Rice Eclipse

MK 2.0 MOTOR PRELIMINARY DESIGN REVIEW

February 25, 2016

Contents

Background

       This project was originally inspired by the ESRA IREC competition. Our goal was to build a hybrid motor that could fly a rocket with a small payload to 10,000 ft. Much of the design of this rocket builds off of experience building and testing a substantially smaller hybrid motor called the Mk 1. This motor, the Mk 2, is designed to produce an impulse of 35,000 Newton seconds. Due to the incredibly complex nature of this project, we have no intention of flying this motor or even putting it in a flight vehicle in the immediate future. For the sake of this review, please consider this motor and test stand as a standalone system. Some components, however, have been designed to be compatible with theoretical airframe designs should this motor be developed to a flight ready configuration. Additionally, most components have been designed with weight saving in mind.

       Our intention with this motor is for it to be our 'base case,' the most simple possible hybrid of this scale. Once we have established a strong foundation, we intend to optimize individual components to contribute to the overall efficiency of the motor. Simultaneously, other parts of the Eclipse team will be developing entirely separate technologies, including smaller rockets to be flown and efforts to certify as many team members as possible to fly high powered rockets.

       Eclipse has existed as a team for under two years and this is our first design review. In fact, this is our first major documentation effort at all. The primary purpose of this review is to receive feedback on our Motor and testing design. However, we welcome feedback on organizational and procedural matters as well. I'm entirely confident that this packet itself could be improved in countless ways and I would appreciate hearing what they are before our next round of documentation and review.

       Thank you very much for taking the time to review our preliminary design. We have had a tremendous amount of fun and have learned an incalculable amount during this process and we look forward to learning more!

Motor

OVERALL DESIGN

This motor is designed to be a 3500 N thrust motor with a burn time of 10 s. The initial test is only intended to be 2 s. However, in the interest of learning about the initial burn characteristics, everything other than the amount of oxidizer loaded will be held constant. The motor is a hybrid utilizing solid HTPB and liquid nitrous oxide. The design is kept simple by a lack of any kind of internal actuation. The motor is fueled through the injector plate and those fill lines are terminated by ignition. Once ignited, self pressurizing nitrous oxide in the oxidizer tank will flow through a short length of plumbing, past a pressure transducer and emergency relief burst disk, and to a bulkhead. The bulkhead houses the injector plate and mates with the combustion chamber walls. The combustion chamber includes an ablative fiberglass liner to aid in thermal management. The nozzle at the end of the combustion chamber includes a primarily aluminum body with a graphite insert in the high-temperature region. The Nozzle bolts directly to the test stand structure and the combustion chamber. The combustion chamber is friction fit to the bulkhead to allow for thermal expansion. The bulkhead is mounted directly to the test stand structure. The oxidizer is held in place by two aluminum retaining rings mounted directly to the test stand.

OXIDIZER TANK

Alex Jiang, Andrew Gatherer

The Oxidizer tank must hold 30 lb of nitrous oxide at a pressure of 700 psi, and include a small hole to allow excess internal gasses to vent during filling.

The selected design is an aluminum pressure vessel, milled down to a 7.81 inch outer diameter. The tank also includes a seating for a 6-32 bolt which will itself have a 1mm hole drilled in it. Due to issues with machining, the tank has uneven wall thickness. Despite this, the thinnest part of the wall has a thickness of at least 0.25". This leads to a calculated factor of safety of 2.95. Extensive analysis is included in Appendix C: Oxidizer Tank.

Ø 7.81

D

A

D

B

B

47.20

40.08

A

A

SECTION A-A

SCALE 1 : 8

B

0.389

Ø 0.25

0.272

DETAIL B

SCALE 1 : 1

SECTION D-D

SCALE 1 : 8

0.10

6-32 Machine
Screw (Hole OD
0.1380")

3/4" NPT
Fitting

A

A

Mk 2 Motor

TITLE:

Oxidizer Tank

SIZE | DWG. NO. | REV

A | 1 of 1

SCALE: 1:12 | WEIGHT: | SHEET 1 OF 1

INTERNAL PLUMBING

Alex Jiang

Piping

The internal piping is a conduit for nitrous oxide from the oxidizer tank to the bulkhead. Additionally, it interfaces with the burst disk and with a pressure transducer.

The selected design is composed entirely of ½" Swagelok components.
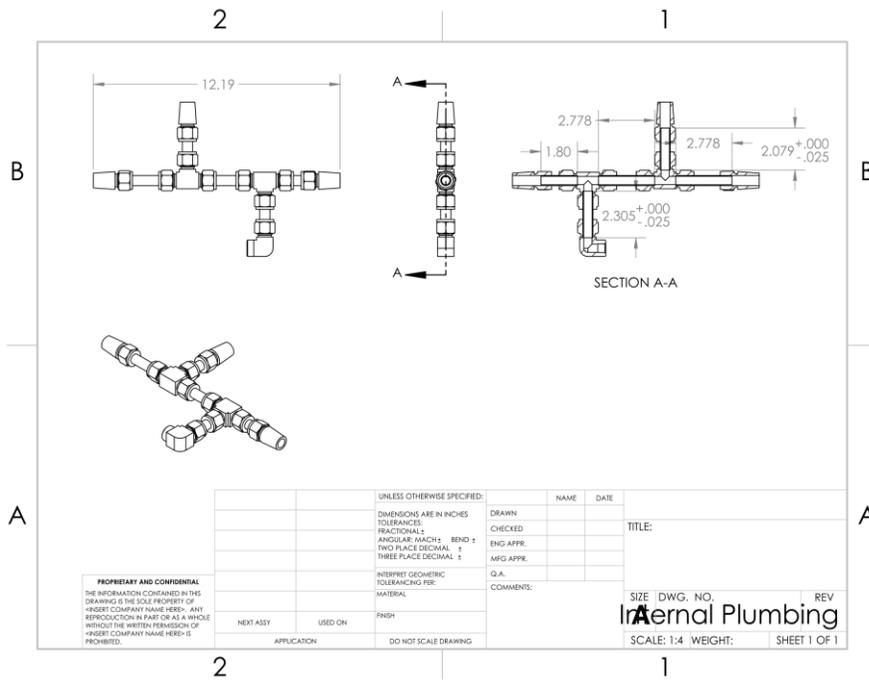
Figure 1. Internal Plumbing Drawing

Burst Disks

The purpose of the burst disk is to rupture at 1200psi as a way to vent excess pressure and avoid CATO with regard to the combustion chamber, internal piping and oxidizer tank. The burst disk will only function during firing of the motor. During filling, the fill lines will rupture well below the failure point of any other component. The burst disk consists of an aluminum casing with an npt fitting that mounts directly to the internal plumbing. The casing holds a steel disk which is electrolytically scored to ensure predictable failure. The disk is sealed using a silicon O-ring.

16 disks were created using an identical construction procedure. 2 have been tested and have failed consistently. 10 more will be tested to ensure consistent failure patterns.
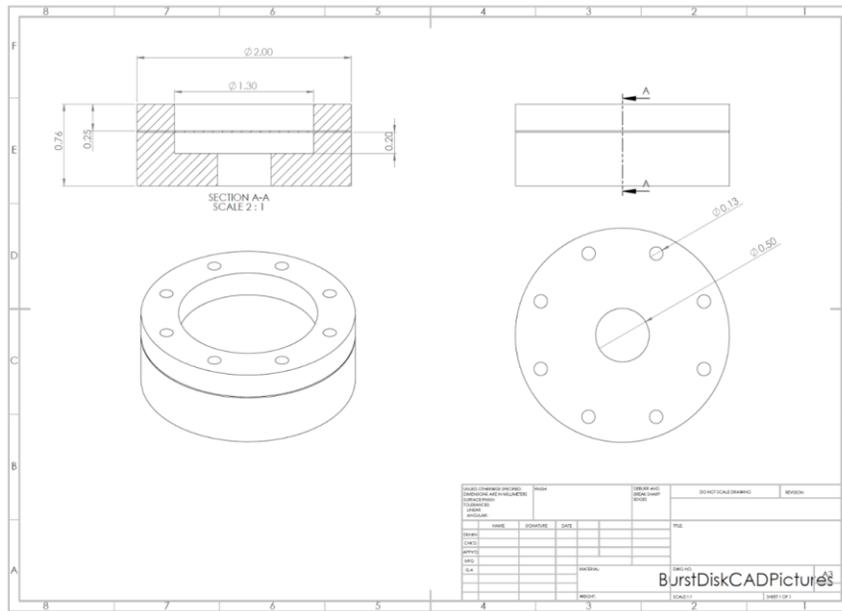
Figure 2. Burst Disk Drawing

COMBUSTION CHAMBER

Andrew Gatherer

The purpose of the combustion chamber (including the bulkhead and the walls) is to contain the controlled burn that is happening, disallow hot spots in the walls, and to integrate the injector plate and ignition source. Also, it is meant for fuel storage and directed mass flow.

Key Considerations
Bulkhead Chamber: ~700 psi
Bulkhead Temperature: ± 20˚C

Combustion Chamber: 500 psi
Combustion Temperature: 3100

Overall Design
The combustion chamber consists of the Bulkhead, the Injector Plate, The Chamber walls (structural), the Fuel Grain
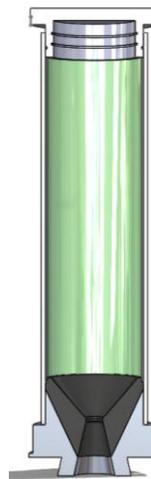
Figure 1. Combustion Chamber Cross-section

and Fiberglass liner, and the Nozzle assembly. The Bulkhead, Chamber Wall, and Outer Nozzle are Aluminum. The Injector Plate is Steel with stainless steel fittings. The high-temperature region of the nozzle is graphite.

Bulkhead

Andrew Gatherer
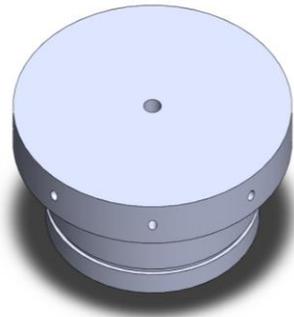
Figure 1. Bulkhead Render

The bulkhead is required to pneumatically seal with the combustion chamber walls, but due to the growth of aluminum undergoing severe heating, it will not be bolted into the chamber walls, only the test stand. Also, the bulkhead should be able to structurally contain the injector plate, withstand the pressures of the combustion, and connect into the internal plumbing system. It mounts directly to the inner tower of the test stand.

The bulkhead is constructed with Aluminum 6061-T6. It features a female NPT fitting at the top to interface with the plumbing. On the outside, it has a lip to prevent sliding into the combustion chamber, and an O-ring seal to contain combustion gases. The fiberglass liner butts up directly to the bulkhead as it is not anticipate to appreciably thermally expand. The inside of the bulkhead features two snap rings to retain the injector plate on either side, and accommodations for an o-ring seal around the plate.

Longitudinal Stress FOS of **20.7**

Bolts (singularly loaded) FOS of **46,415**

Must provide
good seal for
o-ring.

Ø7.810

Ø5.015

Ø6.00

1.00

1.35

.50

.15

.11

A

A

Ø.25

1/2" NPT

.526 +.015 / -.000

.75

.13

.12

SECTION A-A

Mk 2 Motor

TITLE:

Bulkhead

SIZE A

DWG. NO.   1 of 1

REV 3

SCALE: 1:2   WEIGHT: SHEET 1 OF 1

2

1

B

B

A

A

2

1

Injector Plate

James Phillips, Sam Zorek
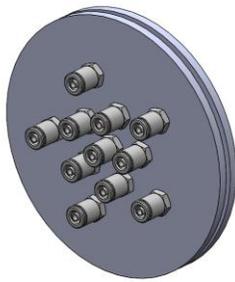
Figure 1. Injector Plate
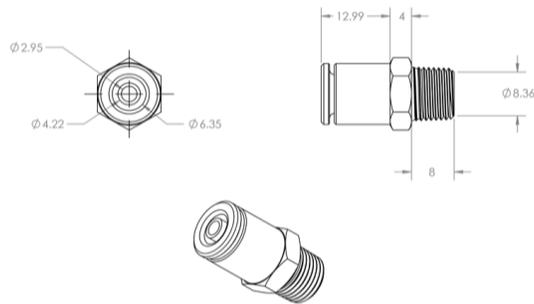
Figure 2. Push to connect plugs

The injector plate is primarily to atomize the oxidizer that is coming from the oxidizer tank as it goes into the combustion chamber. This is done to increase surface area, and thus, combustion and interaction with the solid fuel grain. Additionally, the motor will be fueled through holes in the plate. (See External Plumbing)

Key Considerations
Pressures drop of ~200psi
Mass flow rate: 1.36 kg/s
Cold Side temperature: ± 20 °C
Combustion Temperature: 3100 °C

Design

The plate is 6061-T6 Aluminum, 5 inch diameter disk, 0.515 inches thick. It has 11 holes on it, one in the center, and two star patterns consisting of 5 holes each, the first at 0.75 inches from the center and the second at 1.5 inches from the center. These holes are each 0.322 in diameter and threaded with quarter inch npt threads. There is a groove on the side that is 0.13 inches wide, and is .25 inches deep to house a silicone O-ring.

Commented [CT1]: This should be elaborated, or a reference made elsewhere

Commented [JPK2R1]: It is

Chamber Wall

Andrew Gatherer
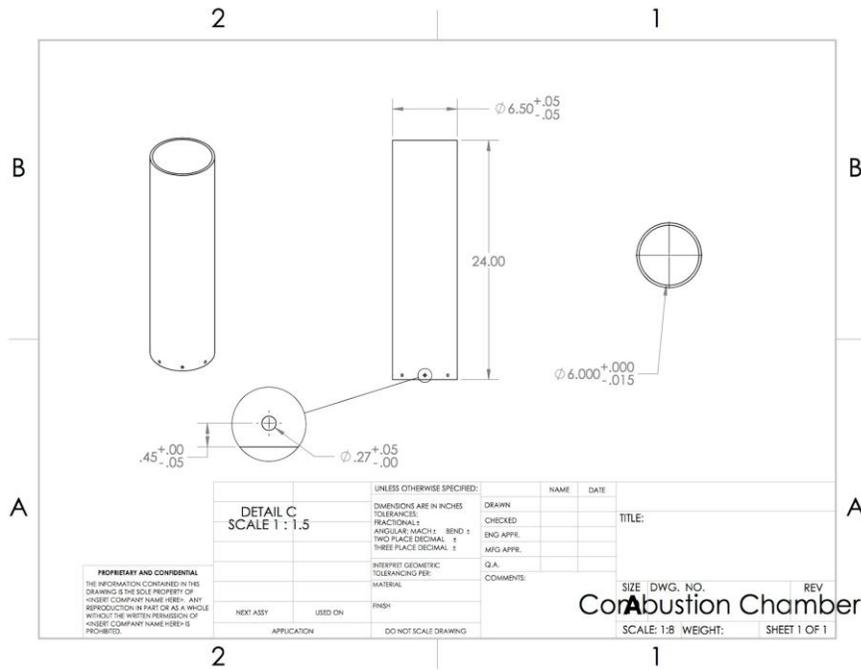
Figure 1. Chamber Wall

The chamber wall is the structural element constraining the combustion process of the motor. Anticipated chamber pressure is 500 psi. Anticipated combustion temperature is 3400 K (3100 °C). However, most of this heat is expected to be diverted out the nozzle and not

transferred to the chamber walls. Chamber temperature is expected to reach 150°C.

The chamber is constructed of 6061 Aluminum with a length of 24 in, an OD of 6.5 in, and wall thickness of 1/4 in. The bottom has 8, 1/4 in holes to accommodate bolts to the nozzle.

Factors of safety calculated for various temperatures are below. Due to the free end of the tube, stress was modelled as pure hoop stress.

Temperature (C)	Yield Strength (MPa)[1]	FOS
24	276	6.418

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[1]http://www.matweb.com/search/datasheet_print.aspx?matguid=1b8c06d0ca7c456694c7777d9e10be5b

100	262	6.093
149	214	4.977
204	103	2.395
260	34	0.791

Fuel Grain

Morgen Smith, Evan Biggers

The Fuel Grain is designed to sustain a 10 second burn with nitrous oxide with a mass flow rate of $1.36\frac{kg}{s}$.

Constants for Combustion at 500 psi, Oxidizer to Fuel ratio = 7.1[2]

$$c* = 5264 \ \frac{ft}{s} \quad Isp = 247 \ s$$
$$Heat \ of \ Ablation \ of \ HTPB = 750 cal/g$$

The selected grain will weigh 5.5 lbs with dimensions 3" ID, 5.973" OD, 17.21" height Composition: **88:12** HTPB to E744 curative

HTPB with carbon black has shown to have a positive effect on the radiation flux of the system. It has also been shown that there is an optimal surface area to volume ratio. We decided on a inner radius of 1.5" because it allows us to have a ratio of volume to surface area 2.22:1.[2]

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[2] *Fundamentals of Hybrid Rocket Combustion and Propulsion Volume 218, Chiaverini, Martin J. & Kuo, Kenneth K.*

Nozzle

Chris Wentland
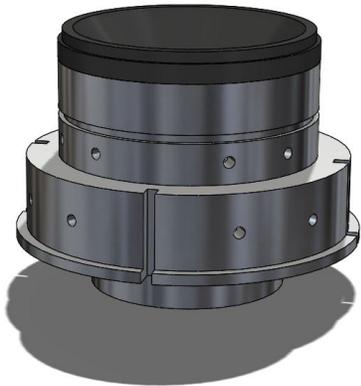
Figure 1. Nozzle and graphite insert
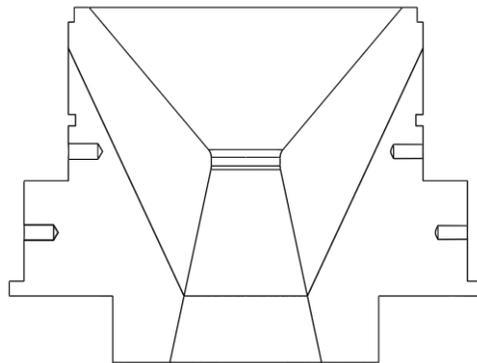
Figure 2. Nozzle cross-section

Key Considerations

1. Supersonic flow – the nozzle's geometry must be designed so as to effectively accelerate the exhaust flow to Ma = 1 at the throat and accelerate the flow to supersonic speeds after the throat. The geometry necessary to achieve this will be discussed later.
2. Starting Values – Combustion chamber key metrics estimated at: Ma = 0, T = 5,480 °F, P = 500 psi. Nozzle should be optimized based on these starting values.
3. Loading – Nozzle must effectively transmit load to test stand frame, including accommodations for an eventual fin can (of smaller internal diameter than regular rocket body).
4. Design Compatibility – Converging portion must be flush with inner wall of fiberglass chamber liner. Outer diameter must accommodate fins to stabilize from external fluttering.
5. Thermal limits –The nozzle must be able to sustain thermal loading without failing or deforming excessively.
6. Weight – Weight should be minimized

Design

The selected nozzle design incorporates an outer aluminum casing and a graphite insert in the high temperature region. The aluminum casing also accommodates bolts for the outer body of the rocket and for the combustion chamber. The graphite insert has a lip for the fiberglass liner to overlap the converging section. The bottom has a lip to transmit the thrust as a linear compressive load onto the test stand structure or rocket body. The alignment ring includes notches to accommodate future fins to help mitigate fluttering.

- Area expansion ratio – 4.864
- Throat area | diameter – 6.8690e(-4) in^2 | 0.0296 in
- Outlet area | diameter – 0.0033 in^2 | 0.0652 in
- Converging half-angle - 40°
- Diverging half-angle - 12°[3]

Expected Flow Properties [4]

1. Chamber
   a. Ma = 0
   b. T = 5,480 °F
   c. P = 500 psi
2. Throat
   a. Ma = 1
   b. T = 4,800 °F
   c. P = 275 psi
3. Exit
   a. Ma = 2.87
   b. T = 2,400 °F
   c. P = 14.6 psi

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[3] Full machining drawings included in Appendix
[4] See appendix for dimensional callouts

EXTERNAL PLUMBING

Small (>1mm) hole in run tank to indicate when tank contains correct level of oxidizer and create pressure drop from fill tank to run tank

LI 1

TK-001
OXIDIZER RUN TANK
7.81" X 47.2"
700 psi @ 25 C

Pressure transducer moved to after the burst disk on the main line

PY 1

1/2"-316SS-N02-1

PSV 1

Pressure Burst Disk (1000-1500 psi) to replace shutoff valve for pressure relief

Emergency Oxidizer Vent Valve allows run tank oxidizer to be vented if launch is aborted

FV 1

1/2"x1/4"

R-001
COMBUSTION CHAMBER
6.625" X 28.75"
500 psi @ 25 C

1/4"x1/8"

Injector plate now has five ⅛" holes for quick-connect fittings that hold the nylon fill lines while filling the run tank.

Each of the nylon fill lines has a ignition charge secured to it that will start burning fuel and detach the nylon line from the injector plate.

Fill Tank Control Valve controls flow of oxidizer from fill tank into the motor

FC 1

1/2"-316SS-N02-2

1/4"-Nylon-N02-3 to 7

TK-002
OXIDIZER FILL TANK
9" X 51"
700 psi @ 25 C

Pneumatic manifold splits the 1/2" SS piping into five 1/4" nylon fill lines

The external plumbing system includes all the components to be used to fill the on-board oxidizer tank. The Oxidizer will be stored in 2 50 lb Nitrous oxide tanks provided Airgas. Each tank with have a manual pressure regulator. Past the regulators, the flow will be combined into a single conduit, controlled by a remotely actuated ball valve. At the test stand, the stainless steel conduit will join with a manifold which divides flow into 5 nylon tubes which then mount into the push-to-connects on the injector plate. There will also be 3 nylon tubes that connect from one port on the injector plate to another, to seal off those holes.

Test Stand

Sean Kelley
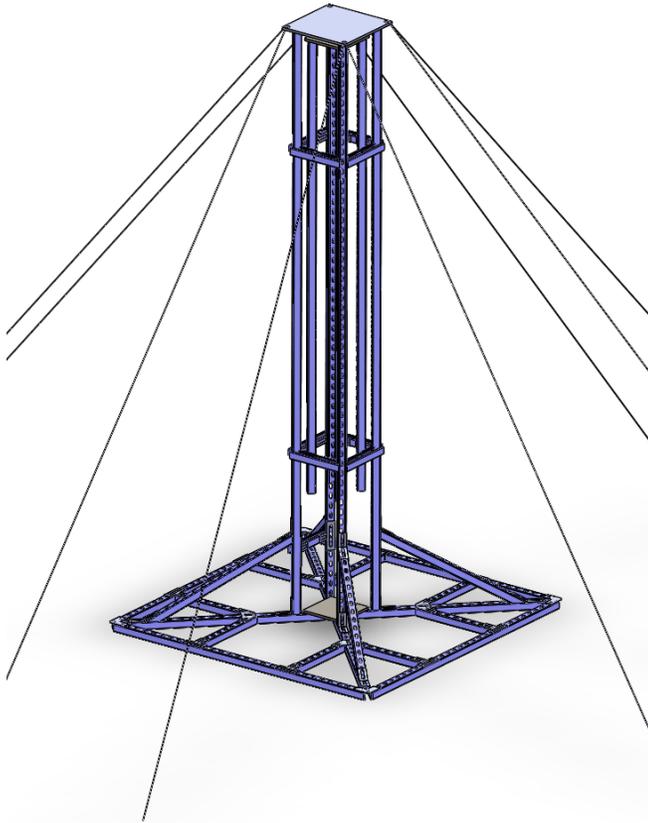
Figure 1. Test Stand Render

The purpose of the test stand is to provide a stable platform to record data from firing the Mk. 2 motor. It will support the weight of the motor and restrain its thrust to preserve safety during testing.

KEY CONSIDERATIONS

Maximum load force: 800 lb. load

Thermal Stress from exhaust

DESIGN OVERVIEW

The test stand consists of a base support structure, an inner tower attached to the motor, an outer tower restraining the inner tower supported by eight cables in tension (each with a load strength of 2600 lbs), and a concrete flame scoop underneath the motor. The outer tower will be loaded primarily in tension while the inner tower will be loaded in compression. The main component for all structures is Unistrut, which was used for its versatility in design and strength. The struts are galvanized steel made to ASTM A569 standards. These struts are bolted together using brackets, made of A36 steel. Additionally, the current design has the outer tower welded to its top plate. However, for practicality of assembly, we are considering removing the welds and instead mounting the outer tower with brackets.
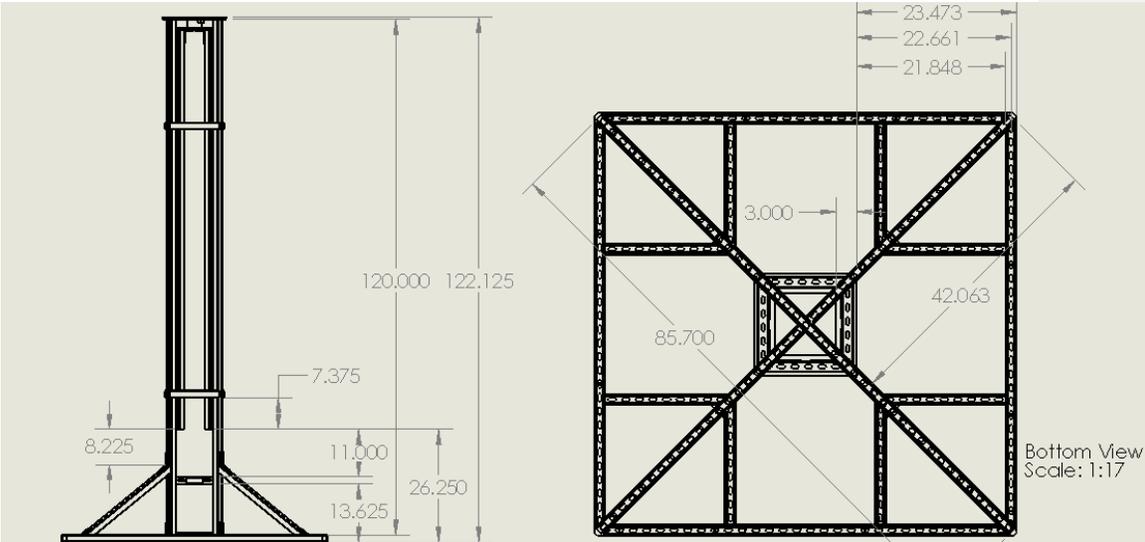
Safety Factors
Tension loaded outer struts **20.73**
Cables 3.36

Shear Bolts (outer to inner towers) **9.95**
Turnbuckles **1.55**
Eyebolts **3.01**
Anchor Pullout **6.83**
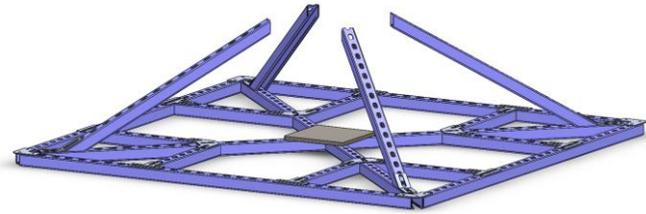
Figure 2. Test Stand Base
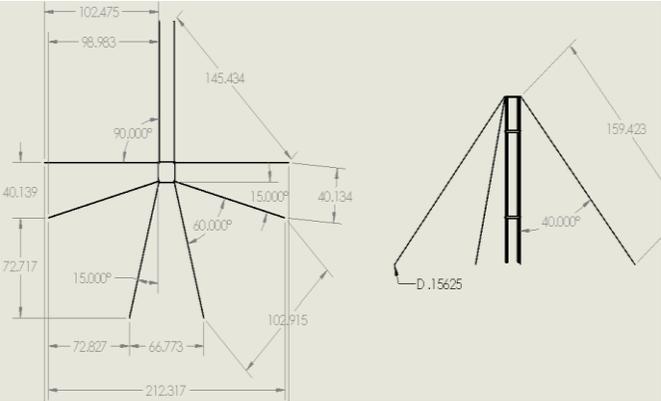
Figure 3. Exterior Tower Drawing
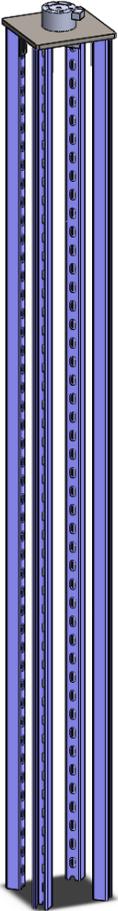
Figure 5. Inner
Tower Render
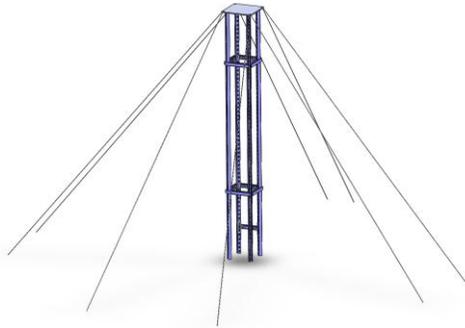
Figure 4. Exterior Tower Render

Flame Diverter

To avoid doing excessive damage to the runway or test stand, we constructed a steel reinforced concrete flame diverter or 'flame scoop.'

The flame scoop serves to divert the exhaust from the nozzle, located approximately three inches above it. It is concrete reinforced with rebar. It diverts the flame horizontally out to one side of the stand. The decision to locate the nozzle so close the flame scoop was made to reduce the risk of the struts (more structurally important than the flame scoop) being affected and possibly melted by the exhaust. Against the back of the flame scoop, a horizontal support will be placed to take the lateral load from the flame scoop. This load will be at a maximum of 800 pounds, but is likely to be lower.
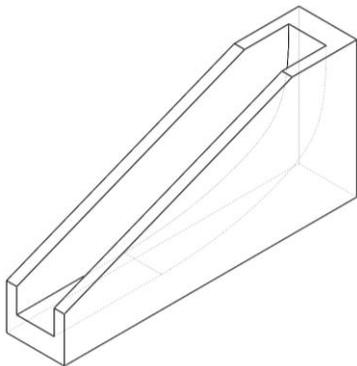
Oxidizer Tank Retaining Rings

The oxidizer tank requires a mechanism for mounting to the inner tower of the test stand.

The selected design is 2 aluminum rings with geometry designed for maximal safety and minimum weight. The shape of the rings is determined by the shape of the oxidizer tank. The rings, when mounted, will have 1/8" neoprene glued to their surface to ensure a snug fit with the tank and reduce vibrations.

Figure 1. Oxidizer Tank Retaining Rings Render

TEST STAND ASSEMBLY PROCEDURE

During a test, the stand will be assembled in four steps:
1. Pre-Test preparation
2. Base assembly
3. Motor, inner, and outer tower assembly
4. Tower to base connection and cable attachment

Pre-Test preparation

1. The cables looping through the outer tower plate will be installed with padding
2. Bolt and nuts that in locations difficult to reach, such as on the bottom of the strut will be put in place loosely to hold their place for use during assembly

Base assembly:

1. The locations of the anchors will be measured, and the anchors will be installed in the concrete
2. The flat pieces of the base (outer square, diagonal struts, and supporting struts) will be laid out with brackets, and loosely bolted together
3. The outer struts will be bolted to each other first, followed by the diagonal and supporting struts
4. Many pieces will be bolted together upside down as needed so that the nuts can be reached
5. All bolts in this assembly will be checked (marked) and tightened

Motor, inner, and outer tower assembly:

1. The tower struts will be loosely bolted to the top inner plate
2. The top retaining ring for the oxidizer tank will be slid through the struts and bolted into place
3. The oxidizer tank will be slid through the struts, and the bottom retaining ring will be bolted into place to restrain the tank, with the ring being pushed on to ensure a tight fit

4. The central plumbing fixture (without burst disk or Pressure Transducer) will be attached for length
5. The bulkhead, combustion chamber, and nozzle will be slid through the struts until the nozzle lip reaches the struts, and the bulkhead and nozzle will be bolted into place
6. Spring nuts will be placed into the struts to designated bolt locations, each strut will have four of these
7. The inner tower will be slid into the outer tower, lined up and bolted into place
8. All bolts in this assembly will be checked for tightening

Tower to base connection and cable attachment:

1. Anchors and eyebolts for the cables will be installed in the proper locations
2. The outer tower will be raised by hand and held in place by people on the base
3. With the tower still being held, the vertically angled supports will be attached
4. The cables, already attached and hanging from the plate, will be attached to turnbuckles
5. The turnbuckles will be attached to the eyebolt anchors, and tension will be applied

This type of assembly process was chosen because the inner tower assembly can not fit horizontally through the outer tower, and the motor components can not fit horizontally through the inner tower. The base assembly and tower construction can occur simultaneously, as there is no interface until the tower assembly is complete.

Some parts of the assembly may take place before transporting the test stand to the test site.

Avionics

A. GENERAL DESCRIPTION
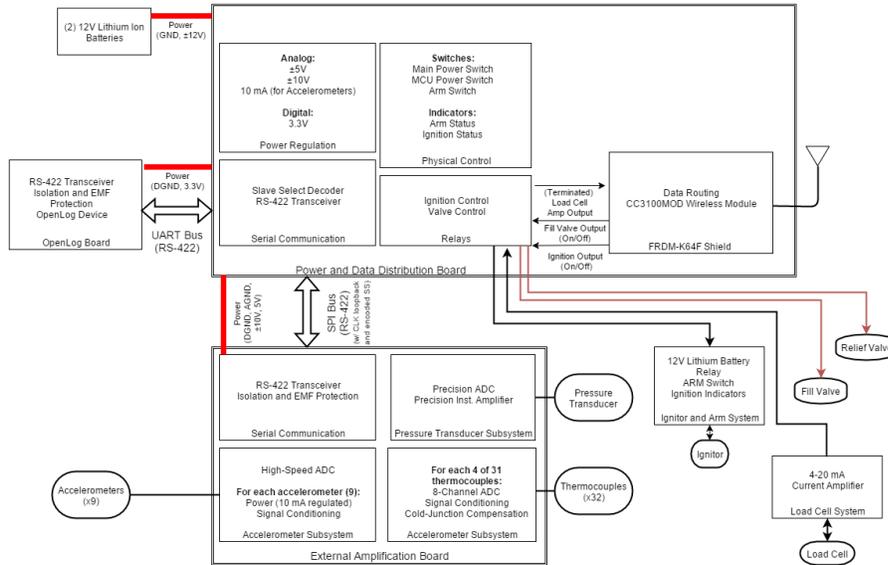
Figure 1. Block Diagram of Test Stand Avionics Systems

The Avionics systems of the Mk. 2 test stand consist primarily of data acquisition, communication, and open control loop systems, as shown in Figure 1 and detailed in the following sections. These systems allow for the collection of test data, including flow line pressure, motor force as measured by the load cell, motor oscillations as measured by 10 mono-axial accelerometers, and near-nozzle chamber temperature as measured by a ring of 30 K-Type Thermocouples.

This data will be continually sampled and stored redundantly to an onboard SD card and a remote logging device at least 30m away. A filtered and down-sampled subset of the data will also be streamed back to Ground Control. Control signals will be received from Ground Control to initiate the Fill Sequence, to stop the Fill Sequence early, to initiate the Ignition Sequence, or to perform an Emergency Vent. No other controls are possible. Software and Hardware checks are included to thoroughly defend against the possibility of accidental ignition before the device has been properly armed and the pad cleared, or when sensors indicate unsafe conditions.

B. SENSORS

1. Pressure Transducer

Purpose

The Pressure Transducer allows for the measurement of fuel line pressure, which provides insight into the burn profile, the status of the combustion chamber, and any motor oscillations that might occur. For more information on these oscillations, see 3. Accelerometers.

Specifications

The instrument should have a response time of under 100 μs and should achieve a Frequency Response from DC to at least 1 kHz. It must be able to measure and sustain pressures of up to 2000 psi, and it should be secured using a ¼" MNPT connector. The device should be compatible with an excitation in the range of 5-12VDC. The instrument we have selected to correspond to these requirements in the AST4300[5].

Data Conditioning and Acquisition

The AST4300 includes built-in amplification to a 1-5 VDC signal that, after filtering, can be read directly by the relevant ADC in the Data Acquisition System (See F. Data Acquisition Board). Although the 3dB-bandwidth of the instrument is only up to 1 kHz, a first-order analog filter with a cutoff frequency of 1.5 kHz will be implemented to increase our rejection at the Nyquist frequency by 21dB. The excitation of the instrument will be provided by regulated

Relevant Calculations

Filter Magnitude at 5 kHz $\approx -40 \log_{10} {5 \text{ kHz}}/{1.5 \ kHz} = -21 \text{ dB}$

2. Load Cell

Purpose

The load cell allows us to determine the amount of thrust generated by the rocket, as well as how that thrust varies over time, i.e. its burn profile. Secondarily, the load cell allows for weighing the motor assembly on the pad and is crucial for determining when the motor has been sufficiently filled and the fill sequence is complete.

Specifications

The load cell and its amplifier must be capable of measuring up to 1000 lbf, as well as withstanding without damage a maximum load of 1500 lbf. and a side load of 400 lbf. The full scale error of the device and amplifier should be less than 1.0%. The response time should be under 100 μs, and the resonant frequency must be above 10 kHz. The frequency response should include DC to at least 1 kHz, and filtering should be employed to minimize frequency components above 5 kHz. To meet these criteria, we have selected a Honeywell Model 41 Low Profile Load Cell with a full scale output of

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[5] http://www.astsensors.com/hazardous_location_pressure_transmitters/AST4300

3000 lb.[6] The output of this device is a 3 mV/V signal (0-30 mV total signal range @ 10V excitation) that is then conditioned and amplified before being input to an ADC on the main Microcontroller Unit.

Data Conditioning and Acquisition

The Honeywell Model U3W in-line current amplifier[7] provides all necessary excitation of the instrument, as well as filtering and amplification to a 4-20 mA signal. This output is terminated on the Power and Data Distribution Board with a 165 Ohm resistor to provide a 0.66V – 3.2V signal to the microcontroller. The data will be sampled at a rate of 10 kS/s to allow for frequency analysis to detect motor oscillations and distinguish between their kinds.

3. Accelerometers

Purpose

Accelerometers, in addition to the load cell and pressure transducer, allow for us to analyze the appearance and propagation of standing waves in the combustion chamber. These oscillations can be reflective of various problems in the motor, assembly, or fuel grain. The frequency and location of these oscillations can provide insight into their cause and consequently allow for the design to be modified to mitigate them.

Specifications

The accelerometers should be standard IEPE accelerometers and should be able to measure up to 30g. They should be compatible with an excitation of 8-10 mA, and they should provide a frequency response from at least 1 Hz to 3 kHz. The rise time should be under 100 μs, and the transverse sensitivity should be under 10%. The resonant frequency must be above 10 kHz. The devices should be capable of withstanding at least 125°C. To meet these specifications, we have selected the Wilcoxon HT-780A accelerometers.[8]

Data Conditioning and Acquisition

The HT-780A accelerometers require a constant current source of 2-10mA capable of rising to at least 18VDC, and their output includes a large DC offset of 12-13 VDC. This will be removed using a bandpass filter with cutoff frequencies of under 1 Hz and over 1 kHz, respectively. The details of this filter design are not yet fully determined. Once the signal is filtered appropriately, the signal will be re-biased around 2V to allow the reading of negative and positive accelerations by the relevant ADC. All of these excitation and filtering requirements are accommodated for in more detail in the Data Acquisition Board detailed in Section F.

4. Thermocouples

Purpose

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[6] https://measurementsensors.honeywell.com/ProductDocuments/Load/Model_41_Datasheet.pdf
[7] https://measurementsensors.honeywell.com/ProductDocuments/Instruments/Model_U3W_Datasheet.pdf
[8] http://www.wilcoxon.com/prodpdf/HT780A%20spec%20(99198)A.pdf

Thermocouples allow for the identification of a critically uneven burn in the combustion chamber that threatens to burn through the wall of the chamber. These pockets of heat can often be less than 1" wide, so over 30 thermocouples will be needed to form a complete ring around the bottom of the combustion chamber.

Specifications

Thermocouples should be K Type and capable of measuring up to 1250 K. Thermocouples must be ungrounded to prevent the formation of ground loops to the combustion chamber. A ring clamp will be used to affix them to the outside of the combustion chamber.

Data Conditioning and Acquisition

Thermocouple signals are on the order of 41 µV/K, giving us a full signal range of about 0-41mV. Consequently, the signal will have to be amplified by a gain of about 100. Furthermore, cold junction compensation is necessary to correct for variation in the temperature of the reference junction. This will be provided using a basic thermistor circuit. The AD7124 ADC that will be used for thermocouple data acquisition has specialized functionality for amplification, filtering, and cold junction compensation of thermocouples. For more information, see section F. Data Acquisition Board.

C. ACTUATION AND CONTROLS

1. Fill Valve

Purpose

The fill valve mounts to the external plumbing system immediately adjacent to the flow regulators. It remotely controls oxidizer flow from the fill tanks through the external plumbing system. See External Plumbing for more information.

Specifications

The valve assembly should include a ball valve, pneumatic actuator, and a DC solenoid coil rated at either 12 or 24VDC. The current drawn by the solenoid coil should be no greater than 500 mA. The valve must be normally closed when the solenoid coil is de-energized.

Control

The valve is on/off, so the control signal is a digital signal directly from the main MCU. This signal is connected to a relay that, when activated, closes the solenoid coil circuit to the battery, energizing the coil and opening the valve. Flyback diodes will be employed in the circuit to guard against the danger of feedback voltage when the inductive load is turned off. These will slow down our switching times, but the valves take at least 0.25s to actuate and so this effect is not considered significant in comparison.

2. Relief Valve

Purpose

The relief valve is used to vent nitrous oxide from the external plumbing system. If, at any point before firing, the line needs to be vented, this will be done by the relief valve. It

is important to note that this is a preventative safety measure; active safety for the filling system comes from the nylon fill lines which will rupture first and vent nitrous should the lines over-pressurize.

Specifications and Control

Specifications and Control are the same as in 1. Fill Valve.

3. Ignition and Arm System

Purpose

The ignition and arm system allows for beginning the burn of the motor and includes several safety precautions to ensure that this is not done while anyone is within an unsafe distance of the pad. The ignition system both lights the fuel grain and starts the flow of oxidizer to begin the burn proper. The arm system provides an indication of the status of attempted ignition, as well as safety features that physically disconnect the ignitor from the ignition control of the MCU while the device is unarmed.

Specifications

Ignition must include physical open switches obstructing the path of current flow while the device is unarmed. It must also include a buzzer to alert those on the pad that the device is armed. Indicator lights should be included to notify when current is flowing and when an ignition signal is being received from Ground Control. Ignition power must be drawn from a separate battery, to prevent a brownout from occurring in the rest of the Avionics systems.

The ignitor itself will be a simple solid fuel ignitor that works in conjunction with pyrogen on the fuel lines for ignition and cutoff of the fueling lines. For more information on ignition, please reference the External Plumbing section under motor design.

Control

The ignition signal is ultimately a single digital signal from the main MCU that is connected to the ignitor relay and battery assembly. However, software must include various redundant checks to verify that operating conditions are safe and as expected and that a go-ahead has been received by all relevant engineers at Mission Control. That is, the software must enforce to the full extent possible the safety requirements outline in the Standard Operating Procedures.

D. WIRELESS COMMUNICATIONS LINK

1. Purpose

The Wireless Communications Link will provide long-range (>300m) wireless communication between Ground Control and the Test Stand. This link will be responsible for the transmission of all control signals to the test stand, including Ignition, Fill Valve, and Relief Valve control. Furthermore, the link will allow for a select subset of test data to be streamed in real time back to ground control. This stream will have a data rate of approximately 1.2 kbps (For more information, see G. Software).

2. Specifications

The link will include an 802.11b connection capable of sustaining 500 kbps transfer at a range of 400m. The system will implement a full TCP/IP stack, and all data streams will use TCP for its robust built-in transmission ordering, error detection, and recovery.

The system will operate within standard FCC regulations for point-to-point unlicensed communications in the 2.4 GHz band.[9] The EIRP (Equivalent Isotropically Radiated Power) of the system will be no greater than 42 dBi, allowing for a maximum transmit power of 18 dBm.

3. Current Design

Major system components include:
- Test Stand
  - TI CC3100 Wi-Fi Network Processor[10]
  - TP-Link TL-ANT2424B 24 dBi Parabolic Antenna[11]
- Mission Control
  - EDUP EP-DB1607 Wireless USB Adapter with RP-SMA connector[12]
  - TP-Link TL-ANT2424B 24 dBi Parabolic Antenna

The CC3100 module includes an ARM processor to allow offloading of all network stack and wireless protocol details. This greatly simplifies any complications for the data acquisition and controls loops, allowing them to run largely uninterrupted on the main Microcontroller Unit (MCU). The SPI protocol is used for all communication with the MCU, and a dedicated SPI bus not shared by other devices and running at 10 MHz will be used for wireless transmissions.

4. Relevant Calculations

$$\textbf{Cable Loss} = \left(32.2\,\frac{\text{dB}}{100}\,\text{ft.}\right)(10\ \text{ft.}) = \textbf{3.22 dB}$$

$$\textbf{Free Space Loss} = \frac{4\pi(400\ \text{m})(2.4\ \text{GHz})}{2.9979\times10^8\ \text{m/s}} = \textbf{92.12 dB}$$

RX Power

$$(Effective\ TX\ Power) - 2\times(Cable\ Loss) - (Free\ Space\ Loss) + (RX\ Antenna\ Gain)$$

$$= (17\ dBm + 24\ dBm) - 2\times(3.22\ dB) - 92.12\ dB + 24\ dB = -45.6\ dBm$$

RX Power = **-45.6 dBm**

$$\textbf{Link Budget} = 17\ \text{dBm} - (-87\ \text{dBm}) = \textbf{104 dBm}$$

F. DATA ACQUISITION BOARD

1. Purpose

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[9] http://www.air802.com/files/FCC-Rules-and-Regulations.pdf
[10] http://www.ti.com/lit/ds/symlink/cc3100.pdf
[11] http://www.tp-link.com/resources/document/TL-ANT2424B_V1_Datasheet.pdf
[12] http://www.hiroinc.com/product_details.php?item_id=34

The data acquisition board will be an auxiliary to the power and data distribution board where sensor data will be collected from the accelerometers, thermocouples, and pressure transducer. The analog data from the sensors will be fed into analog to digital converters and communicated to the power and data distribution board using an SPI bus.

2. Specifications

Major system components include:
- ADS8332 Low-power, 16-bit, 500-kSPS, 4 differential input Analog-to-Digital Converter[13]
- AD7124-8 Low-power, 24-bit, 4.8-kSPS, 8 differential input Analog-to-Digital Converter[14]
- 74AC11138 3-line to 8-line decoder (for Slave Select lines)[15]
- SN65C118E RS-422 Transceiver[16]
- Constant-current diodes rated at 7-10 mA (for Accelerometers)

The ADS8332 will be used to sample the accelerometers and pressure transducer is the. It is an 8-channel, unipolar ADC with a sampling rate of 500kSPS. Samples from this device will be taken in a round robin pattern at 10kSPS per channel, for a total of 80kSPS per device. Samples from multiple devices will be taken synchronously using built-in daisy chain support, and reads to the MCU will be triggered by an interrupt output indicating that conversion is complete and data is ready. A total of 2 units will be used to accommodate the 10 accelerometers and 1 pressure transducer.

Excitation and filtering of the accelerometers is provided by additional circuitry on-board. Each accelerometer is dedicated a constant-current diode made up of a Fairchild J112 JFET and a resistor (~250 Ω).[17] The precise value for this resistor must be chosen for each diode experimentally due to the wide manufacturing variations in Gate-Source Cutoff Voltages of these JFET devices (-1 to -5 V). A bandpass filter with a 3dB bandwidth of 1 Hz to 3 kHz provides additional filtering and removes the large DC bias of 12-13V, but the details of this filter design are not yet determined. After filtering, the signal will be re-biased around 2V for reading into the ADC, to allow for the reading of negative accelerations.

The AD7124-8 will be used for sampling all thermocouples. It is an 8 channel, differential input device with a sampling rate of 4.8 kHz. Given the very slow response time of K Type thermocouples (>0.1s), the channels will be sampled at no more than 10 Hz. The ADC will be used in conjunction with a thermistor which will provide cold junction compensation, and will behave as a reference for the thermocouples. A total of 4 units will be used to accommodate the approximately 32 thermocouples.

The SPI Bus will be clocked at 5 MHz and will be carried over a differential link (RS-422) to the Power and Data Distribution Board using an SN65C1168E transceiver. In response to the length of this connection and the corresponding propagation delay, we

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[13] http://www.ti.com/lit/ds/symlink/ads8332.pdf
[14] http://www.analog.com/media/en/technical-documentation/data-sheets/AD7124-8.pdf
[15] http://www.ti.com/lit/ds/symlink/74ac11138.pdf
[16] http://www.ti.com/lit/ds/symlink/sn65c1168e.pdf
[17] http://www.farnell.com/datasheets/1887779.pdf

have modified the SPI implementation include a feedback clock from the slave to the master, which is fed in conjunction with the slave data into a separate SPI device on the main MCU configured as a slave. This allows for the MCU to receive a fully skewed clock and to correctly interpret the skewed slave data on the MISO line. This implementation follows results published by TI for extending the SPI Bus for long distance communication.[18] Additionally, a 3-wire chip select signal from the MCU will be sent separately from the SPI bus and will be decoded using a 74AC11138 3-to-8 line decoder to allow for a maximum of 8 SPI devices. No propagation concerns have been considered for these lines, since they switch only at the beginning and end of the communication sequence.

3. External Connections

The SPI bus will use a 10m CAT5e STP cable and jack terminated with 100 Ω to carry the differential RS-422 signal. A separate signal and power bus provides from the main Power and Data Distribution Board the 3 Chip Select wires as detailed in the previous section, in addition to Analog power rails of ±10V, 5V, and AGND and digital power rails of 5V and DGND. External connections to the thermocouples will be provided using standard mini ANSI thermocouple connectors. The pressure transducer and accelerometers will be connected using 3-wire connectors of an as-of-yet undetermined kind.

E. POWER AND DATA DISTRIBUTION BOARD

1. Purpose

This board acts as a primary interface between the MCU and the rest of the Avionics system, including data acquisition and telemetry components. The boards primary responsibilities include voltage regulation, signal and power distribution between various systems, and providing a direct interface for the wireless link via the CC3100 wireless transceiver module.

2. Specifications

Major system components include:

- REG1117 Low dropout Positive Regulator[19]
- LT1175 Low dropout Negative Regulator[20]
- LM2576HV Adjustable 3A Step-down Regulator[21]
- SN65C118E RS-422 Transceiver[22]
- SparkFun OpenLog data logger[23]
- CC3100 Wireless Transceiver Module[24]

[19] http://www.ti.com/lit/ds/symlink/reg1117.pdf
[20] http://cds.linear.com/docs/en/datasheet/1175ff.pdf
[21] http://www.ti.com/lit/ds/symlink/lm2576.pdf
[22] http://www.ti.com/lit/ds/symlink/sn65c1168e.pdf
[23] https://github.com/sparkfun/OpenLog/wiki/datasheet
[24] http://www.ti.com/lit/ds/symlink/cc3100.pdf

The power and data distribution board will regulate the ±12V coming from two external lithium ion batteries to 3.3V, ±5V, and ±10V. 3.3V will be achieved using an LM2576HV to first step down from 12V to 5V, then an REG1117 will step down from 5V to 3.3V. Such a regulation scheme was selected to reduce heat dissipated over a single regulator and increase current output. +10V regulation uses an REG117, +5V regulation uses an LM2576, while both -5V and -10V regulation use LT1175 negative regulators. This regulated power is routed to the DAQ board, OpenLog device, load cell amplifier, and the MCU, while also powering onboard components.

This board will also hold the physical power switches for the system, as well as physical control measures for arming the ignitor. All control signals transmitted by the MCU are routed through this board to the external ignitor relay as well as the fill and relief valves using onboard relays.

The same RS-422 transceiver will be used on this board as on the DAQ board (SN65C118E) to handle SPI communication between itself and the DAQ board. Another transceiver of the same model will be used to transmit a data stream created by the MCU to the OpenLog device using a UART protocol. The analog signal coming from the load cell amplifier is routed to the ADC onboard the MCU, then back to the power and data distribution board after being digitized and processed with other signals into 1 data stream consisting of all data needing to be recorded (load cell, pressure transducer, accelerometers, thermocouples). It is then sent to the OpenLog device to be recorded. The MCU itself will save a copy of the data stream locally, but in the event of catastrophic failure, the OpenLog device will be able to preserve important data needed to troubleshoot the failure.

The CC3100 wireless module will communicate with mission control via 802.11 b/g/n. All data to be transmitted will be sent directly from the MCU via SPI.

3. External Connections

The SPI and UART buses will use a 10m CAT5e STP cable and jack terminated with 100 Ω to carry the differential RS-422 signals. Power will be distributed separately to the DAQ board. Control signals, power, wireless, and the SPI bus will be wired directly from the power and data distribution board to the MCU by making the power and data distribution board into a shield to fit on top of the MCU.

F. TESTING METHODOLOGY

All circuits will be tested in operating conditions from 25°C to 75°C. Power regulation circuitry will be characterized for various resistive loads and its corresponding temperature measured. The SPI bus will be tested at operating frequencies up to 20 MHz, and we expect that at least 10 MHz will be achievable with the current system. Sensor data will be logged for at least 1 hour on three distinct dates and then manually reviewed to ensure accurate and stable readings. Connectors will be disconnected and reconnected upwards of 50 times to ensure reliable connection and disconnection. Assembly will be performed by the designated Mk. 2 test personnel and should be completed correctly within 30 minutes on at least 5 separate occasions.

The various possible states of safety circuitry (armed, disarmed, unsafe pressure, etc.) and instrument connections (thermocouple disconnected, load cell disconnected, etc.)

will be simulated using artificial sensor data to the MCU, and correct operation of the control signals will be manually verified. A toolset and standard procedures will be created for performing this test exhaustively, and the test will be performed 24 hours before any test of the Mk. 2 motor.

Preliminary Filling and Firing Procedure

I. Assembly

Once the test site is reached (most probably Hearne Municipal Airport in Hearne, TX), the motor will need to be assembled. This motor is not initialy to be tested around stranger, onlookers, or any kind of audience, as that would create unnecessary chaos during the building and firing phase with extra people. Similarly, every team member or adult who is there is to have a designated job. The assembly group will be divided into the following positions and/or groups:

Range Safety Officer: The responsibility of the RSO, most likely to be Chris Harris, is to ensure the safety of the entire team throughout the testing process. He or she may or may not be accompanied by another safety officer, such as the Chief Safety Officer for Rice Eclipse.

Lead Engineer: The responsibility of the LE is to oversee the assembly, filling, and firing of the motor. He or she will instruct the other groups when to assemble and disassemble, when to fire and when to fill in corroboration with the RSO.

Test Stand Group: The responsibility of the test stand group is to assemble and disassemble the stand on site. This is the most fundamental and first thing that needs to be done on site, so immediately when boots hit the ground, this team will begin assembly. This is also the last portion of the motor to be disassembled and the very end of the test.

Combustion Chamber Group: The responsibility of the combustion chamber group is to delicately assemble the combustion chamber. This is one of the most intricate pieces of the motor, and time must be taken to ensure correct assembly. All seals must be checked by the LE, and extra care must be taken with the graphite and nozzle.

Motor Insertion Group: The responsibility of the motor insertion group is to take all pieces of the motor and build them systematically in the test stand. This process cannot be started until the test stand group is finished, so this group may be made of members who are also part of the test stand group. The parts that will be inserted are: Ox tank (with retaining rings), plumbing, and finally the combustion chamber.

Plumbing Group: The responsibility of the plumbing group is to build and ensure the functionality of the plumbing that connects the tanks and fills the motor. This includes constructing the blast wall for the filling tank(s), building the line from the fill tank(s) to the run tank, and checking all fittings for their security.

Avionics Group: The responsibility of the avionics group is to set up and operate all electronic equipment throughout the testing process. This includes, but is not limited to, the valve control, the pressure transducer(s), the load cell, data collection, and ignition. This is the last group to give the okay before the motor can be tested, and it will also most likely be the largest group on the site.

When the team reaches the site, all groups will immediately get to work with their responsibilities to the best of their ability. If any team members are idle or waiting for their turn, they should move away from the test site so as not to hamper the efforts of the other groups. Additionally, this increases the safety factor of the entire test. Overall, the assembly process will operate in the following manner. Initially, many things will be constructed in tandem. The test stand will be put up, including the inner tower attached through the load cell. The combustion chamber will be assembled on a table or surface. The plumbing and tank interface will be erected, including the blast wall for the filling tank(s). The avionics will be set up at the control site and the test site, and the connectivity will be secured. After the test stand is finished, the motor insertion group will begin to insert the ox tank and the plumbing (with the help of the plumbing group), and will also insert the combustion chamber when it is finished.

II. Safety Checklist

Before initiating the filling process, there should be a list of procedural safety items that should be addressed. This is to ensure that if there is a design flaw of the system, it can be dealt with in the best possible way. The following are items that should be address, but they are not the only items that need to be addressed.

- All structural bolts must be in place and tightened
- Cables and grounded bolts should be in place and tightened
- There should be no significant deformation of the test stand due to its own structure or the weight of the motor
- The flame scoop should be inserted and aligned
- The combustion chamber should be sealed completely, with a ½" gap between the bulkhead and the combustion chamber
- The graphite should be sealed to the nozzle, attached through epoxy or another adhesive agent
- The combustion chamber must be at least 3 inches above the lip of the flame scoop to ensure that the concrete does not interfere with the exhaust
- The ring securing the nozzle lip to the inner tower must be in place
- All motor parts must be inserted and calibrated
- The measured length of the motor assembly must be within 5% of the designed length to ensure that there is no considerable warp
- The nylon filling bundle must be inserted and aligned, with the pyrogen bundle secured
- All plumbing must be connected and tightened
- Plumbing that is designed with insulation should be insulated
- The blast wall should be constructed and physically sound
- All avionics must be responsive and all code must be finalized before initiating the test procedure
- The load cell and pressure transducer must be calibrated

- The local fire department and any other community parties must be alerted as to an approximate time of ignition

III. Filling Procedure

Due to the both the nylon filling method through the combustion chamber and the vented screw in the ox tank that allows a pressure difference, the filling procedure cannot really be separated from the firing procedure, as one will happen directly after the other. In other systems, the filling happens minutes or even hours before the fire, but this system requires all participants to be ready for a fire as soon as the filling begins.

Once the safety checklist has been cleared, and the LE, the LSO and all groups are comfortable with beginning the filling portion, the process can begin. The lead avionics engineer on site will audibly confirm with the above parties that they are ready to begin, and then actuate the main filling ball valve. Once this is actuated, nitrous oxide will immediately begine entering the run tank. This process should take around 10 minutes plus or minus 5 minutes, depending on the temperature and the ambient humidity (the explanation of this calculation can be found in the plumbing documentation).

The LE and relevant engineers should watch the motor, as generally if something is dangerous or going wrong, there is a visual sign. For instance, if the plumbing is not tight, plumes will be seen at the joints. Additionally, if the nylon lines get blown out of their sockets, the plume will be seen. There will be a pressure transducer in the fill line that will give solid data as to the pressure at the exit of the fill tank. If the nylon lines come out, though, this system will not be able to see it due to the pressure at the fill tank being identical. This is why a visual examination should be kept at all times. The only place on the motor where there should be a plume is the vented plug at the top of the oxidizer tank.

When the engine is full, this plume should become denser due to liquid being expelled from the motor instead of gas. The motor should be safe at all times, as every part of the motor is rated to over 700 psi, but all personnel should be at the blast radius or above in case there is a failure in the structural integrity of any pressurized component. Once the filling is completed and confirmed by the RSO, the main valve can be shut off, which will conclude the filling process.

IV. Pre-Fire Checklist

Because of the rigorous safety checklist before filling, there is a relatively small pre-fire checklist. Also, the motor will continuously be venting to ambient due to the vented bolt in the top of the oxidizer tank, which means that the time between the end of filling and ignition should be cut down by as much as possible. The following items need to be checked before ignition:
- The connectivity of electronic components must be checked
- There should only be one plume of nitrous coming out of the vented screw, and a visual check should uncover no other sources of nitrous on the motor
- The RSO must be comfortable with the proceedings

V. Firing Procedure

Once the decision to ignite has been reached, all groups must confirm again that they are prepared for the test. All parties must be alerted as to the coming test. The lead

avionics engineer will engage the ignition, and the process will start. Additionally, when the ignition is flipped, the vent valve should also be triggered to prevent any kind of explosion in the fill line. If any accident occurs during firing, the system will automatically switch off due to the software put into place in the engine, but if this does not engage or there is a more catastrophic danger, the avionics engineer must always have the ability to immediately disengage the test at his or her discretion without the permission of any other person at the site, including the safety officers.

If the igniter does not function or there is another issue with the motor that requires a discharge of the oxidizer, the avionics engineer will have the ability to confirm this course with the LE and RSO, and then trigger the secondary empty valve attached to the fill line that will drain the motor of its oxidizer in a similar amount of time to filling.

If the test is completed without any hiccups or malfunctions, the motor will automatically finish and sit idle. Then the team should wait approximately 15 minutes or more, depending on the recommendation of the LSO, to approach the motor. Additionally, if the motor has had an issue, catastrophic or not, it is up to the LSO to determine the amount of time before it is safe to approach the motor.

VI. Post-Firing Procedure

After the test fire has ended and the LSO has determined that the motor is safe to approach, the team may examine the motor. Caution is encouraged, as the motor will be very hot and could even be structurally frail. If the team is attempting another test in the same day, the entire motor must be disassembled and examined between tests, including the oxidizer tank and the run tank plumbing. This is to ensure that all components are still sufficient to use again on the same day.

The test stand does not need to be disassembled, as all parts are clearly visible and apparent while assembled, but it should still be examined closely. The most important part of any successful test is the structural integrity of the test stand, so if there is any question regarding that aspect, the test should not be conducted.

If the test was the final test of the day, the test stand will be disassembled and the team will resort to their assembly groups in order to take apart and pack all aspects of the motor.

Further Work

There are several things we wish to do in terms of both design and documentation that are not included in this packet. This includes but is not limited to:

- o Material compatibility check to ensure that the Nitrous Oxide does not interact adversely with any of our components. This will inherently include a comprehensive wetted materials list
- o Hydrostatic test of the oxidizer tank to 1000 psi (~1.5x operating pressure)
- o Actuation and Control stress testing
- o Practice assembly, modification to assembly procedures as necessary
- o Cleaning of all wetted surfaces after assembly including Acetone, Isopropyl Alcohol, water, and drying steps
- o Heat Transfer Analysis of the combustion chamber leading to accurate predictions of transfer to the chamber walls and exhaust temperatures
- o Completion of Burst disk testing circuit to verify reliability

- o Full, comprehensive machining drawings of every machined component
- o Categorized bill of materials

Appendix

A. ADDITIONAL DESCRIPTION

Oxidizer Tank
The run tank stores the oxidizer needed for the hybrid rocket motor to ignite.

The tank is made of 6061-T6 aluminum alloy and is designed to be 7.81" in diameter and 47.201" tall, to hold the maximum of 29.85 pound-mass of nitrous needed to achieve the full 35,000 Newton-second impulse over a 10 second burn time. A simulation on the specified tank was done in SOLIDWORKS with a load of 1000 psi normal to the interior faces of the tank and with the max von Mises stress criterion as the default failure criterion. The simulations yielded a minimum Factor of Safety (hereafter FOS) of 3.02 and a maximum resulting displacement of 0.328477 mm (see Figures 1-6 below).

Internal Plumbing
Nitrous Oxide
Our plumbing system was designed with respect to the properties of nitrous oxide (hereafter "nitrous"). The critical temperature of nitrous is 36.37 Celsius (97.47 Fahrenheit), and the critical pressure of nitrous is 72.45 bar (1050.8 psi) [1]. The fact that nitrous is subcritical (i.e. slightly below critical temperature) at room temperature means, as the liquid nitrous flows out of the bottom of the run tank (i.e. the oxidizer tank inside the rocket) and into the combustion chamber and vapour above it loses pressure, some of the liquid nitrous vaporizes to counteract the loss of vapour pressure. But the energy for vaporization is gained by cooling the liquid nitrous, which reduces the temperature and thus pressure of gas vaporized afterwards. This results in the run tank pressure falling over time, but nitrous loses tank pressure more slowly than other oxidizers [2]. More details on the run tank are covered in the component-specific "Run Tank" subsection below.

Desired Impulse
Our propulsion system has been designed for a 10 second burn time, which results in an impulse of 35,000 Newton-seconds. However, for our test-fire of the rocket, we plan for a 2-second burn time, which reduces the total impulse to 7000 N s.

Wetted Materials
The entirety of the plumbing system may be wetted, so all components must be chemically compatible with the process fluid (nitrous oxide) and also resistant under the expected pressure and temperature conditions. 316 Stainless Steel has good chemical compatibility with nitrous oxide, so it is the primary material for the plumbing components [source: chemical compatibility]. Additionally, the primary tube OD is 1/2" for 316 Stainless Steel tubing with tube wall thickness of 0.049", as it has a maximum working pressure of 3700 psig [source: swagelok tubing datasheet] The internal piping connects all of the IPS components. It consists of a main line that connects the run tank and the injector plate, and two branches that connect the pressure transducer and the burst disk to the main line.

All internal piping is 1/2" 316 Stainless Steel pipes, and the various components are connected with Swagelok tube fittings. The two tee junctions on the main line are SS Swagelok Tube Fitting, Union Tees, 1/2 in. Tube OD (part no. SS-810-3), and the elbow for the pressure transducer is a SS Swagelok Tube Fitting, Female Elbow, 1/2 in. Tube OD x 1/4 in. Female NPT (part no. SS-810-8-4). In addition, the connection between the run tank and the rest of the IPS is a SS Swagelok Tube Fitting, Male Connector, 1/2 in. Tube OD x 3/4 in. Male NPT (part no. SS-810-1-12), and the connection between the burst disk and the IPS is a SS Swagelok Tube Fitting, Male Connector, 1/2 in. Tube OD x 1/2 in. Male NPT (part no. SS-810-1-8). However, the connection between the combustion chamber and the IPS is an Alloy 254 Swagelok Tube Fitting, Male Connector, 1/2 in. Tube OD x 1/2 in. Male NPT (part no. 254-810-1-8). This was due to a mistake in ordering, and it can be seen that Alloy 254 has the sufficiently similar physical qualities as 316 SS, except that it is more resistant to corrosion.

Because the internal piping will not be supported (as opposed to the run tank and combustion chamber, which will be supported with retaining rings), the piping was cut to be as short as possible, while still accommodating the entire IPS.

The pressure transducer is a non-incendive AST4300 pressure transducer/transmitter [25]with a male 1/4" NPT process connection and a pressure range of 0-40,000 psig.

Combustion Chamber

Design Explanation

It is important to note that we chose not to bolt the combustion chamber walls into the bulkhead because we did not want extra stress to fall on anything as the aluminum expands. Also because of this, we put about ½" in between the top of the combustion chamber walls and the bottom of the bulkhead. The thermal expansion coefficient of aluminum is 22.2E-6 (m/(m*K)), and therefore the expected expansion of the chamber (assuming a peak combustion chamber temperature of around 400 C) will be (22.2E-6)(0.6096m*(673-293))=0.0051425856 m, or .202 inches, which gives us a factor of safety of 2.5 on the expansion. Also, one of the reasons that the factors of safety are so high for the combustion chamber is to ensure that if failure occurs, it is not catastrophic. That is to say, if the pressure drastically increases, the failure point will be through an o-ring instead of through a hole created in the combustion chamber wall. Contrary to the usual approach, this method was instituted to attempt to circumvent issues due to temperature fluctuation. It should be noted, however, that the bulkhead (and the pre-combustion chamber) will effectively be actively cooled by the expanding nitrous, so it remains to be proven if this method is completely effective. The radial deformation of the bulkhead due to cooling will be significantly less than the longitudinal deformation of the combustion chamber, through, which means it is more likely to encounter problems with the heated combustion chamber pushing against the bulkhead than the bulkhead losing contact with the combustion chamber.

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[25] http://www.astsensors.com/files/pdf/AST4300-C1D2-pressure-transmitter.pdf

Simulations
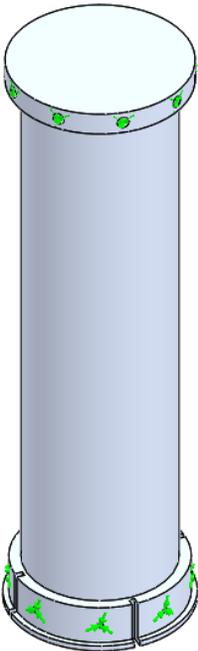
26
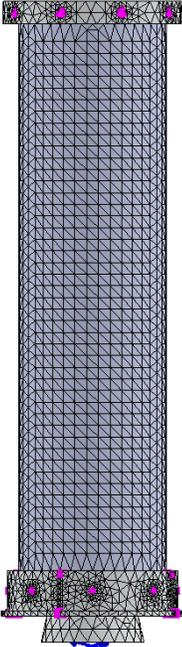
27
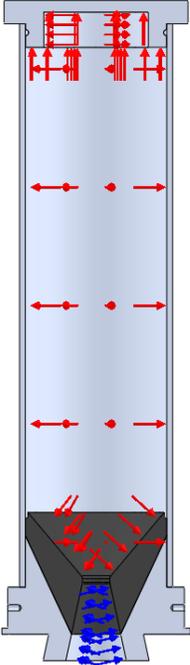
28

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[26] Hinge restraints applied to combustion chamber CAD model
[27] Generated mesh using fine mesh around bolted connections.
[28] Pressures applied to combustion chamber, 500 psi within the chamber and 220.3 psi on the diverging end of the nozzle. The basis for those number can be found in the calculation section.
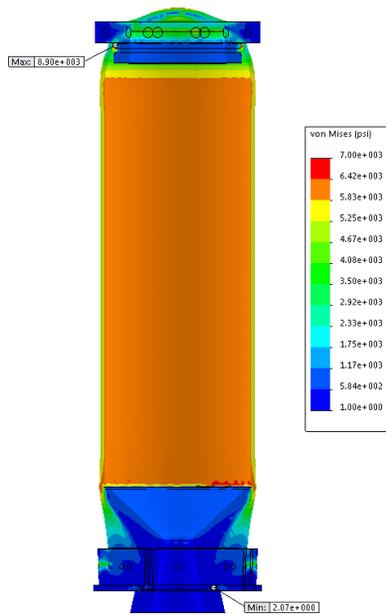
29
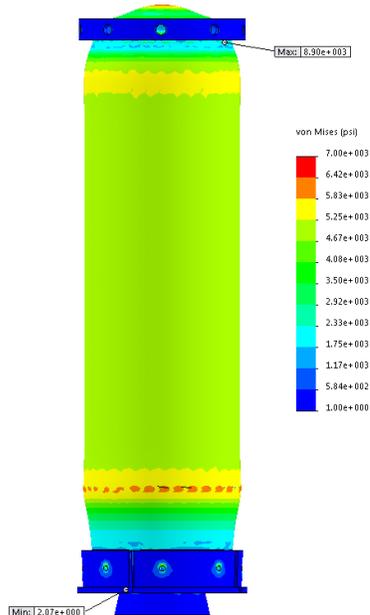
30

The above figures show the von Mises Stresses in section and exterior views, respectively. The maximum von Mises stress occurs at the edge of one of the lower restraint bolt positions on the nozzle casing. However, with a value of 8470 psi, this stress is less than a fifth of 6061 T6 Aluminum's 39885 psi yield strength. More importantly, the combustion chamber walls and bulkhead face both experience relatively low stresses as well and are nowhere near failure.

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[29] Combustion Chamber Stresses (Section View)
[30] Combustion Chamber Stresses (Exterior View)
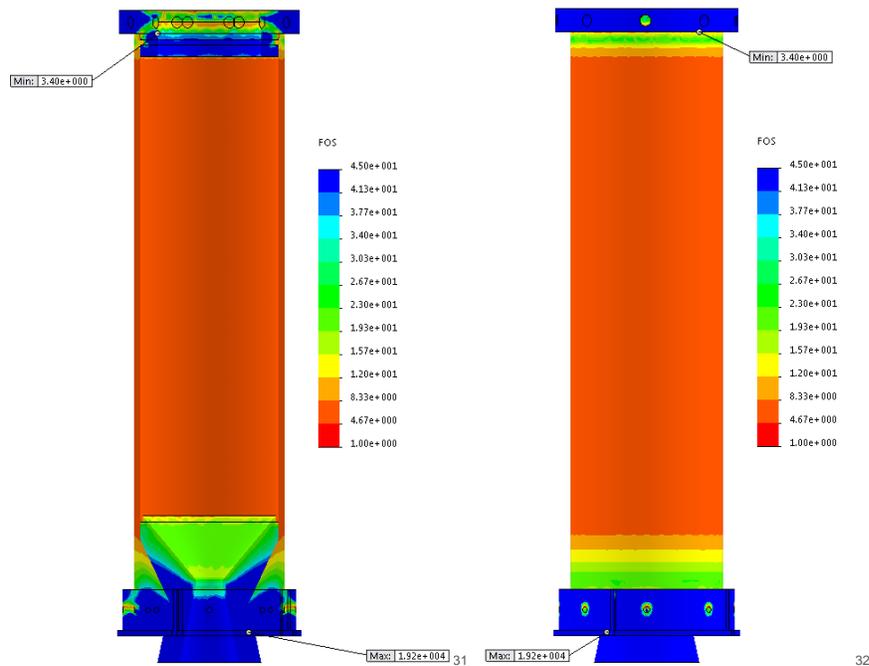
To reinforce the positive nature of the results, a factor of safety result was also calculated comparing the stress to the ultimate yield stress. The above figures show a minimum aluminum factor of safety of 4.71 at the edge of the restraint bolts, replicating the von Mises Stress results as expected. Additionally, the combustion chamber walls have a factor of safety between 5 and 25, as does the bulkhead.

Fuel Grain

Background

The fuel grain provides the combustion reaction that propels the rocket. The use of a solid fuel grain provides a measure of safety as well as the future possibility of customizing the fuel using additives to optimize c*. The fuel grain is a significant limiting factor to the thrust and therefore the overall efficiency of the rocket. Another major area of concern is the type of fuel used. Hybrids typically use a high-density polymer, such as HTPB (hydroxyl-terminated polybutadiene) or PVC, and a liquid oxidizer. Some research has been done using liquid fuel and solid oxidizer, however it has not been as promising and is significantly less stable or safe. The Eclipse Mk 2.0 motor uses 100% HTPB, with the option of future optimization by doping with paraffin wax

Nozzle
As part of the rocket's propulsion system, the nozzle is responsible for accelerating the extremely energetic gases produced by the combustion of fuel and oxidizer to supersonic speeds. The

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[31] Section View of Factor of Safety
[32] Exterior View of Factor of Safety

ejection of these gases at such high velocities produces the thrust necessary to propel the rocket. In order to accelerate the combustion products, which can be assumed to be initially at rest relative to the rocket, laws of fluid mechanics for flow through a conduit can be utilized, namely the following equation:

$$dVV(Ma2-1) = dAA$$

Where V represents the gas's velocity, A represents the cross-sectional area of the conduit, and Ma represents the flow's Mach number (a dimensionless relationship between velocity and the local speed of sound) for the given cross section.

This relationship tells us that for Ma < 1 (subsonic flow), the change in the fluid's velocity is inversely proportional to the change in the conduit's cross sectional area. This means that a decreasing cross sectional area will increase a subsonic flow's speed. On the other hand, when Ma > 1 (supersonic flow), the change in the fluid's velocity is directly proportional to the conduit's cross-sectional area. This means that an increasing cross-sectional area will increase a supersonic flow's speed.

Using this information, the converging-diverging nozzle was designed, by which the initial subsonic flow is accelerated through a decreasing nozzle cross section, reaching Ma = 1 at the so-called *critical area*, and then accelerated into supersonic speeds through an increasing nozzle cross-section.

Several nozzle designs, such as the bell nozzle, plug nozzle, and aerospike nozzle have demonstrated much greater levels of efficiency than the conical nozzle. Due to the limited capabilities of the Rice Oshman Engineering Design Kitchen machine shop (which lacks a CNC turning center but does have several lathes) and inadequate funding (preventing outsourcing to a private manufacturing firm such as Proto Labs), we are unable to construct any of these advanced nozzle designs for the Mk II motor, and instead opted for the conical nozzle. This design can easily handled by manual lathes by nature of its purely linear geometry.

Design Specifications
Broad Design

Unfortunately, Mk II combustion chamber temperatures are calculated to exceed 3300 K (determined by ProPEP 3, see Section X for ProPEP 3 walkthrough), which would rapidly melt a purely-aluminum nozzle. Graphite, an industry standard for nozzles in amateur rocketry, was chosen for the manufacturing of an insert which would be placed inside an aluminum casing. This casing would in turn be fixed to the rocket body, firmly attaching the assembly to the rocket. The aluminum casing is necessary, as graphite performs well under compression (suitable for an insert) but fails easily under shear (not suitable for fixing to rocket body). Full design drawings can be found in Section X for better visualization.

The combination of the graphite insert's resistance to high temperatures and aluminum's strength allows this design to maintain structural integrity under the extreme temperatures and forces experienced by a rocket nozzle.

Materials & Machining

In terms of raw materials necessary for manufacturing and integration, the nozzle is relatively simple. The list of components and any corresponding raw materials is as follows:
1. Aluminum casing – Aluminum Alloy 6061-T6. The aluminum casing is the backbone of the nozzle, serving to hold the graphite insert in place and acting as an appropriate connecting surface between the nozzle and both the combustion chamber and rocket body (more specifically the fin can). It also forms the nozzle outlet, the geometry of which is important for optimal exhaust expansion.
2. Graphite insert – Graphite Grade GR060. The graphite insert acts to resist the high temperatures generated by the combusting gases, shielding the aluminum casing and preventing it from melting. The graphite insert mates with both the aluminum casing and the combustion

chamber (see assembly drawing for detailed visualization). The insert also forms the converging cone, the throat, and a portion of the diverging cone. Thus, the insert plays a crucial role in accelerating the exhaust gases to supersonic speeds.

3.   Fasteners - ¼-20 SAE Grade 5 hex head bolts. These fix the nozzle to both the combustion chamber and fin can, and prevent the pressure forces in the combustion from ejecting the nozzle.

4. Helical inserts - 3534-1/4x1.5D Aluminum Alloy 6061. In order to ensure that the threads of the aluminum casing bolt holes are not stripped, helical inserts are installed in the bolt holes. These helical inserts better distribute the shear forces on the hole threads and reduce the risk of the bolts tearing out and allowing the nozzle to eject. These inserts are installed with Loctite 272 Red High Temperature Threadlocker to prevent the inserts from unscrewing due to vibrations.

Geometry

As noted previously, the converging-diverging nozzle takes advantage of the laws governing subsonic and supersonic flows to accelerate the exhaust gases to and beyond Mach 1. In order to achieve this, two dimensions of the nozzle are of particular importance: the throat area (the narrowest cross-sectional area in the nozzle conduit) and the outlet area (the exit of the nozzle, where the supersonic gases are expelled into the atmosphere). The throat area is designed so that the exhaust gases achieve Mach 1 at the throat, and the exit area is designed so that the combustion gases are optimally expanded for thrust efficiency. If the gases are not able to expand enough (underexpansion) or the gases are expanded too much (overexpansion) in the diverging section of the nozzle, thrust efficiency is decreased.

The calculations which were used to determine the throat and outlet dimensions are discussed in section X. The dimensions are as follows:

- Area expansion ratio – 4.864
- Throat area | diameter – 6.8690e(-4) in^2 | 0.0296 in
- Outlet area | diameter – 0.0033 in^2 | 0.0652 in

These dimensions ensure that the exhaust flow will achieve supersonic speeds in the diverging section of the nozzle.

Other critical dimensions necessary for defining the geometry of the nozzle is the converging half-angle (the half-angle of the converging cone) and the diverging half-angle (the half-angle of the diverging cone). Here, general rules of thumb used in amateur rocketry were applied. Typically, a converging half-angle of 20-45° and a diverging half-angle of 12-18° are used (Braenig, 2012). We opted for the following dimensions:

- Converging half-angle - 40°
- Diverging half-angle - 12°

Higher half-angles result in a shorter, lighter nozzle. Due to the nozzle's conical (opposed to bell) geometry, lower half angles were chosen to maximize impulse by minimizing inefficiencies arising from flow separation from the boundary layer (nozzle wall) after the throat and from possible underexpansion. At the same time, weight considerations were taken into account, as is apparent in the relatively large converging half-angle.

The following remaining dimensions are necessary to fully define the geometry of the nozzle. They are:

- Combustion chamber ID - 6"
- Fin can ID - 7.315"
- Rocket body OD - 8"

Using these dimensions, the basic geometric features of a nozzle can be defined.

Additional Design Features/Considerations

The following elements of the nozzle design go beyond basic geometric and material considerations. They aid in ensuring the integrity of both the nozzle and the entire propulsion system.

- Fiberglass liner seating diameter - a portion of the graphite insert OD (at the converging end) is turned down in order to securely seat the combustion chamber's fiberglass liner.

The tight clearance between the two surfaces also has the effect of partially sealing the combusting gases from escaping around the nozzle.

- O-ring gland – an O-ring gland and corresponding O-ring are placed in the mating surface between the aluminum casing and the combustion chamber to further seal the combustion chamber and prevent gas from escaping around the nozzle. The O-ring being used is is an oil-resistant Buna-N O-ring, which is chemically compatible with nitrous oxide. The actual cross-sectional area of the O-ring is 0.139", for which a gland of depth 0.121" and width 0.193 is prescribed.
- Fin notches - in an effort to further stabilize the rocket fins, the fins are designed to extend through the fin can and firmly seat in four notches milled lengthwise into the aluminum casing at 90° intervals about the circumference. The fins are not bonded to the aluminum casing (they will be bonded to the fin can) and simply serve to reduce the deflection of the fins during flight due to aeroacoustic vibrations.
- Thrust plate - there is a distinct risk of the motor tearing up through the rocket if the force of thrust is not effectively translated to the entire rocket body. This, in theory, could be accomplished by the fasteners which connect the forward bulkhead and nozzle to the rocket body. Bolt holes in a fiberglass fin can may not be able to sustain the stresses exerted by the fasteners, and so a small lip on the aluminum casing was designed to extend to the full rocket body outer diameter, coming flush with the bottom edge of the fin can and distributing the thrust force to the rocket body in a safer fashion.

Test Stand

Design Description

The test stand consists of a base support structure, an inner tower attached to the motor, an outer tower restraining the inner tower supported by eight cables in tension, and a concrete flame scoop underneath the motor. The main component for all of these is unistrut, which was used for its versatility in design and strength. The struts are galvanized steel made to ASTM A569 standards. These struts are bolted together using brackets, made of A36 steel. Some brackets are currently made of aluminum but these will be remade in steel by the time of the test.

The base support structure consists of a square base, with struts protruding inwards from the corners for the outer tower to sit on. These diagonal struts have a supporting strut on either side to prevent horizontal or rotational movement of the outer tower. Each diagonal strut also connect to an angled support which is bolted to the top of the base, and to the side of the outer tower. This is to hold the tower in its vertical position. Each strut along the outside of the base has two bolts connecting to drop in anchors in the concrete.

The outer tower consists of four struts that are ten feet long and welded to a .5" thick steel plate on one end. Each strut is held to the diagonal strut and angled support by a steel bracket. Between each of the outer tower struts there are two sets of horizontal struts to prevent twisting of the tower, although there should be minimal force to cause rotation.

The flame scoop serves to divert the exhaust from the nozzle, located approximately three inches above it. It is concrete reinforced with rebar. It diverts the flame horizontally out to one side of the stand. The decision to locate the nozzle so close the flame scoop was made to reduce the risk of the struts (more structurally important than the flame scoop) being affected and possibly melted by the exhaust. Against the back of the flame scoop, a horizontal support will be placed to take the lateral load from the flame scoop. This load will be at a maximum of 800 pounds, but is likely to be much lower.

The inner tower serves as the connection between the outer tower and the motor itself.

It also consists of four struts, 92 ⅞" long each, bolted to a .5" steel plate at the top using steel brackets, and touching the lip of the nozzle at the bottom. This results in the nozzle being approximately 4 inches above the top of the concrete flame scoop, with approximately eight inches of extra space between the oxidizer tank and the plate at the top. Each strut bolts to the motor in four places: the nozzle, the combustion chamber bulkhead, and the bottom and top retaining rings on the oxidizer tank. Each inner strut is bolted in four places to the nearest outer strut. These bolts support the weight of the inner tower as well as the thrust of the motor. They prevent motion relative to the outer tower which is fixed by the base and cables.

The cables, 159.4" long, connect through holes at the outer corners of the outer top plate. There are two cables at each corner, each cable perpendicular to the other and to the side of the plate it is facing. They are attached at a 40 degree angle vertically. The cables on the side of the exhaust will be splayed away from perpendicular by 15 degrees to avoid the flame. The cables directly next to these will then be splayed towards them by 15 degrees to account for the horizontal force from the flame scoop and the decrease in force in that direction caused by splaying the other cables. The cables have closed loops at each end fixed by compression sleeves. These loops are connected by a thimble to the outer plate, to prevent any cutting force from potentially sharp corners on the plate. At the other end, six of the eight cables loop through a closed connection turnbuckle which will be used to tension the cable on site. The other two cables will connect to a come-along with over three feet of adjustable length to allow for imperfection in the anchor placement. The turnbuckle or come-along will then connect to an eye bolt, bolted to the concrete using a drop in anchor. This anchor will be in a hole at least four inches deep to ensure connection to strong concrete, and tubing will be placed above the anchor around the bolt to prevent hole collapse during use. The 40 degree angle was chosen so that the angle of the connection to the eyebolt would be greater than 45 degrees, reducing risk of bending the eyebolt, while maintaining significant horizontal tension on the test stand to prevent tipping or twisting.

The anchors will be the same for both the cables and they will be installed prior to assembly of the test stand. They will be 5/32" diameter threads, installed in a ½" diameter hole to a depth of at least four inches. The bolts on the base will need to be at least 5 ⅝" long in order to fully contact the anchors, depending on the final depth of the anchors. This depth is currently uncertain because the site will be visited in February the month before the test in order to determine this depth and have the stand examined.

Throughout the stand, spring nuts are used in many places for better connection to the struts. Hex nuts are used where spring nuts are not applicable.

The force of the motor is measured by a load cell held between the top outer and inner plates. It can be configured to work in tension and compression; the weight of the motor and inner tower will be in tension, and once the motor is firing the thrust will be in compression. The load cell is two inches thick and has a cylindrical shape.

Testing
Weight - The force directed down by the weight of the motor and inner tower has not yet been precisely measured. It is approximately between 200 and 300 lbs. To test this force, two or three people, whose total weight is greater than 300 lbs, will hang from the stand assembled without the inner tower.

Thrust - The thrust is known to be near 800 lbs and is directed upward through the center of the stand. To test this, a pump jack will be used to apply a vertical force to the test stand.

VIEW A-A
45.000°

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Test Stand

32.799
29.046
30.000°
4.594
28.436
18.000
16.950
9.000
10.836
45.000°
17.524
20.399
58.697
60.322
61.947

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± .10

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
Steel

FINISH

DO NOT SCALE DRAWING

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

TITLE:
Base Assembly

SIZE DWG. NO. REV
A 1 of 1

SCALE: 1:17 WEIGHT: SHEET 5 OF 6
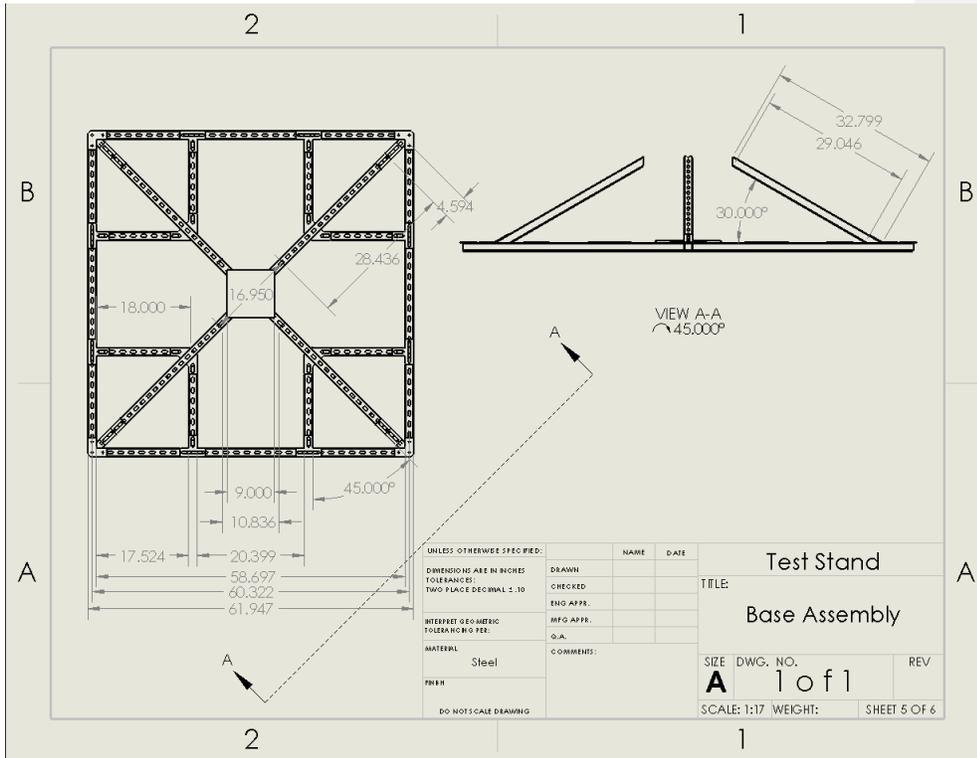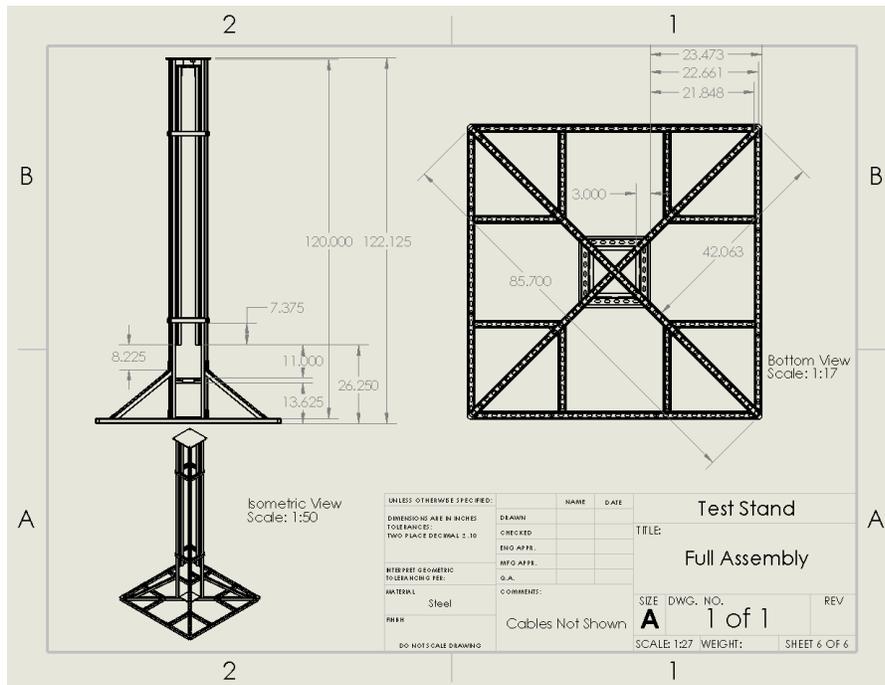
External Plumbing

The External Plumbing System (EPS) includes all of the components needed to prepare the IPS for a test fire or a launch (in other words, filling the run tank and disconnecting from the rocket). Our design for the EPS interfaces directly with the injector plate (the oxidizer is delivered through nylon piping that attaches to fittings on the injector plate), though we considered other filling methods (see Appendix C, "Filling Methods").

Fill Lines and Pneumatic Manifold

The fill lines are 1/4" nylon pipes, which connect to the injector plate holes with 1/4" x 1/8" quick-connect connections (McMaster part no. 9396T31). The pneumatic manifold (Pneumadyne model M30-250-5) functions as a 1-to-5 splitter that has one 1/2" NPT connection on its side and five 1/4" NPT connections on its top face for the fill lines. The manifold is made of machined Aluminum 6061 and has an maximum operating pressure of 1000 psi with non-shock air at 72 F and a temperature range of -10 to 200 F [source: Pnuemadyne Spec Sheet].

Fill Tank (External Oxidizer Supply)

The fill tank will store the oxidizer and will fill the run tank before each test-fire or launch.

The fill tank is a size 200 cylinder (9" in diameter and 51" tall) with a volume of 200 cubic feet [source: https://www.mathesongas.com/industrialgas/pdfs/Industrial-Cylinder-Dimensions.pdf].

We chose this size to provide at least enough nitrous for two full-impulse test-fires or launches.

The fill time was estimated through a two step process. First, we calculated how much oxidizer would be needed to cool down the fill tank to 0 degrees celsius, where nitrous can exist as a liquid around 300 psi. After that, we assumed that the pressure in the run tank was a constant at 300 psi, and used Bernoulli's equation to find how long it would take to fill with the fill line apparatus. It was determined to be 9.05 minutes, with an added unknown of plus or minus 5 minutes.

Fill Tank Control Valve
The fill tank control valve is an pneumatically actuated ball valve that controls the flow of the nitrous out of the fill tank. This valve will be placed immediately after the fill tank regulator, so that closing this valve (which will be done remotely) will make the fill tank approachable.

The valve is a 1/2" stainless steel ball valve (series 700076), and it has a C_v of 18.90, requires 53.10 in-lbs of torque (tested at 68 F, 0 psi, and purified water), and is pressure rated to 1000 psi. The actuator is a DA 32 that has a torque output ranging from 34 in-lbs to 101 in-lbs depending on the pressure of its air supply (from 40 psi to 115 psi) [source: Bonomi catalog].

Emergency Oxidizer Vent and Valve
The emergency oxidizer valve is an pneumatically actuated ball valve that, when opened (remotely), allows all of the oxidizer in the fill lines (and in the IPS) to flow out of the plumbing system. This will effectively abort any test-fire or launch, and is necessary to provide a safe option to depressurize the system if the test-fire or launch cannot continue. This valve will be placed immediately after the fill tank control valve, and will remain closed unless the entire plumbing system needs to be quickly relieved of the oxidizer.

The parameters of this part are outlined in the part examination at the beginning of this documentation. The emergency oxidizer vent will be connected to the main fill line with a SS Swagelok Tube Fitting, Union Tee, 1/2 in. Tube OD (part no. SS-810-3), and the valve will be connected to the 1/2" stainless steel piping with a 1/2" x 1/4" Medium Pressure Brass Hex Nipple (McMaster-Carr part no. 5485K36).

The time it takes to release the oxidizer should be almost identical to the time it takes to fill the tank. Extra time may be added due to the decreased radius of the vent valve (¼" versus ½"), but this value was not deemed to need a more specific estimation, as it will have no effect on the running of the motor, rather how long we have to wait after filing for the tank to empty.

B. PURCHASED PARTS

Injector Plate

O-ring: The O-ring store -425 S70 Silicone O-rings 70D
http://www.theoringstore.com/index.php?main_page=product_info&cPath=367_104_105&products_id=4523

Push-to-Connect : High-Pressure D.O.T. Push-to-Connect Fitting Straight Adapter for 1/4" Tube OD x 1/8 NPT Male, purchased from Mcmaster unit #:5148K123. $4.53 each, bought 11, one for each hole. http://www.mcmaster.com/#5148k123/=10xj96z

Test Stand
Anchors: McMaster 97045A041; ⅜"-16 Screw size, ½" Drill size, 2.375" length
http://www.mcmaster.com/#97045a041/=112kjd0

Cables: Web Rigging Supply 01AC1077G; 7x7 Wire Rope, 5/32" Diameter
http://webriggingsupply.com/pages/catalog/wirerope_cable/wirerope-galvanized.html

Come-Alongs: Haul Master 61964; 10' Length, winch puller
http://www.harborfreight.com/2-ton-cable-winch-puller-61964.html

Compression Sleeves: McMaster 3898T15; 5/32" Diameter, Zinc Plated Copper
http://www.mcmaster.com/#3898t15/=112kf6k

Eye-Bolts: E-Rigging 51710807; ⅜"-16 Screw size, 4.5" length
http://www.e-rigging.com/three-eighths-inch-X-4-half-inch-Eyebolt

Spring Nuts: Home Depot 798567; ⅜" Channel Spring nut
http://www.homedepot.com/p/Superstrut-3-8-in-Channel-Spring-Nut-5-Pack-ZA1003-8EG-10/100179881

Struts: Home Depot 455470; SuperStrut Metal Framing System - 12 Gauge Galvanized A-series
http://www.homedepot.com/catalog/pdfImages/77/779693a3-d428-4f9b-96d5-f2791538b5ee.pdf

Thimbles: McMaster 30335T3; ⅝" Opening, ⅜" rope
http://www.mcmaster.com/#30335t3/=112lham

Tubing: McMaster 9056K65; Aluminum 6061, ½" OD, .402" ID
http://www.mcmaster.com/#9056k65/=112kk9d

Turnbuckles: Cargo Control JJTBGV38X6; Jaw Connection, 6" adjustable length
http://www.uscargocontrol.com/Rigging-Supplies-Hardware/Jaw-Jaw-Galvanized-Turnbuckles/Galvanized-Turnbuckle-Jaw-Jaw-3-8-x-6

Plumbing
Internal piping: 1/2" 316 Stainless Steel
Internal plumbing fittings:
- 2x SS Swagelok Tube Fitting, Union Tee, 1/2 in. Tube OD (part no. SS-810-3)
- 1x SS Swagelok Tube Fitting, Female Elbow, 1/2 in. Tube OD x 1/4 in. Female NPT (part no. SS-810-8-4)
- 1x SS Swagelok Tube Fitting, Male Connector, 1/2 in. Tube OD x 3/4 in. Male NPT (part no. SS-810-1-12)
- 1x SS Swagelok Tube Fitting, Male Connector, 1/2 in. Tube OD x 1/2 in. Male NPT (part no. SS-810-1-8)
- 1x Alloy 254 Swagelok Tube Fitting, Male Connector, 1/2 in. Tube OD x 1/2 in. Male NPT (part no. 254-810-1-8)

Fill lines: 1/4" nylon pipes,
connect to the injector plate holes with 1/4" x 1/8" quick-connect (McMaster **9396T31**).
Aluminum 6061 pneumatic manifold with one 1/2" NPT input and five 1/4" NPT output ports (Pneumadyne M30-250-5)

Fill tank: size 200 cylinder (9" in diameter and 51" tall), volume of 200 ft^3 (to be provided by airGas)

Fill tank control valve: 1/2" bonomi stainless steel ball valve (series 700076), C_v of 18.90,
requires 53.10 in-lbs of torque (tested at 68 F, 0 psi, and purified water),
pressure rated (WOG) to 1000 psi.
The actuator is a DA 32 that has a torque output ranging from 34 in-lbs to 101 in-lbs

Secondary Vent Valve: 1/4" bonomi stainless steel ball valve (series 700076), C_v of 7.91,

requires 60 in-lbs of torque, pressure rated (WOG) to 1000 psi. The actuator is a DA 32 that has a torque output ranging from 34 in-lbs to 101 in-lbs

C. CALCULATIONS

Oxidizer Tank
The tank is made of 6061-T6 aluminum alloy and is designed to be 7.81" in diameter and 47.201" tall, to hold the maximum of 29.85 pound-mass of nitrous needed to achieve the full 35,000 Newton-second impulse over a 10 second burn time. A simulation on the specified tank was done in SOLIDWORKS with a load of 1000 psi normal to the interior faces of the tank and with the max von Mises stress criterion as the default failure criterion. The simulations yielded a minimum Factor of Safety (hereafter FOS) of 3.02 and a maximum resulting displacement of 0.328477 mm (see Figures 1-6 below).

Model Information

Model name: A-80TankModified
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Cut-Revolve1	Solid Body	Mass:19.0372 kg Volume:0.0070569 m^3 Density:2697.68 kg/m^3 Weight:186.565 N	C:\Users\tan3\Desktop\A-80TankModified.SLDPRT Oct 15 14:34:16 2015
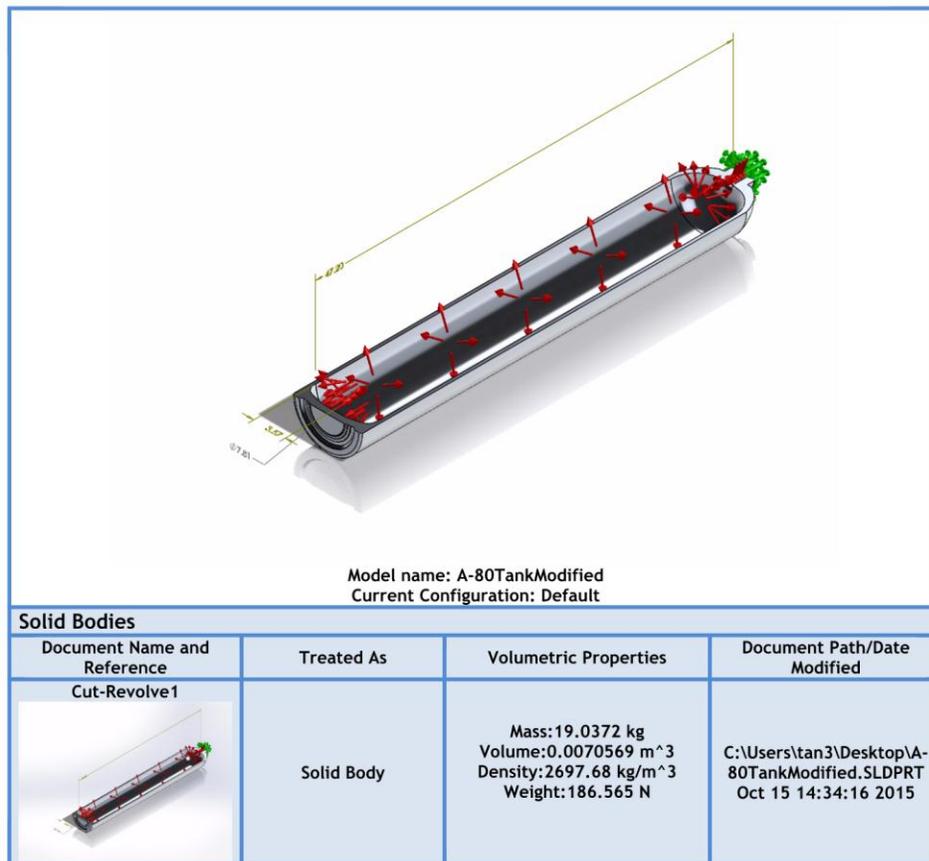
Figure 1: Solid Body Model Information

Material Properties

Model Reference	Properties	Components
	Name: 6061-T6 (SS) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Max von Mises Stress **Yield strength:** 2.75e+008 N/m^2 **Tensile strength:** 3.1e+008 N/m^2	SolidBody 1(Cut-Revolve1)(A-80TankModified)

Figure 2: Material Properties

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-7		**Entities:** 1 face(s) **Type:** Fixed Geometry
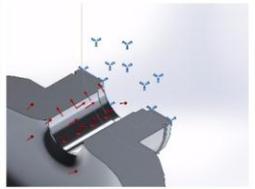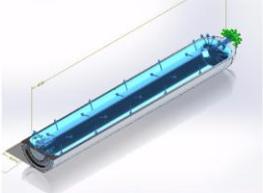
Load name	Load Image	Load Details
Pressure-1		**Entities:** 5 face(s) **Type:** Normal to selected face **Value:** 1000 **Units:** psi

Figure 3: Loads and Fixtures

Model name:A-80TankModified
Study name:SimulationXpress Study(-Default-)
Mesh type: Solid Mesh

Figure 4: Solid Model Mesh

Name	Type	Min	Max
Stress	VON: von Mises Stress	635413 N/m^2 Node: 18903	9.10019e+007 N/m^2 Node: 4495

Model name:A-80TankModified
Study name:SimulationXpress Study(-Default-)
Plot type: Static nodal stress Stress
Deformation scale: 364.99

von Mises (N/m^2)

9.100e+007

Min: 6.354e+005

7.594e+007

6.843e+007

6.088e+007

5.335e+007

4.582e+007

3.829e+007

3.076e+007

2.323e+007

1.570e+007

8.166e+006

6.354e+005

Yield strength: 2.750e+008

Max: 9.100e+007

A-80TankModified-SimulationXpress Study-Stress-Stress

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 3730	0.328477 mm Node: 4497

Figure 5: Results of Static Stress Simulation

A-80TankModified-SimulationXpress Study-Factor of Safety-Factor of Safety

Figure 6: Results of Factor of Safety Simulation

Hoop Stress is given by this equation:

$$=Prt$$

Eq. 1 - Cylinder Stress

Plugging this in for the oxidizer tank for its lowest chamber thickness (.25") is (700 psi*(7.81"/2)/.25")= 10,934 psi, or 75.387276 MPa. At room temp, Aluminum 6061-T6 has a yield strength of 276 MPa, which gives us a FOS of 3.66.

However, when lathing the tank from 8.00" in diameter to the specified 7.81", the tank was about 1/16" off-center, resulting in a thinner side of the tank (with wall thickness of 0.296") and a thicker side of the tank (with wall thickness of 0.365"). A simulation on this offset tank was done in SOLIDWORKS with a load of 1000 psi normal to the interior faces of the tank and with the max von Mises stress criterion as the default failure criterion. The simulations yielded a minimum FOS of 2.95 and a maximum resulting displacement of 0.126769 mm (see Figures 7-14 below).

Model Information

Model name: A-80TankModified (3)
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Cut-Extrude4	Solid Body	Mass:19.0309 kg Volume:0.00705584 m^3 Density:2697.19 kg/m^3 Weight:186.503 N	C:\Users\ayj3\Downloads\A-80TankModified (3).SLDPRT Feb 17 17:32:33 2016
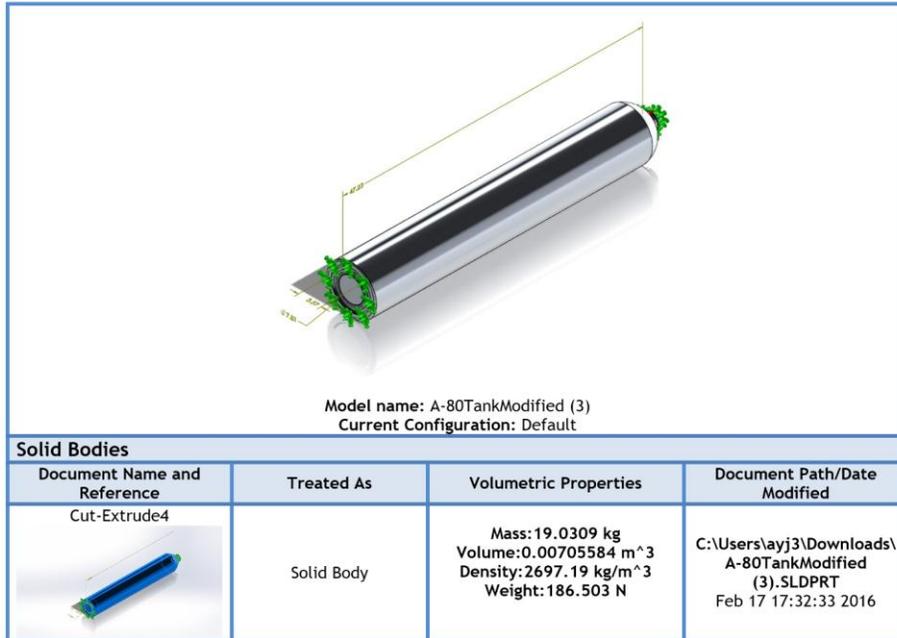
Figure 7: Model Information

Material Properties

Model Reference	Properties	Components
	Name: 6061-T6 (SS) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Max von Mises Stress **Yield strength:** 2.75e+008 N/m^2 **Tensile strength:** 3.1e+008 N/m^2 **Elastic modulus:** 6.9e+010 N/m^2 **Poisson's ratio:** 0.33 **Mass density:** 2700 kg/m^3 **Shear modulus:** 2.6e+010 N/m^2 **Thermal expansion coefficient:** 2.4e-005 /Kelvin	SolidBody 3(Cut-Extrude4)(A-80TankModified (3))
Curve Data:N/A		

Figure 8: Material Properties

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-5		**Entities:** 1 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	9.22577	146.612	45770	45770.2
Reaction Moment(N.m)	0	0	0	0

Fixture name	Fixture Image	Fixture Details
Fixed-6		**Entities:** 1 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-0.185928	-143.559	-49265.1	49265.3
Reaction Moment(N.m)	0	0	0	0
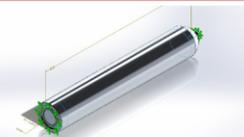
Load name	Load Image	Load Details
Pressure-1		**Entities:** 5 face(s) **Type:** Normal to selected face **Value:** 1000 **Units:** psi **Phase Angle:** 0 **Units:** deg

Figure 9: Loads and Fixtures

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.675133 in
Tolerance	0.0337567 in
Mesh Quality	High

Mesh information - Details

Total Nodes	34200
Total Elements	17724
Maximum Aspect Ratio	21.069
% of elements with Aspect Ratio < 3	89.4
% of elements with Aspect Ratio > 10	1.59
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:05
Computer name:	OEDK-31-1650

Figure 10: Mesh Information
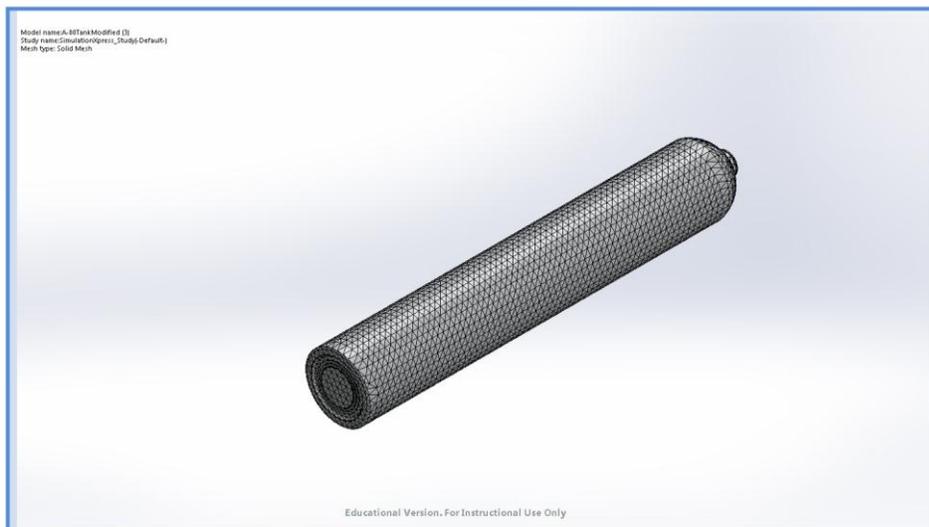
Figure 11: Solid Model Mesh

Study Results

Name	Type	Min	Max
Stress	VON: von Mises Stress	1.08489e+006 N/m^2 Node: 34006	9.30968e+007 N/m^2 Node: 4131
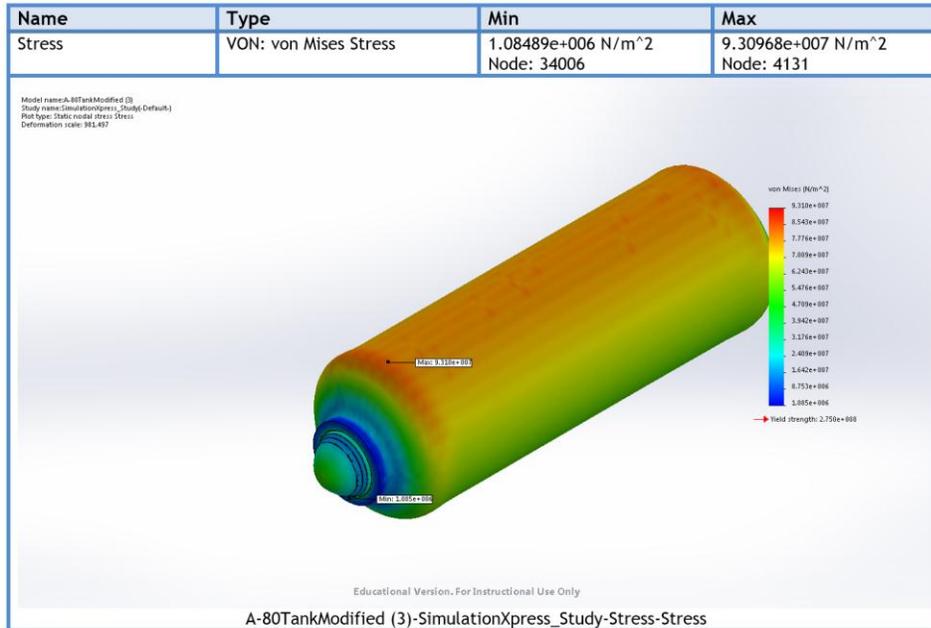
Figure 12: Results of Static Stress Simulation

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 9	0.126769 mm Node: 9253

Model name:A-80TankModified (3)
Study name:SimulationXpress_Study-Default-)
Plot type: Static displacement Displacement
Deformation scale: 981.497

Max: 1.268e-001

URES (mm)

1.268e-001
1.162e-001
1.056e-001
9.508e-002
8.451e-002
7.395e-002
6.338e-002
5.282e-002
4.226e-002
3.169e-002
2.113e-002
1.056e-002
1.000e-030

Min: 1.000e-030

Educational Version. For Instructional Use Only

A-80TankModified (3)-SimulationXpress_Study-Displacement-Displacement

Figure 13: Results of Resultant Displacement Simulation

Name	Type	Min	Max
Factor of Safety	Max von Mises Stress	2.95391 Node: 4131	253.481 Node: 34006

Model name:A-80TankModified (3)
Study name:SimulationXpress_Study-Default-)
Plot type: Factor of Safety Factor of Safety
Criterion : Max von Mises Stress
Red < FOS = 1 < Blue

Educational Version. For Instructional Use Only

A-80TankModified (3)-SimulationXpress_Study-Factor of Safety-Factor of Safety

Figure 14: Results of Factor of Safety Simulation

Injector Plate

1. The design of this plate was driven by the idea that we were filling the oxidizer tank through the injector plate. The inner size of the fitting is .125 inches, and so we used equations from sutton's rocket propulsion elements. These, and an algebraic reorganization of one, are outlined below

   a. $Q\ =\ propellant\ volumetric\ flow\ rate$
   $$\dot{m}\ =\ propellant\ mass\ flow\ rate$$
   $$Cd\ =\ discharge\ coefficient$$
   $$\rho\ =\ propellant\ mass\ density$$
   $$A\ =\ cross\ sectional\ area\ of\ the\ orifice\ (total\ area\ of\ holes)$$
   $$\Delta p\ =\ pressure\ drop\ across\ injector$$
   $$v\ =\ injection\ velocity$$
   $$\dot{w}\ =\ propellant\ weight\ flow\ rate\ =\ \dot{m}*g$$

$$Q = C_d * A * \sqrt{2 * \frac{\Delta p}{\rho}}$$

$$\dot{m} = C_d * A * \sqrt{2 * \Delta p * \rho}$$

$$v = \frac{Q}{A} = C_d * \sqrt{2 * \frac{\Delta p}{\rho}}$$

$$\Delta p = \frac{\rho}{2 * g}\left(\frac{v}{C_d}\right)^2$$

Using these equations and assuming:
- an estimated pressure drop of about 200 psi
- a mass flow rate of 1.36 $\frac{kg}{s}$
- the density of liquid nitrous oxide to be 786 $\frac{kg}{m^3}$
- the orifice is a short tube with a rounded entrance, giving us a discharge coefficient of ~ 0.9

Using these assumptions, and specifically an algebraic reworking of the massflow equation

$$\dot{m} = C_d * A * \sqrt{2 * \Delta p * \rho}$$

we calculated the total area that we needed, and divided that by $0.0123\ in^2$ to get 11 holes.

Chamber Wall and Bulkhead

$$\sigma = \frac{P * r}{t}$$

Eq. 1 - Cylinder Stress

where sigma is the stress, P is the pressure, r is the mean radius, and t is the wall thickness. In our example, $P = 3.447 * 10^6\ Pa, r = 0.15875\ m, t = 0.0127\ m$, so sigma=43 MPa. Because the tensile yield stress of aluminum 6061-T6 is 276 MPa, we have a factor of safety of 6.418. Using different values for yield stress due to different temperatures, the FOS changes. As is shown below in the table (data from http://www.matweb.com/search/datasheet_print.aspx?matguid=1b8c06d0ca7c456694c7777d9e1 0be5b), the chamber fails at around 250 degrees Celsius. Peer research shows us that most hybrid combustion chambers reach around 150 degrees Celsius, which is much within our range.

Temperature (C)	Yield Strength (MPa)	FOS
24	276	6.418
100	262	6.093
149	214	4.977
204	103	2.395
260	34	0.791

Table 1 - Varying FOS due to Temperature

Similarly, the Area of the bulkhead is .5*.127 m2=0.01266768698 m2.
The pressure on the bulkhead is 700 psi (4.82633 MPa), which means the force on the top is approximately 61,139 N. The longitudinal stress on the face is therefore $\frac{4.82*10^6 Pa*0.1397m}{0.0127\ m*4} =$ 13,271,500 Pa, which means a FOS of 20.7 on the Aluminum bulkhead.
Also, the bulkhead has 8 steel bolts that are ¼" in diameter. Let us assume for the moment that the entire possible thrust is operating through these bolts, which would mean up to $\frac{437.5\ N}{\pi*\frac{1}{8}*\frac{1}{8}} = 8,912.68\ Pa$, which gives a factor of safety of 46,415 for even the lowest grade steel. In

the case of the test stand, there are only 4 bolts, so 17,825.36 Pa, and a FOS of 23,207.5. The groove for the o-ring ensured less than a 40% compression by depth of the silicone (rubber has a danger of ablating), and allows for enough room for it to expand. The internal combustion pressure is known to be 500 psi (as a higher pressure would result in unsafe motor conditions). In a complete burn, the motor will produce 1,124 lbs of thrust. This thrust is due to the resultant force of the exhaust pressure on the divergent end of the nozzle. In a design like this, with a constant divergence, that pressure can be calculated as follows: $P_e = \frac{thrust}{A_{nozzle}*\sin(\theta_{divergence})}$ In this case, substituting the correct values for the parameters yields the following:

$$Thrust = 1,124\ lbs$$
$$Nozzle\ Area = 19.71\ in^2$$
$$Divergence\ Angle = 15^o$$

$$\cdot P_e = \frac{1124 lbs}{19.71 sin(15)} = 220.3\ psi$$

Test Stand
The load on the end of the strut was calculated for pure compressive or tensile force:

The SolidWorks file gave an area of $0.55282\ in^2$

With a force of 800 lbs, the stress is $\frac{800}{.55282} = 1447\ psi$

With a yield strength of 30000 psi, the safety factor is $\frac{30000}{1447} = \mathbf{20.73}$

The load on a bolt connecting to the inner tower was calculated for shear force:

The force considered is 800 lbs in the shear plane perpendicular to the bolt axis

The cross sectional area is $\pi * \frac{(.375)^2}{4} = 0.11045\ in^2$

The shear is 800/.11045 = 7243.3 psi
With an approximate shear strength of 72000 psi, the safety factor is 72000/7243.3 = **9.94**
This safety factor is if all 800 lbs of force were somehow transferred to one single bolt
With this safety factor, even the bolts bearing vertical and horizontal load will not shear or yield.

The force in the cables is more complicated due to the geometry of the cables. The vertical force be split by the base anchors, the cables, and the weight, but it will be assumed that the cables take 800 pounds of the vertical force. Each cable is at a 40 degree angle to the vertical axis, resulting in an axial force of
800/cos(40) = 1044.33 lbs in the cables.

The horizontal load will be split by some of the base anchors and the four cables that are in tension against that force, these are the four cables that are splayed to due to the exhaust direction, since the force is opposite to the exhaust.

The two cables on the same side as the exhaust are at a 15 degree angle to this force.
The two cables next to these are at a 75 degree angle to this force.

The cables at the 15 degree angle will take more of the force, and therefore these will have the maximum tension. The horizontal tension from the other two cables in this direction will not be considered, adding extra tension to the two cables considered. Due to vertical symmetry, each cable will be assumed to take 1/8th of the vertical load. By summing the vertical load with the load from the horizontal force divided between these two cables, the total tension is:

$$800/(8 * cos(40)) + 800/(2 * sin(40) * cos(15)) = 774.8\ lbs$$
This force is axial through the cables and the turnbuckle (used here because they are weaker than the come-along)

With a load strength of 2600 lbs, the safety factor in the cables is $2600/774.8 = \mathbf{3.36}$
With a load strength of 1200 lbs, the safety factor in the turnbuckles is 1200/774.8 = **1.55**

The force is at a 50 degree angle to the eyebolt and anchor: 774.8*cos(50) = 498 lbs
With a load limit of 1500 lbs, the safety factor in the eyebolts is 1500/498 = **3.01**
With a pull out strength of 3400 lbs, the safety factor in the anchors is 3400/498 = **6.83**

These safety factors do not take into account the vertical force from the eight base anchors, the weight of the motor and tower, the lateral force in the flame scoop likely being much lower than 800 lbs, or horizontal tension from the two other cables in that direction. For that reason it is very unlikely that the loads in these components will actually be within these factors of the component strengths.

Nozzle
Specific Heat Ratio / Chamber Temperature
　　　　In order to determine the ratio of specific heats and the chamber temperature (the former of which is used in nozzle calculations, and the latter of which is used for combustion chamber calculations), a program called ProPEP 3 is utilized. ProPEP 3 is a program which is able to analyze multiple fuel and oxidizer combinations, along with each component's mass ratio in the mixture, and output several key values, including the ratio of specific heat, chamber temperature, specific impulse, etc.
　　　　Figure X displays the ProPEP GUI. For a 100% HTPB fuel grain, the combustion ingredients are nitrous oxide, HTPB, and PAPI (a curative for the HTPB). The oxidizer and fuel react in a 5:1 ratio by mass, respectively. Under "Operating Conditions," the fuel is assumed to be initially at room temperature, the chamber pressure (a design condition) is set to 500 psi, and the exit pressure (ambient pressure at sea level). One simply presses the "Calculate" button to produce the outputs listed.

As can be seen, we can now grab the desired ratio of specific heats (listed as "Chamber CP/CV") and Chamber Temp.:
- Ratio of Specific Heats = 1.256963
- Chamber Temp = 3307.775 K

Nozzle Cone Dimensions

To determine the area expansion ratio, throat diameter, and exit diameter of the nozzle, we first assign two design conditions (desired thrust and chamber pressure) and determine the ambient pressure (which is ideally the same as the exit pressure of the exhaust gas) and the ratio of specific heats (from ProPEP 3):
- Thrust (T) = 3,500 N | 787 lbf
- Chamber pressure (P_o) = 3.447e+6 Pa | 500 psi
- Ambient pressure (P_e) = 101,353 Pa | 14.7 psi
- Ratio of specific heats (k) = 1.256963

The following procedure is then used to calculate the throat area (A_t), exit area (A_e), and area expansion ratio (A_t/A_e):
1. Calculate thrust coefficient, a value signifying how much the nominal thrust is magnified by the pressure ratio between the chamber pressure and exit pressure:

$$C_f = \sqrt{\frac{2k^2}{k-1} \cdot (\frac{2}{k+1})^{\frac{k+1}{k-1}} \cdot [1 - (\frac{P_e}{P_o})^{\frac{k-1}{k}}]}$$

2. Calculate the throat area using the relationship between throat area, thrust, thrust coefficient, and chamber pressure: $$T = A_t \cdot C_f \cdot P_o$$

3. Solve for A_t, and use the following equation to determine the optimal area expansion ratio; that is, the area expansion ratio which will produce Mach 1 flow in the throat and the greatest achievable supersonic flow in the exit with overexpansion or underexpansion:

$$\frac{A_t}{A_e} = (\frac{k+1}{2})^{\frac{1}{k-1}} \cdot (\frac{P_e}{P_o})^{\frac{1}{k}} \cdot \sqrt{(\frac{k+1}{k-1}) \cdot [\frac{P_e}{P_o}]^{\frac{k-1}{k}}}$$

4. Multiply the inverse of this value by the throat area, A_t, to yield the exit area, A_e. These are the focal dimensions necessary for optimally achieving Mach 1 flow at the nozzle throat and supersonic flow in the diverging section.

Fastener Stresses and Factor of Safety

To ensure that the nozzle is not ejected from the motor assembly due to the high pressures in the combustion chamber, a stress analysis of the fasteners (between the nozzle and combustion chamber, and between the nozzle and fin can) is imperative. The following assumptions were made to simplify the analysis:
- The full chamber pressure is exerted on the projection of the converging cone. Of course, pressure decreases through the nozzle as the pressure head is converted to velocity head, but this assumption greatly simplifies the calculation and models a more extreme case. If the model holds up under this pressure, it will sustain the realistic conditions even better.
- The upwards force of the pressure acting on the diverging cone is negligible compared to that of the chamber pressure, as the diverging cone's projected area is much smaller, and the pressure in the diverging section is significantly less than the chamber pressure.
- The cross sectional diameter of the fasteners experiencing the shear stress is equal to the nominal diameter of the fastener; that is ¼".
- The motor is producing the optimal amount of thrust; that is, 790 lbf of thrust.
- According to the Industrial Fastener Institute, the shear strength of the bolt is roughly equal to 60% of the minimum tensile strength. Shear strength is not a regulated property of fasteners, so this approximation must be made.

The following information is necessary to calculate the forces acting on the nozzle and, in turn, the bolts:

- Thrust (T) = 790 lbf
- Chamber pressure (P_c) = 500 psi
- A_{proj} (projected area of the converging section = pi*[(6/2)^2 - (1.1654/2)^2] = 27.2 in^2
- A_{cross} (cross sectional area of bolt) = pi*(0.25/2)^2 = 0.0491 in^2
- Fastener - SAE Grade 5 hex head bolt, medium carbon steel, tempered and quenched
  - $(sigma)_{yield}$ = 120,000 psi
  - $(tau)_{yield}$ = 0.6*$(sigma)_{yield}$ = 70,000 psi

We can calculate the assumed force produced by the chamber pressure:
F_P = P_c*A_{proj} = (500 psi)*(27.2 in^2) - 13,600 lb

Using force-balance methods we can estimate the the average reaction forces exerted by each of sixteen bolts:
$(SIGMA)F_y$ = 0 = T - F_P + 16F_B = 790 lb - 13,600 lb + 16F_B
F_B = 800 lb

This force is assumed to create a pure shear in the circular cross section of the bolt:
$(tau)_{max}$ = (4*F_B)/(3*A_{cross}) = (4*800 lb)/(3*0.0491 in^2) = 21,700 psi

FS = $(tau)_{yield}$/$(tau)_{max}$ = 70,000/21,700 = 3.23

Pressure Head Loss Code
function pressuredropdriver

% Variables
% values for dynamic viscosity, density, p1 from http://edge.rit.edu/content/P07106/public/Nox.pdf
% value for mass flow rate from design journal
% value for minor loss coefficient from threaded line flow through tee from
http://www.engineeringtoolbox.com/minor-loss-coefficients-pipes-d_626.html
% used values for saturated 25 degrees C (room temp)

p1 = 700;   %initial run tank pressure in psi
dens = 743.9;   %density of liquid nitrous in kg/m^3
mf = 1.35397;   %mass flow rate in kg/s
D = 0.0127;   %inner diameter in meters
vs = 5.20e-5;   %dynamic viscosity of liquid nitrous in kg/(m*s)
rough = .015e-3; %roughness coefficient for stainless steel in m
L = 0.2616708;   %length of tubing in m
z1 = 0.2616708; %tank height in m
z2 = 0;   %motor height in m
teeloss = .9;   %minor loss from threaded line flow through tee
numbertees = 2; %number of tees
sensorloss = .14; %minor loss from pressure transducer
g = 9.81;   %acceleration due to gravity

%Calculations

```
vf = mf/dens;      %volume flow rate
vel = 4*vf/(pi*D^2) %velocity of liquid
Re = dens*vel*D/vs  %calculate reynolds number
f = .5;          %initial darcy for iterations
for i=1:30        %iteratively solves for darcy friction factor
   f = (1/(-2*log10((rough/D)/3.7 + 2.51/(Re*sqrt(f)))))^2;
end
minorlosscoeff = numbertees*teeloss+sensorloss %coeff


%pressure drop
dp=dens*g*(z1-z2-f*(L/D)*(vel^2/(2*g))-(minorlosscoeff*(vel^2)/(2*g))); %pressure drop in Pa
dpinpsi = dp*0.000145037738 %pressure drop in psi
pfinal = p1+dpinpsi
end
```

Result: 26.0466 psi pressure drop from run tank to injector plate (673.9534 psi at injector plate)

D. BUILD PROCEDURES

Combustion Chamber

The bulkhead was made from the 8" aluminum cylinder stock by CNC milling, with a ½" diameter bit, both the outside diameter and the inside hole. Because the CNC bit was rough, some space was left on the outside, and the remainder was lathed down to ensure an acceptable pneumatic o-ring fit. Then an o-ring indentation was place on the outside and a retaining ring indentation was place on the inside. Finally, bolt holes were drilled and threaded around the perimeter and a pipe threat was placed through the top.

The combustion chamber was made by sending the 5.5" ID tube to the Rice space science machine shop, where the ID was lathed out to 6." Then, if any correction was needed to ensure a good fit between the chamber and the bulkhead/nozzle, those pieces were lathed down farther.

Fuel Grain

The fuel cell will be built by assembling the mold will be cylindrical for the first test and subsequent tests will be done using other shapes such as a cross or 5 point star after spraying them with mold release. The grain itself will be cast in 4 equal parts. The order of mixture is HTPB, E-744, then carbon black.

The ratio of HTPB to E-744 suggested is 88:12, the two will be stirred together aggressively until the mixture becomes viscous and begins to form bubbles (the curing process has been stimulated by rapid stirring, producing gas) and then the carbon black will be added and stirred in until the fuel looks uniform in color and consistency.

The fuel will then be poured into the mold and the next mixing part will be started. The reason for casting in parts is to ensure a consistent texture and mixing of the cast. Multiple, smaller mixtures allows for the grain to be more easily stirred. The grain will then be allowed to cure for a week to ensure it has more than enough time to complete. The smaller Mk I grains take approximately 24h to cure.

Nozzle
Aluminum Casing
1. Cut approximately 5.5" length of 8" diameter stock aluminum for aluminum casing blank. Use Johnson saw in Ryon welding shop, and ensure that the blade is well-oiled throughout operation by affixing oil-spraying device to the saw housing (away from guide rollers and blade) and adjusting device to spray an ample amount of oil. Use additional air hose to clean the end of the cut where the blade exits.

2. Turn outer diameter of piece until it is entirely in-round. Take off as little as possible, as the stock material may be quite close to 8" already depending on manufacturing tolerance.
3. Face both ends until casing length is suitably within tolerance.
4. Turn all outer diameters - combustion chamber mating surface, fin can mating surface, and exit outer diameter. Note that the combustion chamber and fin can mating surfaces have tighter tolerances than the exit outer diameter. Due to the large amounts of material that must be removed to achieve these diameters, it is recommended that the machine shop's large boring tool be inverted and chuck rotation be reversed in order to to make deeper cuts.
5. Drill out 1" hole in center of casing using tailstock. The finish on the hole is of no concern, as the smallest inner diameter will be produced by boring the cone faces. The drill simply sets up the piece for boring and the large bit diameter decreases the time of boring operations.
6. Bore both inner cone faces using the large boring tool. *N.B. - It is recommended that boring operations be conducted on a Bridgeport machine. According to Joe, the Bridgeports are "stiffer" and less prone to chatter, which is important due to the length of the large boring tool and greater propensity for deflection.* For the graphite insert-seating surface (the larger one which mates with the graphite insert surface), it should be noted that the travel of the tool on the Bridgeport does not cover the entire length of the face. As such, it is recommended that a full cut of the length be completed in two separate cuts, one starting at the opening of the cone and traveling as far as possible, and another cut starting midway into the first cut (at the same depth) and extending to the end of the surface. Care should be taken to minimize the difference in depth between the two cuts.
7. Use parting tool to cut O-ring gland. Remove piece from lathe.
8. Clamp piece sideways into CNC mill, and mill out first fin notch with a ¼" roughing end mill that is sufficiently deep, using the edge finder to find the very center of the piece's curve. The radial placement of the first notch does not matter.
9. For the next notch, fit a fin into the first notch, turn the piece roughly 90 degrees, and clamp it in. Zero the edge finder at the top of one of the diameters, and moving the edge finder down half this diameter and subtracting half the width of the fin, rotate the piece until the fin presses firmly onto the edge finder and reclamp the piece. You can now repeat the milling process for the next notch. This process should be repeated for the final two fins.
10. With all the fin notches milled, the piece may be moved to one of the other mills, and the angled chuck taken out of storage. Using two ⅛" thick pieces of plastic, the angle chuck should be placed in the clamp on the mill table, the plastic placed between the chuck and clamp, and clamped in. These pieces of plastic are necessary as the base of the angled chuck is not machined to straight, parallel surfaces. The plastic deforms to prevent damaging the chuck or clamp.
11. Rotate the chuck head so that it is parallel to the mill table. Align the piece in the angled chuck so that one fin notch is vertical, and tighten the chuck. Using the edge finder, determine the length along the piece that one set of bolt holes will be drilled. Insert the 17/64" bit into the mill head.
12. Apply machining oil to the bit. Drill holes to the prescribed depth at the correct angle (the angle chuck rotates in increments of 15 degrees) around the diameter for the first set of bolt holes. Repeat the process for the second set of bolt holes.
13. Fit the mill head with the correct tapping tool. Apply a small amount of machining oil to the tapping tool. Align the tool with one set of bolt holes, and begin the tap by bringing the tool down onto the hole and manually turning the tool in the mill head. Once the tool is set, the mill head can be disengaged from the tool and the tap wrench used to finish the tap. Repeat for the remainder of the holes in the set, and repeat for the other set of bolt holes.
14. The machining of the aluminum casing is now done, unless adjustments need to be made to fit the fin can, fins, or combustion chamber.

Graphite Insert
1. Cut blank from graphite stock on the Johnson saw. It is strongly advised that a shop vac be used to remove the graphite dust coming off the cut. Oil is not necessary for this.
2. Mount piece in Bridgeport lathe, fitted with chuck with jaws which grip with a flat curved face, instead of the tapered jaws or ridged and curved jaws. This helps spread the compressive forces out better.
3. Turn and face the blank to the proper diameter and length. *N.B. - During this operation and all other cutting operations on the graphite insert, a shop vacuum should be used to remove as much graphite dust as possible, keeping the mouth of the vacuum tube close to the tool as it cuts. The filter of the vacuum will need to be cleaned somewhat regularly, when a noticeable lack of suction become apparent.*
4. Drill out center hole (as large as possible with respect to the throat diameter). Graphite self-lubricates, but it is wise to draw the drill out of the piece frequently to remove excess dust.
5. Bore converging cone out first. The travel of the tool may not be long enough, so the same process used on the aluminum casing should be repeated here, with care taken to ensure that the depth of the two cuts match as well as possible.
6. Bore diverging cone out next. The travel should be enough for this cut.
7. Turn fiberglass liner seating notch.
8. Mount piece in lathe so that the fiberglass liner seating notch alone is gripped by the jaws. *This procedure is extremely delicate and extra caution should be taken to avoid over-tightening the jaws and shattering the piece.*
9. When the piece is mounted, turn the taper which will mate with the aluminum casing. The travel of the tool will most likely not be enough for this cut, so the same process used for the aluminum casing should be repeated, with similar care to matching the depth of the two cuts.
10. The graphite insert is now complete. Check the fit with the aluminum casing.
11. Store both pieces carefully. The graphite insert and aluminum casing should not be in contact while stored, as they may corrode during extended contact.

Plumbing
Internal Plumbing System Assembly

The internal plumbing was purchased from Swagelok and assembled by cutting the ½" piping with a hacksaw. The distances were measured to reduce the major losses and allow the pressure transducer to be attached to the outer wall of the rocket as well as to put the burst disc slightly outside of the outer diameter. The burst disc holster was made on a lathe and mill, and more can be found in the burst disc design documentation.

Assemble the internal plumbing system first, starting with the main line. For all Swagelok tubing connections, tighten the hex nuts on the connections such that the tubes will not rotate axially in the fittings. Begin by attaching the two tee junctions to their corresponding lengths of tubing. Then attach the pressure transducer to the elbow and then attach the pressure transducer and its corresponding tee junction to the tubing between them. Finally, attach the burst disk tubing to the other tee junction and the burst disk connection but do not attach the burst disk holder to the connection. For all NPT connections, wrap the threading in Teflon tape before tightening with two fingers.

Place the retaining rings on the run tank and then connect the internal plumbing to the run tank. Place the retaining rings on the combustion chamber and then connect the internal plumbing to the combustion chamber. Ensure that all Swagelok tube connections are tightened such that the tubes will not rotate axially in the fittings. Slide the motor into the fuselage and rotate so that the

burst disk connection is centered in the hole in the fuselage, then bolt the retaining rings to the outside of the rocket, and attach the burst disk holder to the burst disk connection.

External Plumbing System Assembly

The external plumbing was constructed similarly to the inside plumbing, by cutting the swagelok pipes with a hacksaw and assembling purchased parts. Additionally, there will be a blast shield included in front of the fill tanks that will be constructed out of free standing cinderblocks. The purpose of this wall is to both support the fill line and protect the fill tank in the case of a catastrophic failure.

To assemble the external plumbing system, construct the blast shield using cinderblocks and secure the fill tank behind the blast shield. Next connect the Swagelok tubing to the tee junction and connect the reducer and emergency oxidizer vent valve. Connect the external piping to the fill tank regulator and then connect the external piping to the pneumatic manifold. As with the internal plumbing assembly, ensure that all Swagelok tube connections are tightened such that the tubes will not rotate axially in the fittings. Connect the nylon fill lines to the connections on the injector plate and to the connections on the pneumatic manifold.

Cleaning and Leak Checking

The run tank will be tested using a hydropump before every test to ensure that there are no leaks in its perimeter. Also, the run tank will be professionally cleaned before each test. This includes initially running the tank through an acetone wash. After the acetone, the tank is similarly run through an IPA wash, and then doused and sunk in water. Lastly, nitrogen is used to purge the tank and heat is added to bake the tank.