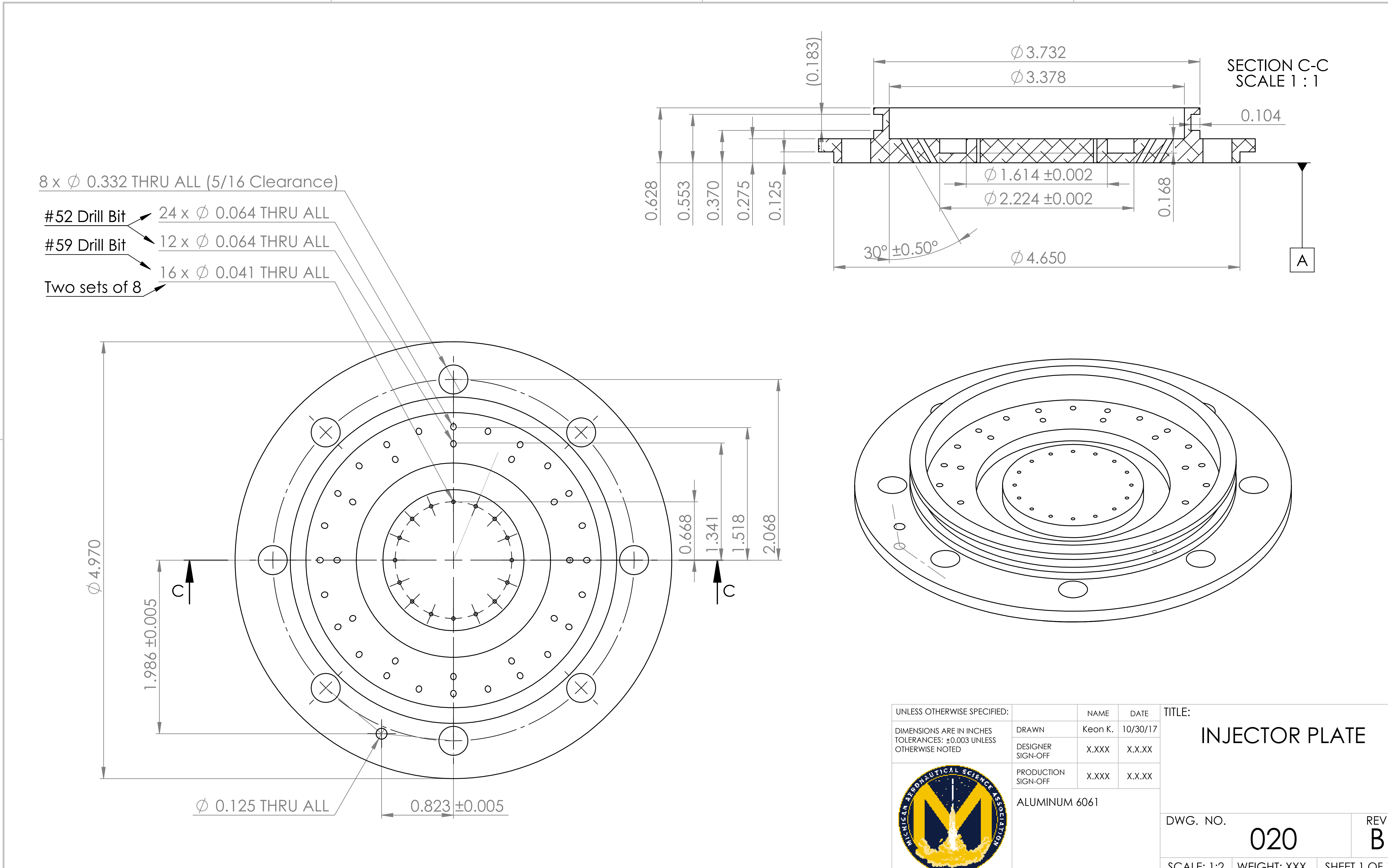
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES:	DRAWN	X.XXX	X.X.XX
	DESIGNER SIGN-OFF	X.XXX	X.X.XX
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX
	ALUMINUM XXXX		

TITLE:

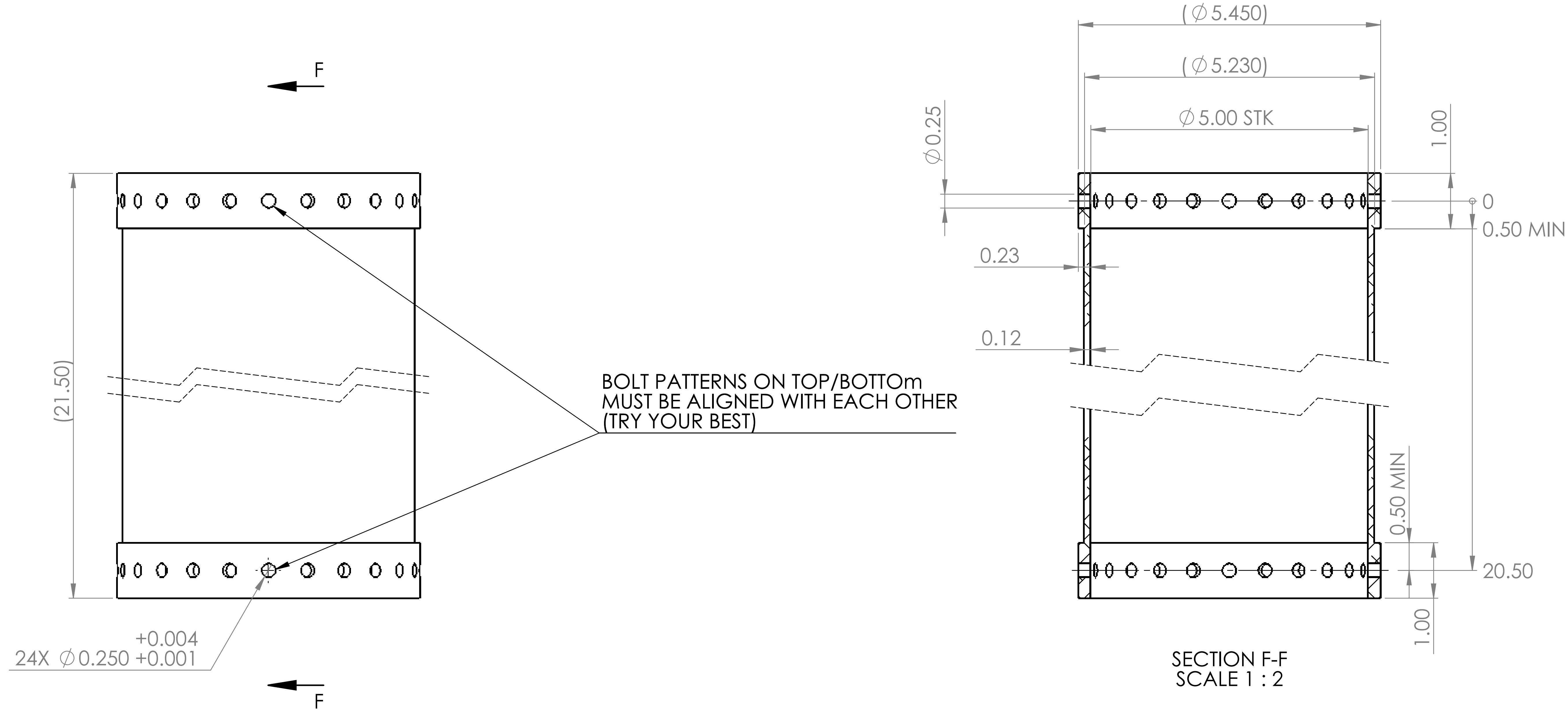
Combustion Chamber Assembly

DWG. NO.	REV
XXX	X

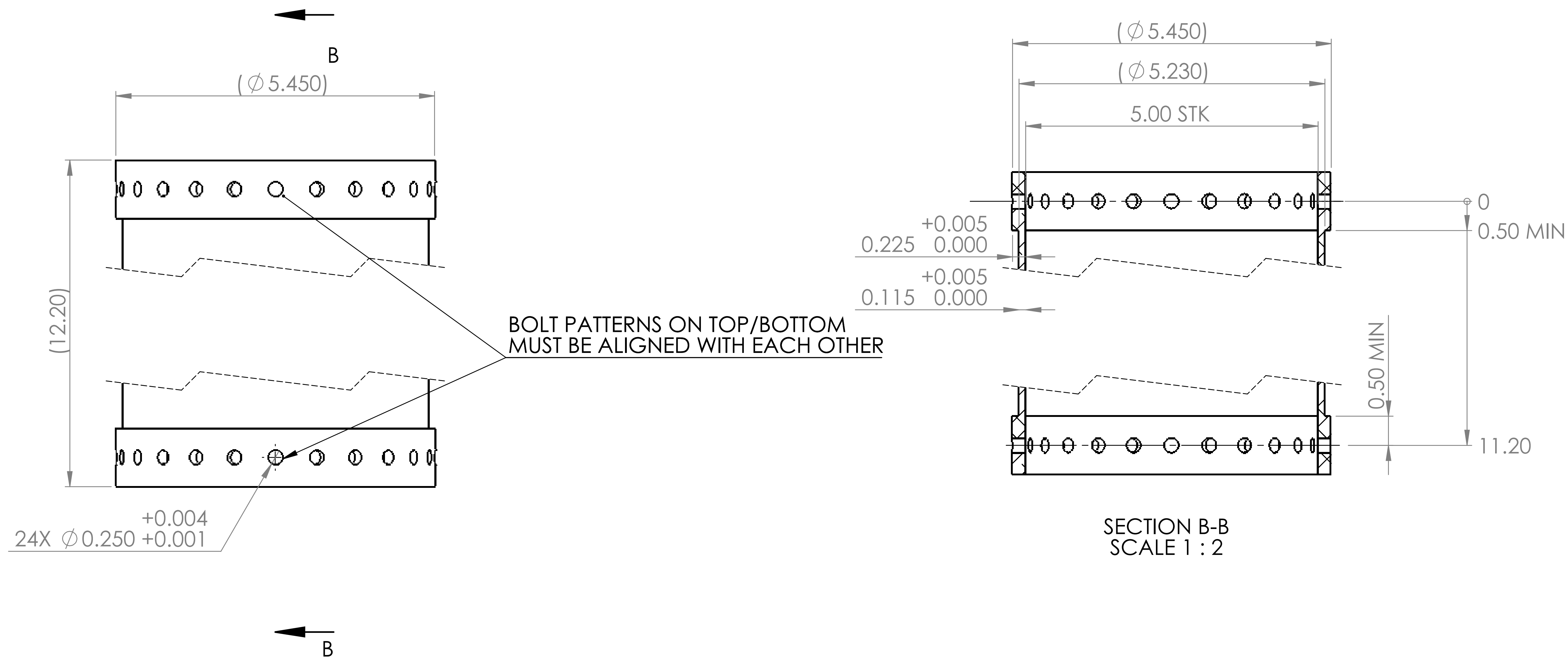
SCALE: 1:5	WEIGHT: XXX	SHEET 1 OF 1



SECTION C-C
SCALE 1 : 1
∅3.732
∅3.378
(0.183)
0.104
0.628
0.553
0.370
0.275
0.125
∅1.614 ±0.002
∅2.224 ±0.002
0.168
30° ±0.50°
∅4.650
A
8 x ∅ 0.332 THRU ALL (5/16 Clearance)
#52 Drill Bit
24 x ∅ 0.064 THRU ALL
12 x ∅ 0.064 THRU ALL
#59 Drill Bit
16 x ∅ 0.041 THRU ALL
Two sets of 8
∅4.970
1.986 ±0.005
C
C
0.668
1.341
1.518
2.068
∅ 0.125 THRU ALL
0.823 ±0.005
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.003 UNLESS OTHERWISE NOTED
NAME
DATE
DRAWN
Keon K.
10/30/17
DESIGNER SIGN-OFF
X.XXX
X.X.XX
PRODUCTION SIGN-OFF
X.XXX
X.X.XX
ALUMINUM 6061
TITLE:
INJECTOR PLATE
DWG. NO.
020
REV
B
SCALE: 1:2
WEIGHT: XXX
SHEET 1 OF 1

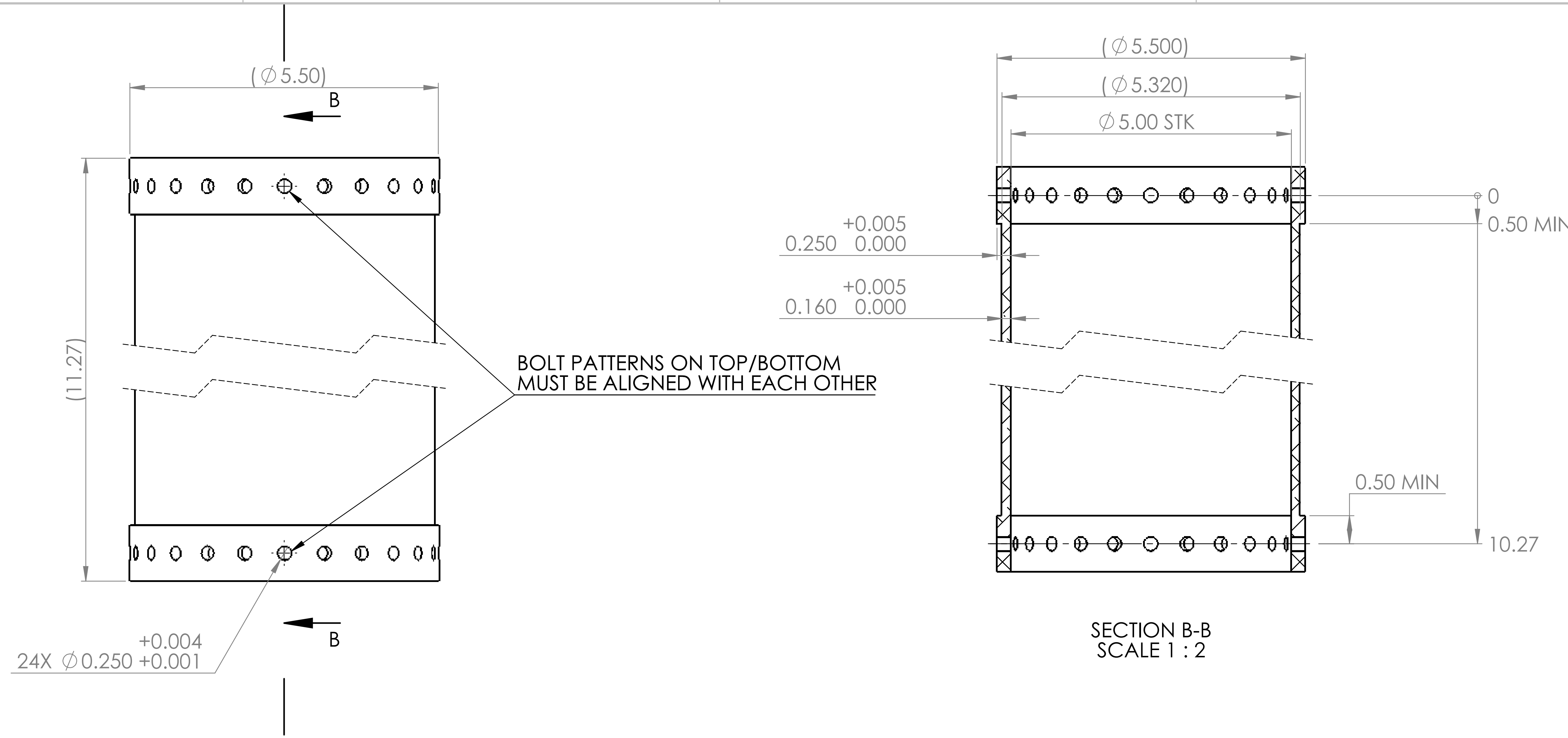


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.01 UNLESS OTHERWISE SPECIFIED	DRAWN	Rory H.	1/16/18	Ox Tank Tube
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	ALUMINUM 6061-T6			DWG. NO. 032 REV C
				SCALE: 1:10 WEIGHT: XXX SHEET 1 OF 1

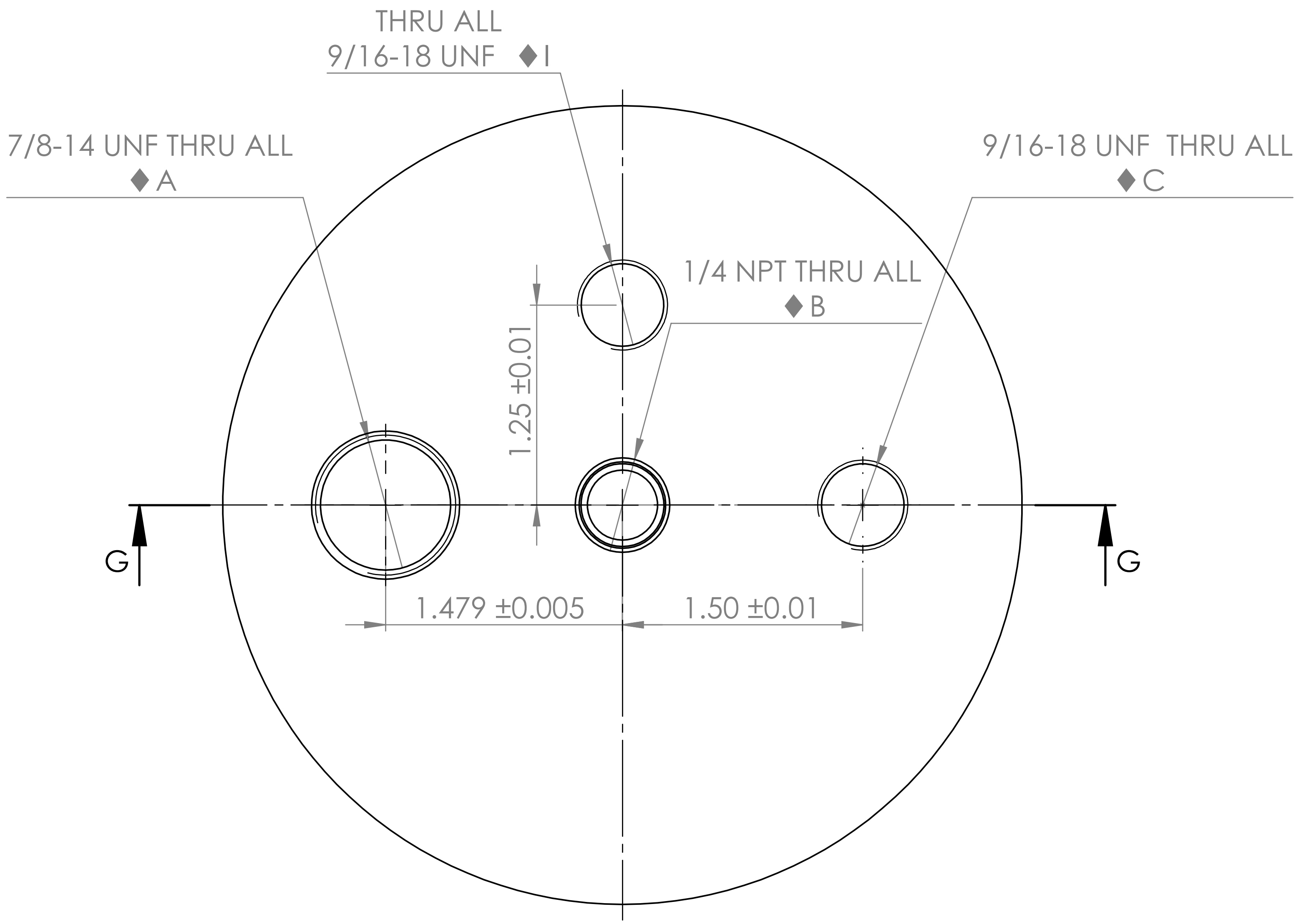


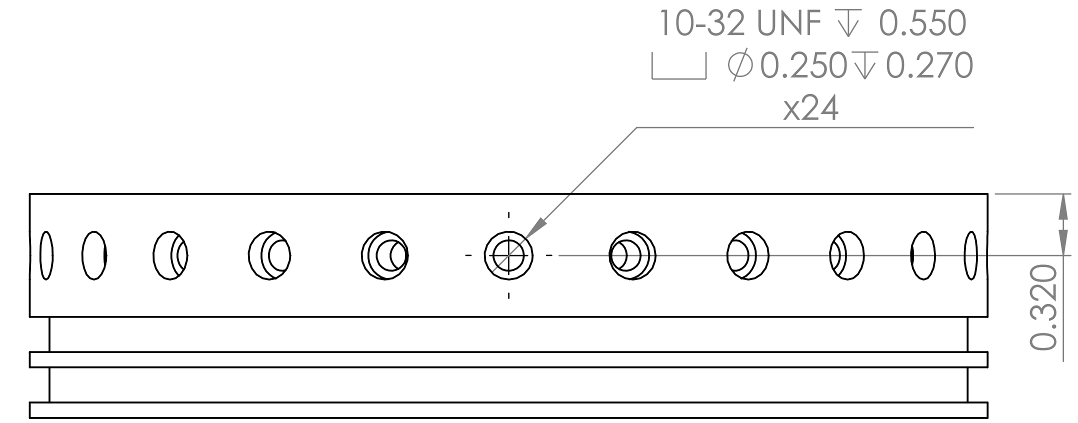
SECTION B-B
SCALE 1 : 2

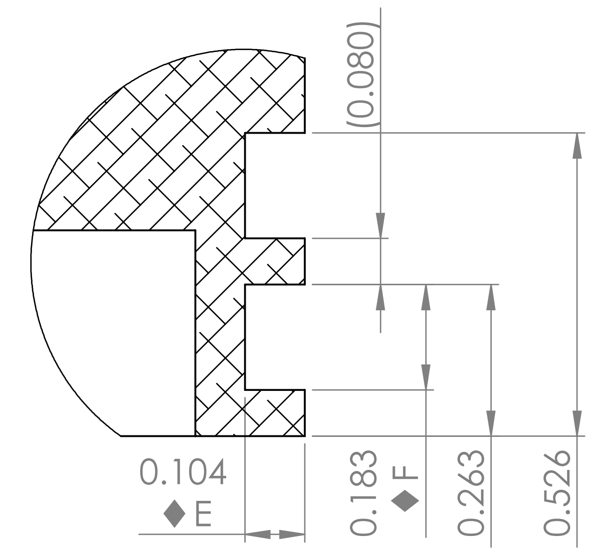
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.01 UNLESS OTHERWISE NOTED	DRAWN	Rory H.	1/16/18	Fuel Tank Tube
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	ALUMINUM 6061-T6			DWG. NO. 033 REV C
				SCALE: 1:5 WEIGHT: XXX SHEET 1 OF 1



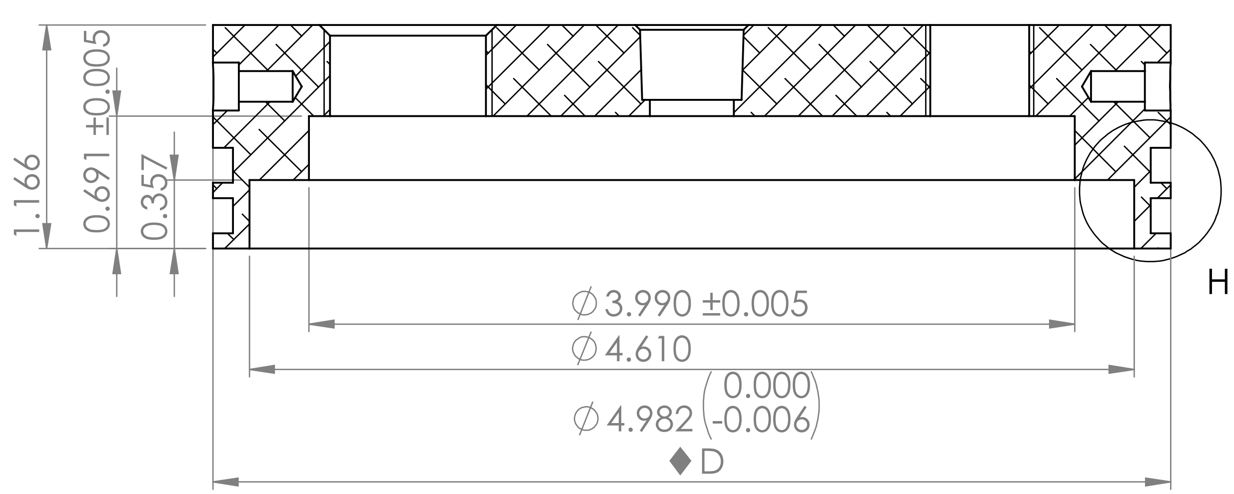
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE: Chamber Tube
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.01 UNLESS OTHERWISE NOTED	DRAWN	Rory H.	1/16/18	
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	ALUMINUM 6061-T6			DWG. NO. 034 REV C
				SCALE: 1:5 WEIGHT: XXX SHEET 1 OF 1







TOLERANCES: ±0.003
DETAIL H
SCALE 3 : 1



SECTION G-G
SCALE 1 : 1

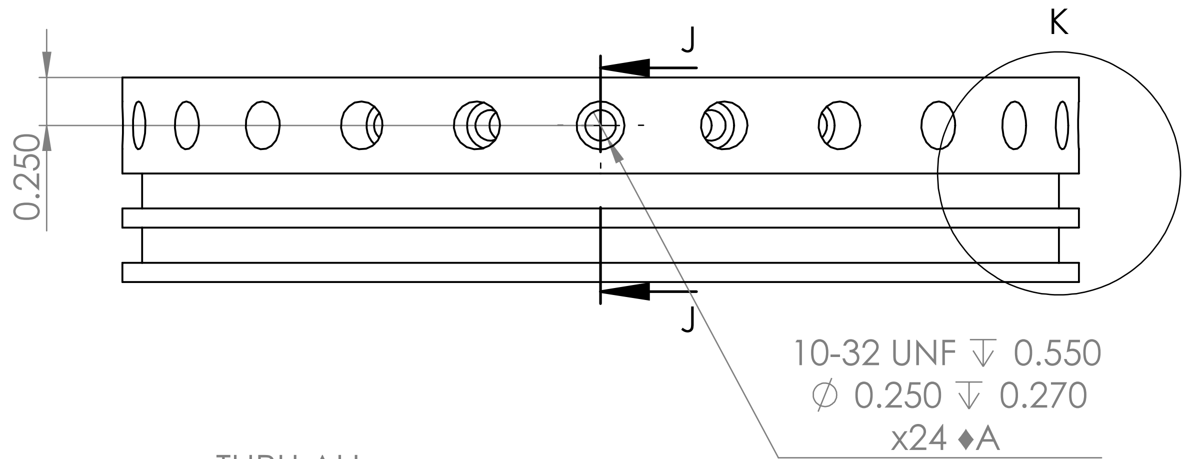
		NAME	DATE
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.007 UNLESS OTHERWISE NOTED	DRAWN	Keon K.	1/7/2018
	DESIGNER SIGN-OFF	X.XXX	X.X.XX
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX
	ALUMINUM 7075		

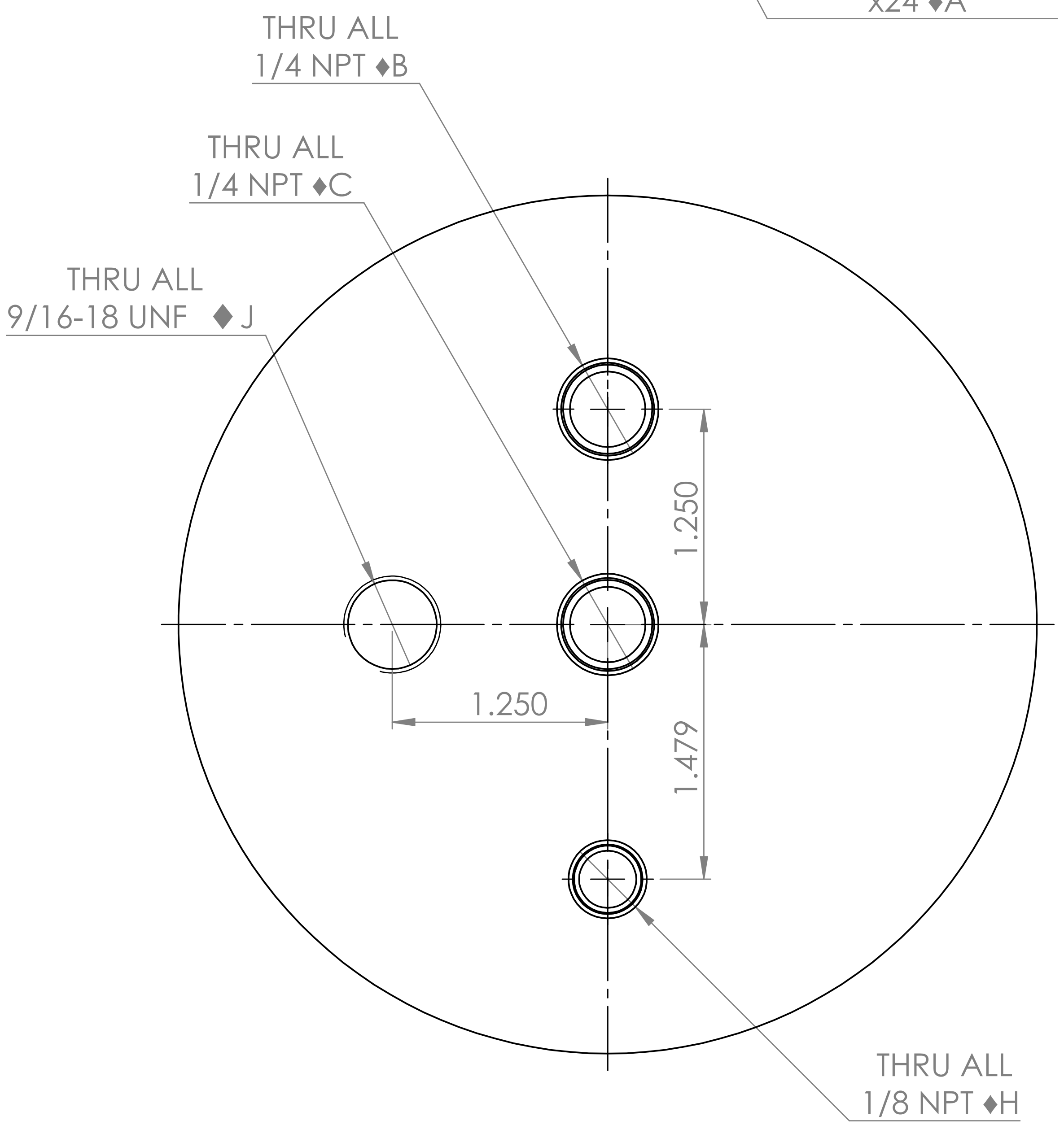
TITLE:

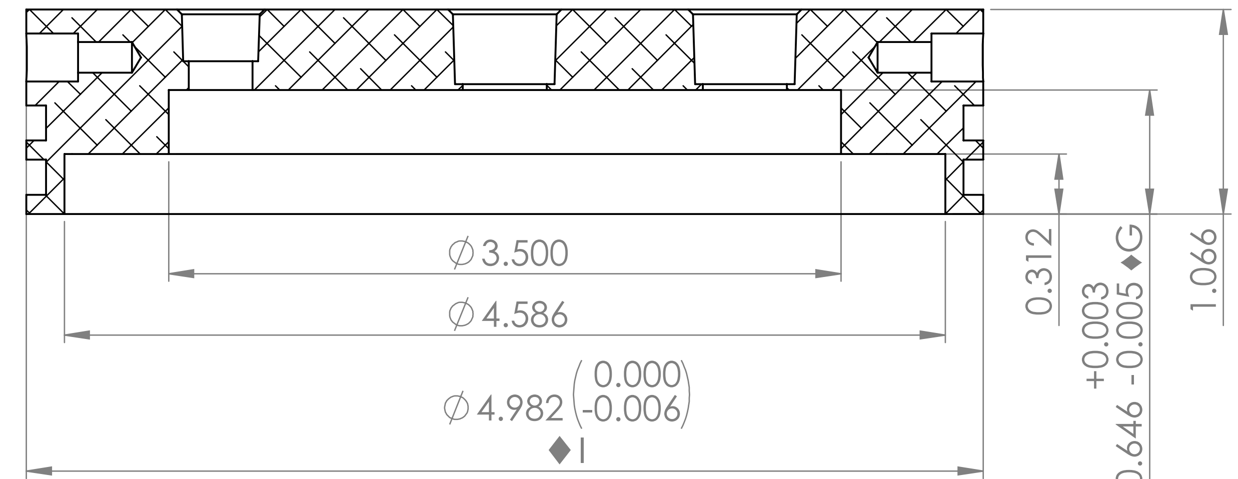
Liquid Ox Tank Bottom Endcap

DWG. NO.	REV
037	C

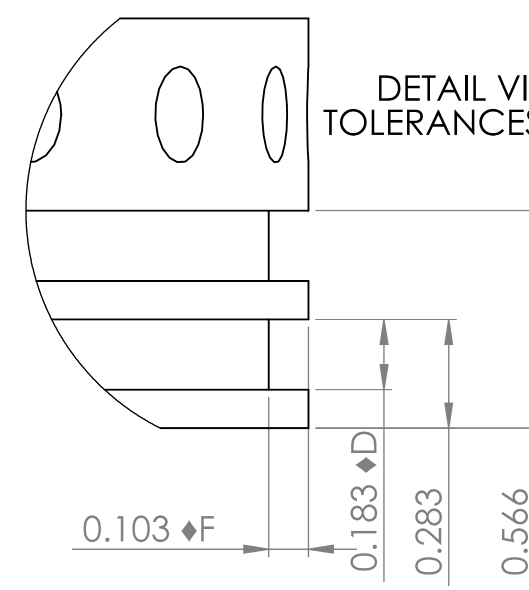
SCALE: 1:2 | WEIGHT: XXX | SHEET 1 OF 1





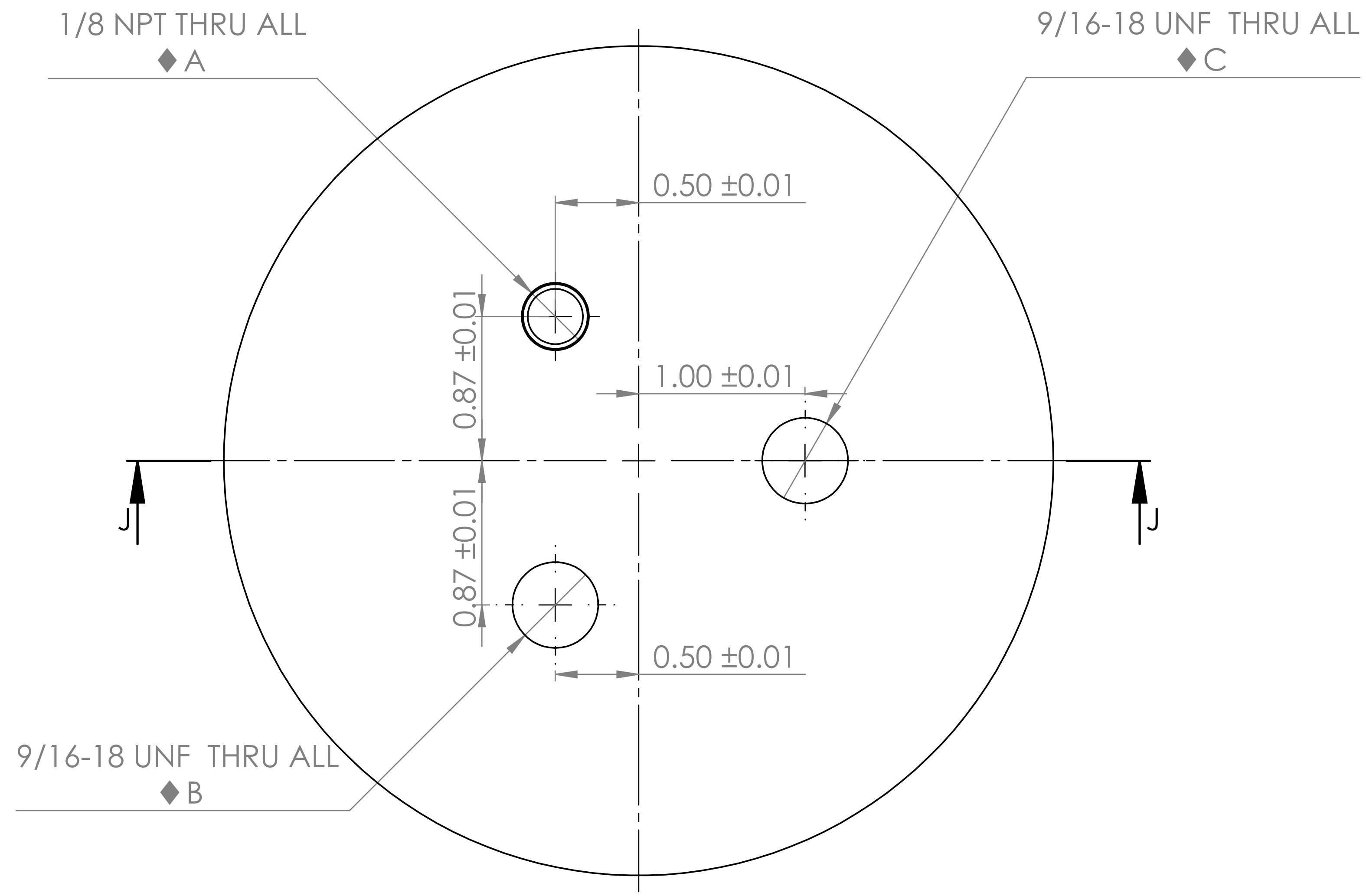


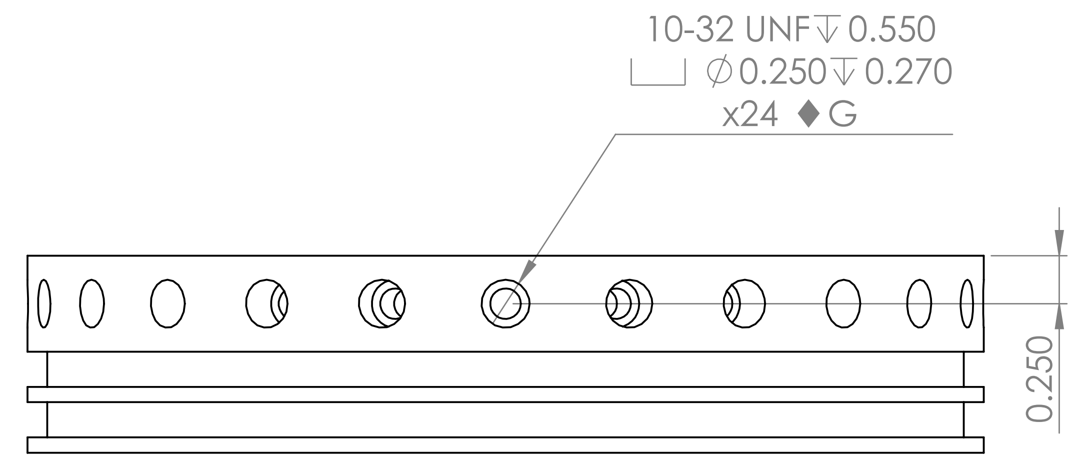
SECTION J-J
SCALE 1 : 1

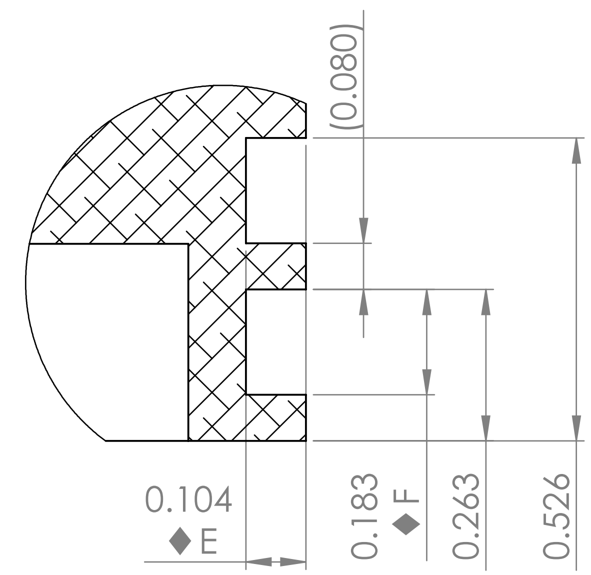


DETAIL VIEW K:
TOLERANCES: ±0.003

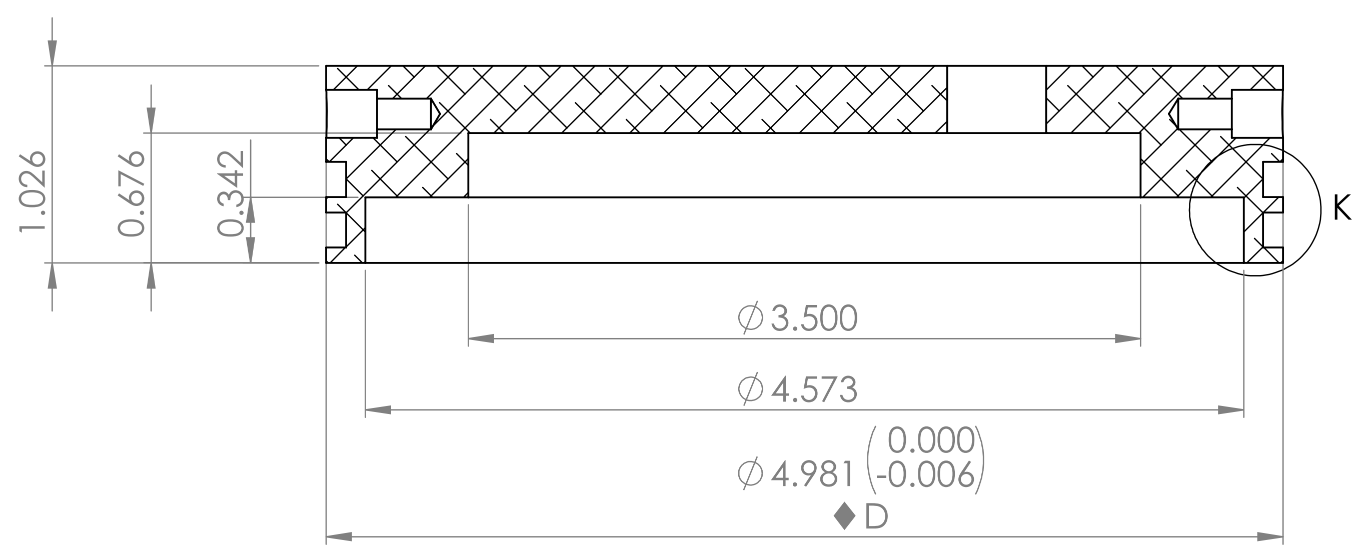
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.007	DRAWN	ethend	10.3.17	OX TANK TOP ENDCAP
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	MATERIAL: Al 7075			DWG. NO. 038 — REV C
				SCALE: 1:1 — WEIGHT: XXX — SHEET 1 OF 1







DETAIL K
SCALE 3 : 1



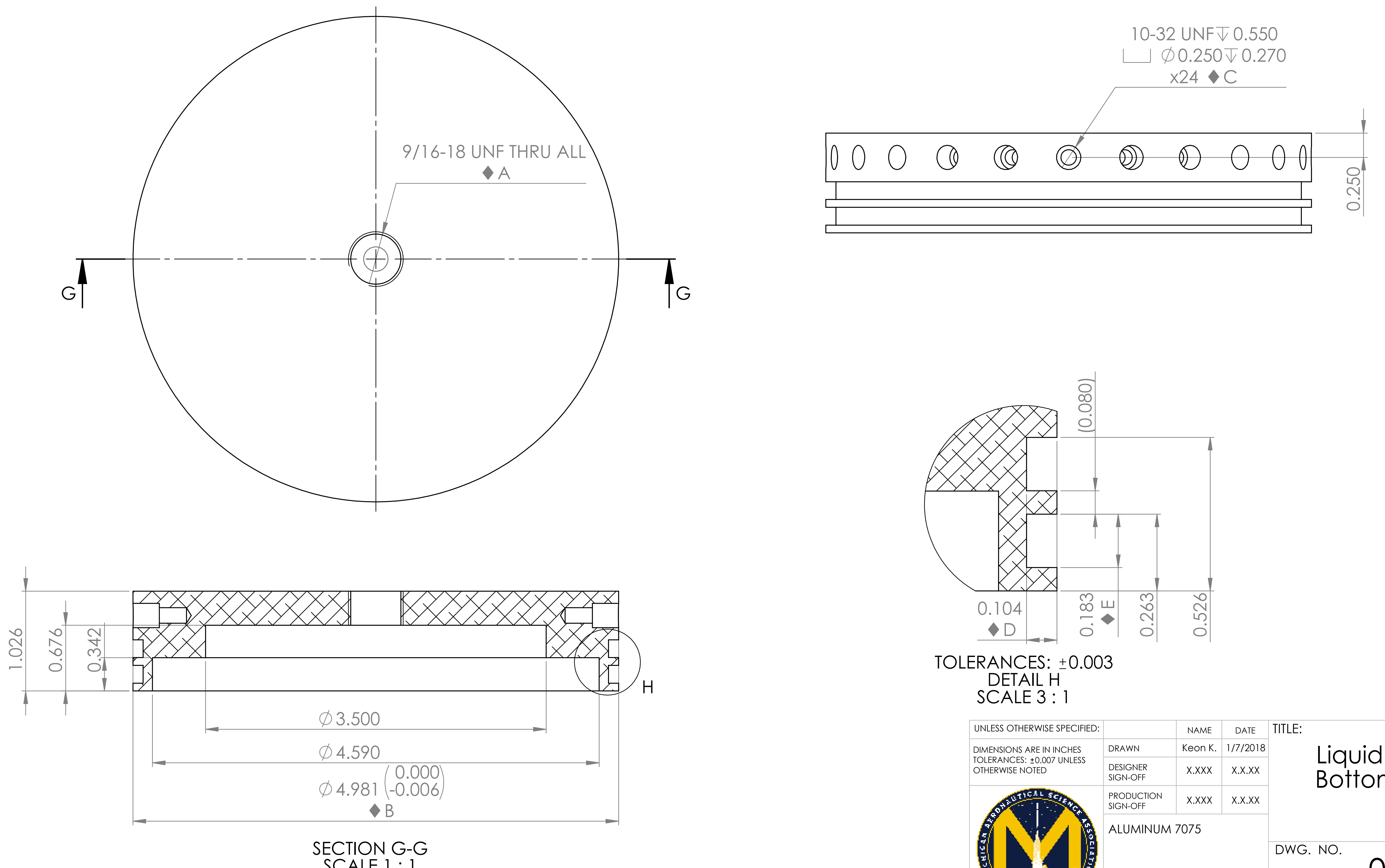
SECTION J-J
SCALE 1 : 1

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.007 UNLESS OTHERWISE STATED	DRAWN	Stefan G	7 Jan 18
	DESIGNER SIGN-OFF	X.XXX	X.X.XX
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX
	ALUMINUM 7075		

TITLE:
Liquid Fuel Tank Top Endcap

DWG. NO.	REV
39	C

1:1	WEIGHT: XXX	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.007 UNLESS OTHERWISE NOTED	DRAWN	Keon K.	1/7/2018
	DESIGNER SIGN-OFF	X.XXX	X.X.XX
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX
	ALUMINUM 7075		

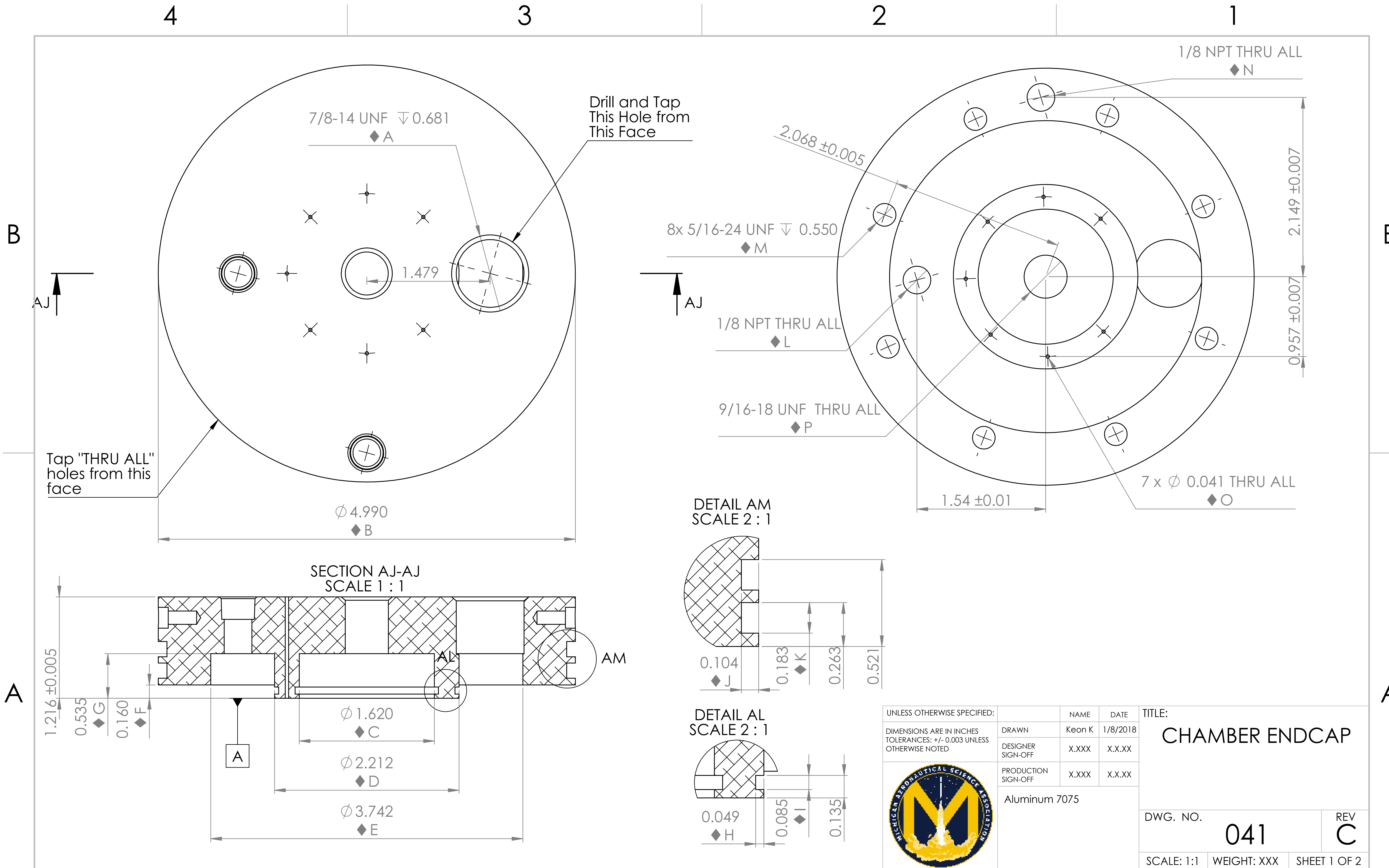
TITLE:

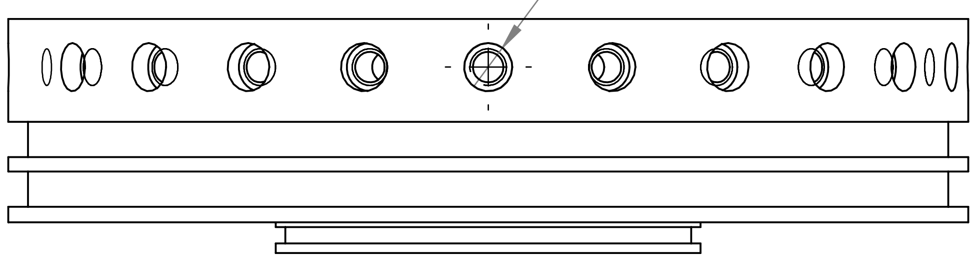
Liquid Fuel Tank Bottom Endcap

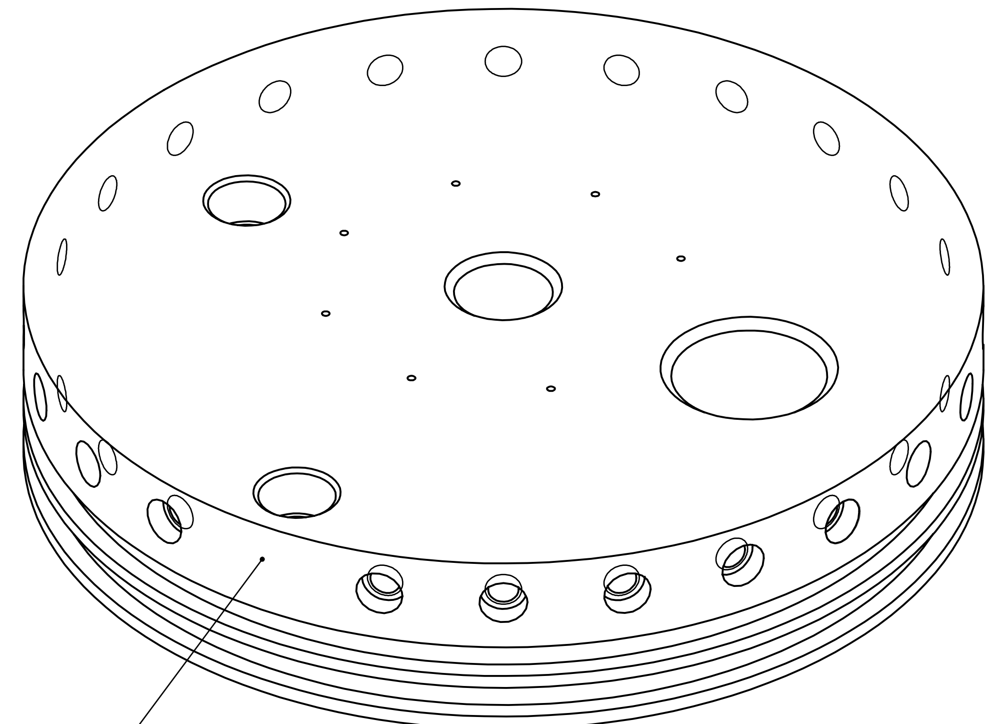
DWG. NO. 040

REV C

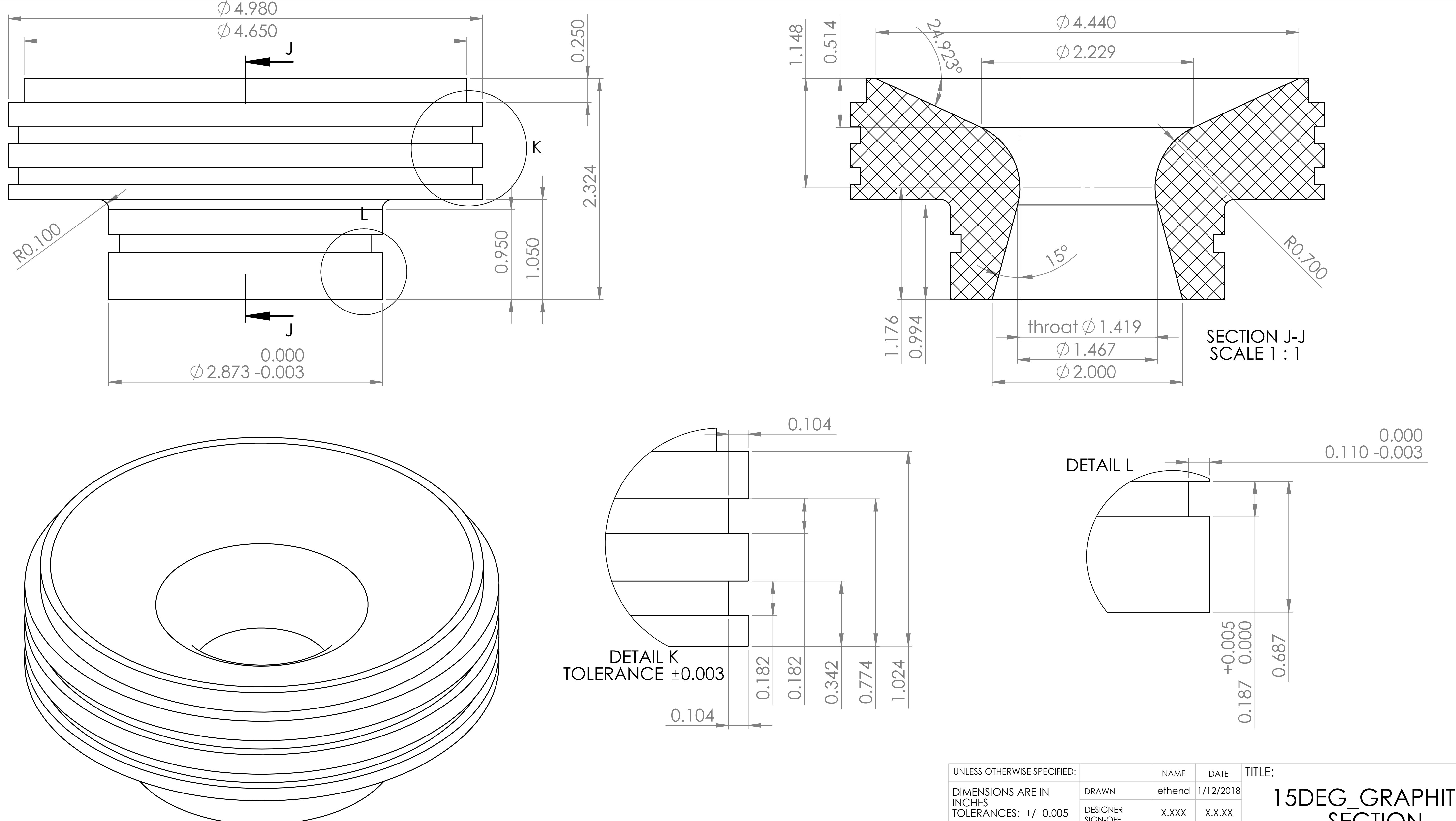
SCALE: 1:2 | WEIGHT: XXX | SHEET 1 OF 1


7/8-14 UNF ⊽ 0.681
◆ A
Drill and Tap
This Hole from
This Face
1.479
AJ
AJ
Tap "THRU ALL"
holes from this
face
∅4.990
◆ B
1/8 NPT THRU ALL
◆ N
2.068 ±0.005
8x 5/16-24 UNF ⊽ 0.550
◆ M
2.149 ±0.007
0.957 ±0.007
1/8 NPT THRU ALL
◆ L
9/16-18 UNF THRU ALL
◆ P
7 x ∅ 0.041 THRU ALL
◆ O
1.54 ±0.01
SECTION AJ-AJ
SCALE 1 : 1
AL
AM
1.216 ±0.005
0.535
◆ G
0.160
◆ F
A
∅1.620
◆ C
∅2.212
◆ D
∅3.742
◆ E
DETAIL AM
SCALE 2 : 1
0.104
◆ J
0.183
◆ K
0.263
0.521
DETAIL AL
SCALE 2 : 1
0.049
◆ H
0.085
◆ I
0.135
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: +/- 0.003 UNLESS
OTHERWISE NOTED
NAME
DATE
DRAWN
Keon K
1/8/2018
DESIGNER SIGN-OFF
X.XXX
X.X.XX
PRODUCTION SIGN-OFF
X.XXX
X.X.XX
MICHIGAN AERONAUTICAL SCIENCE ASSOCIATION
Aluminum 7075
TITLE:
CHAMBER ENDCAP
DWG. NO.
041
REV
C
SCALE: 1:1
WEIGHT: XXX
SHEET 1 OF 2
4
3
2
1
B
A

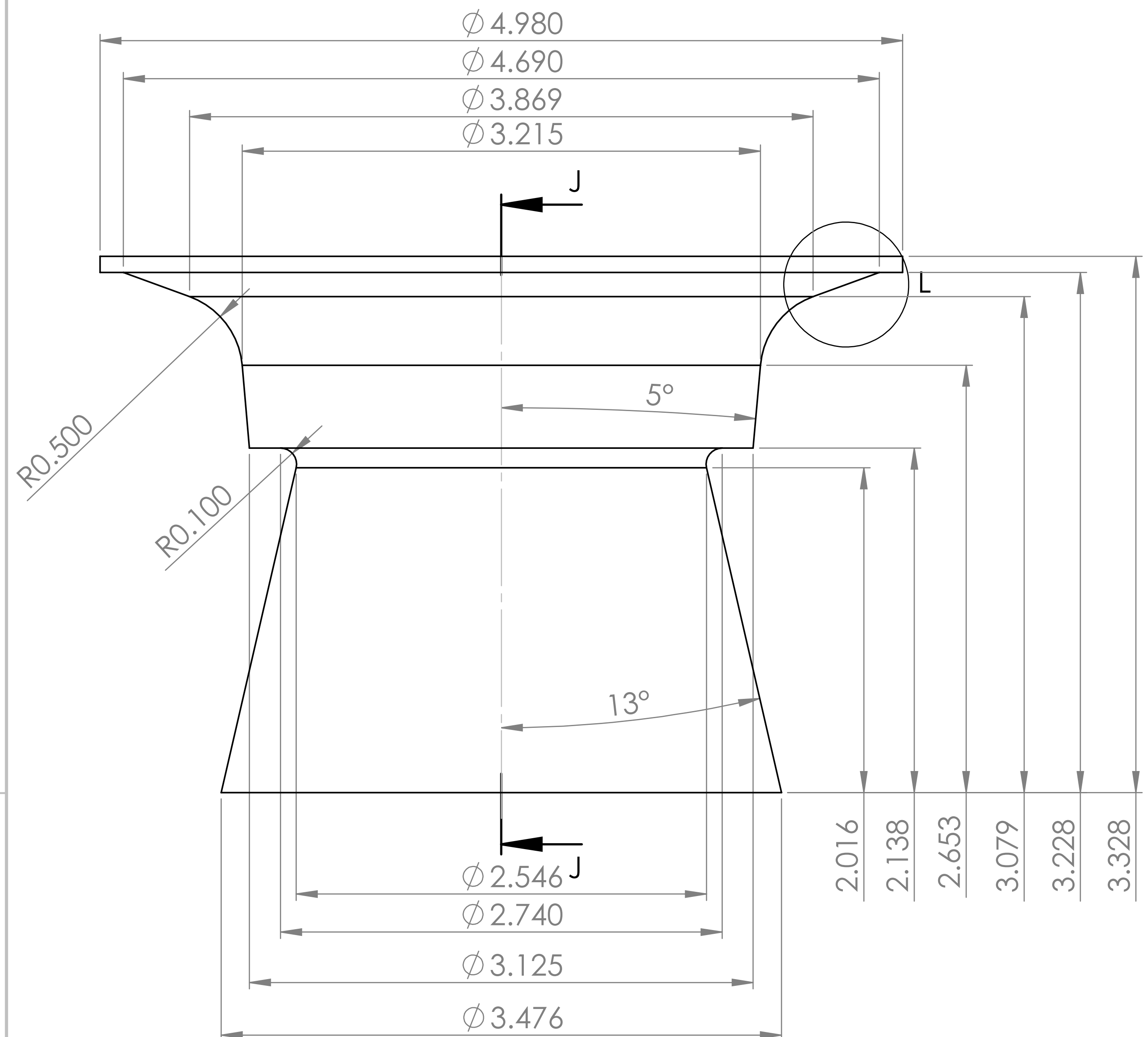


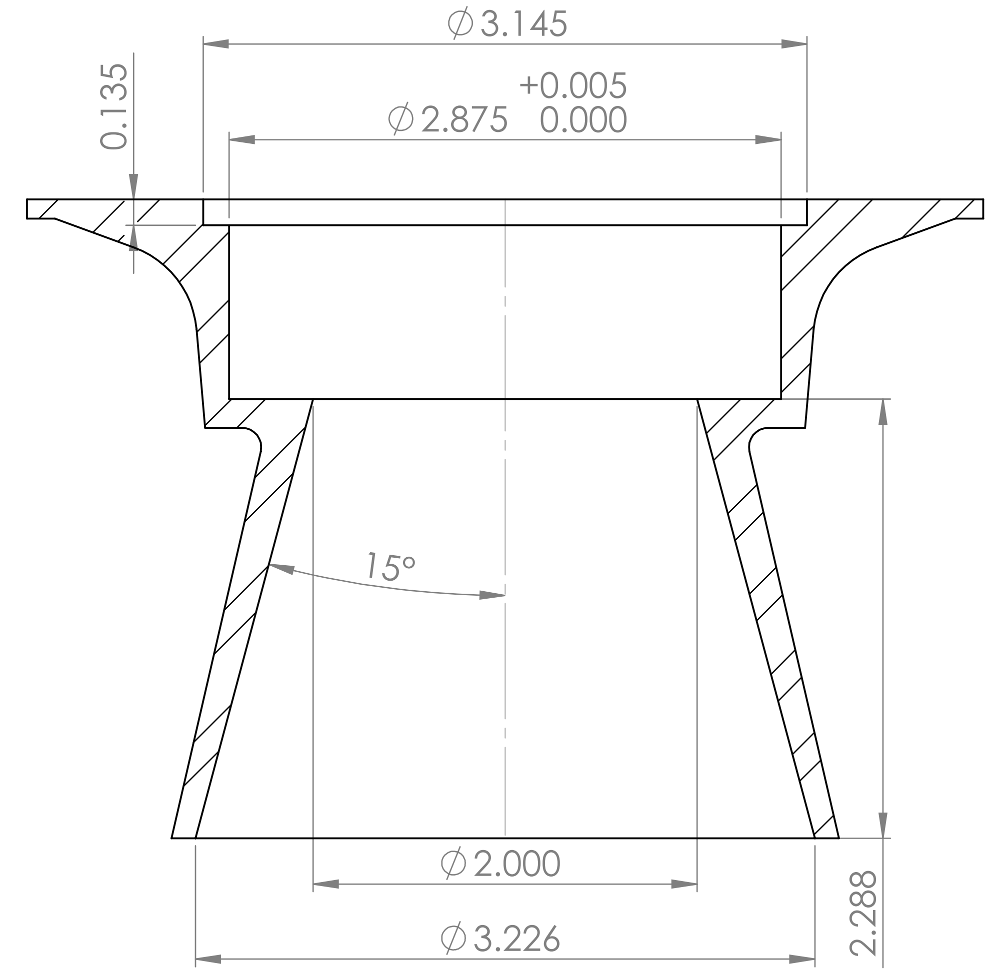


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.003 UNLESS OTHERWISE NOTED	DRAWN	Keon K	1/8/18	CHAMBER ENDCAP
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	Aluminum 7075			DWG. NO. 041 REV C
				SCALE: 1:1 WEIGHT: XXX SHEET 2 OF 2

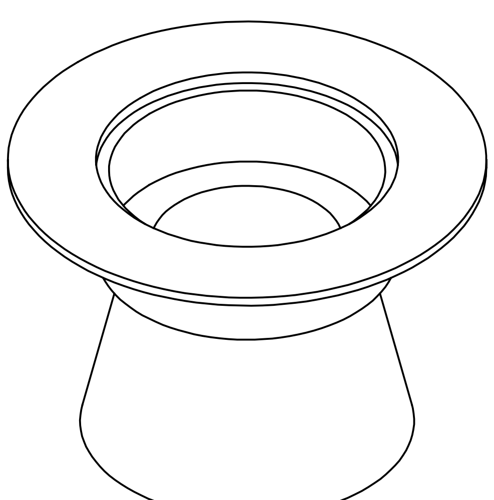


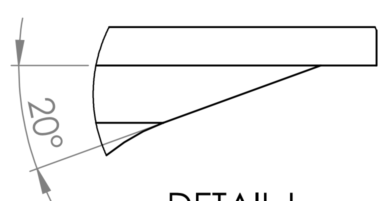
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE: 15DEG_GRAPHITE_SECTION
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.005	DRAWN	ethend	1/12/2018	
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	SUPERFINE GRAPHITE			DWG. NO. 046 — REV C
				SCALE: 1:1 — WEIGHT: XXX — SHEET 1 OF 1





SECTION J-J
SCALE 1 : 1





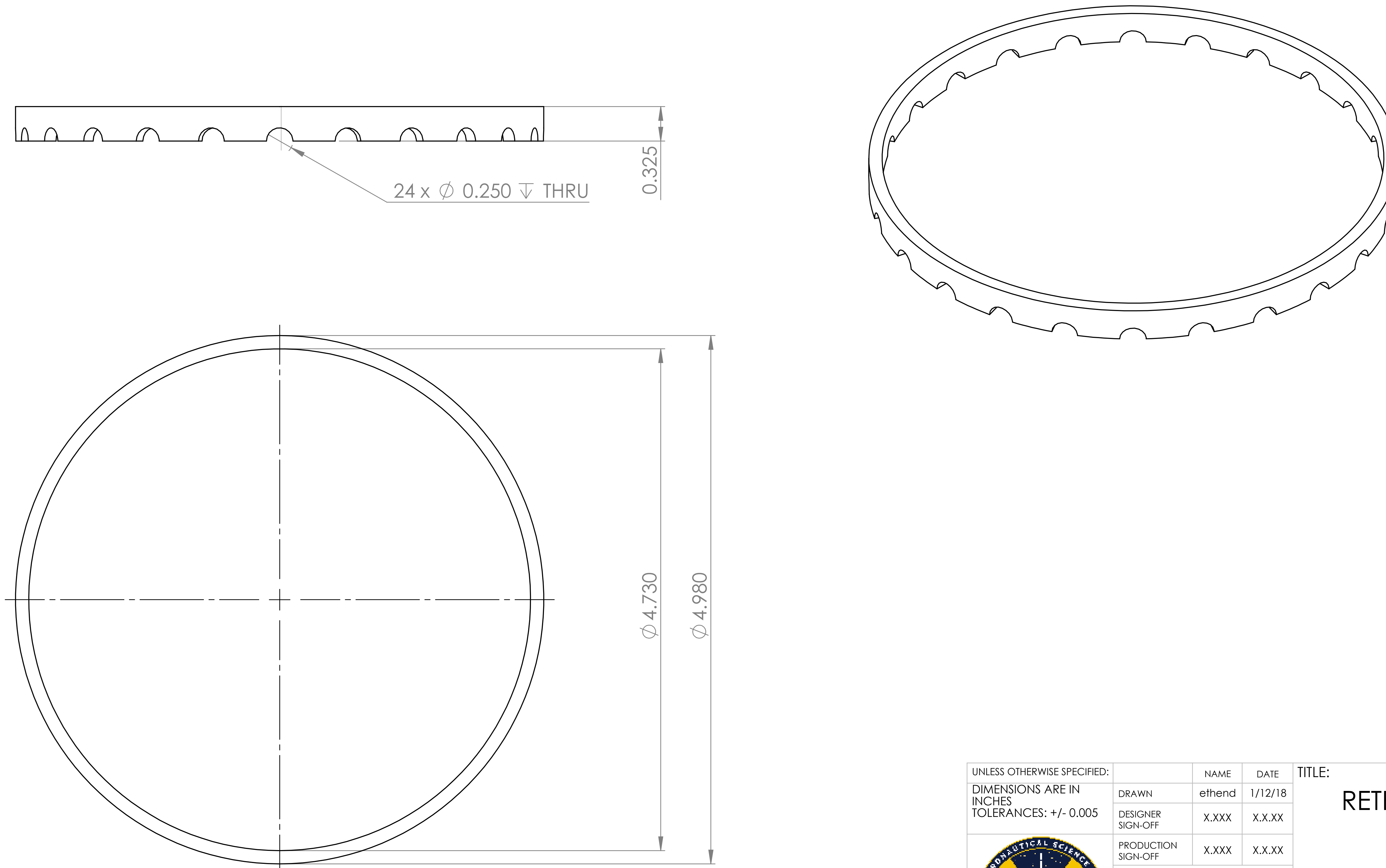
DETAIL L
SCALE 2 : 1

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.005	DRAWN	ethend	1/12/18
	DESIGNER SIGN-OFF	X.XXX	X.X.XX
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX
	304 SS		

TITLE:
15DEG_STEEL_SECTION

DWG. NO.	REV
047	C

SCALE: 1:1	WEIGHT: XXX	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.005	DRAWN	ethend	1/12/18	RETENTION RING
	DESIGNER SIGN-OFF	X.XXX	X.X.XX	
	PRODUCTION SIGN-OFF	X.XXX	X.X.XX	
	304 SS			DWG. NO. 048 / REV C
				SCALE: 1:1 / WEIGHT: XXX / SHEET 1 OF 1

Acknowledgments

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- Chris Gordon, Director (Wilson Student Team Project Center)
- The OrbitalATK Michigan recruitment team

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- Huntsman
- GraphiteStore
- MiSUMi
- OrbitalATK
- Blue Origin

References

[1]Gill, G. S., and Nurick, W. H. , "Liquid Rocket Engine Injectors," NASA SP-8089, 1976.