ESRA 2.1 Propulsion Static Fire Report

January 11th, 2020

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1 Abstract

This static fire test aimed to validate the motor design and collect thrust data to predict apogee. The motor burned at a higher pressure and exerted high thrust than anticipated. However, a slow ignition might have rendered the thrust data somewhat inconclusive. Nonetheless, the lack of catastrophic hardware failure demonstrated the validity of the motor tube design's. Temperature data was gathered, allowing for more accurate estimations of the motor tube's strength under thermal loading, and the development of a composite over pressure vessel motor tube for future years. Quicker ignition is required for the next static fire, and it is difficult to access total impulse with current data. However if total impulse increases with the next test, the motor is approaching its legal limit.

2 Introduction

The purpose of this static fire was to test the motor tube assembly hardware, collect thrust data to predict the rocket's altitude during flight, and compare measured chamber pressure and burn rates to simulations based on sub-scale data on 11/18/2019.

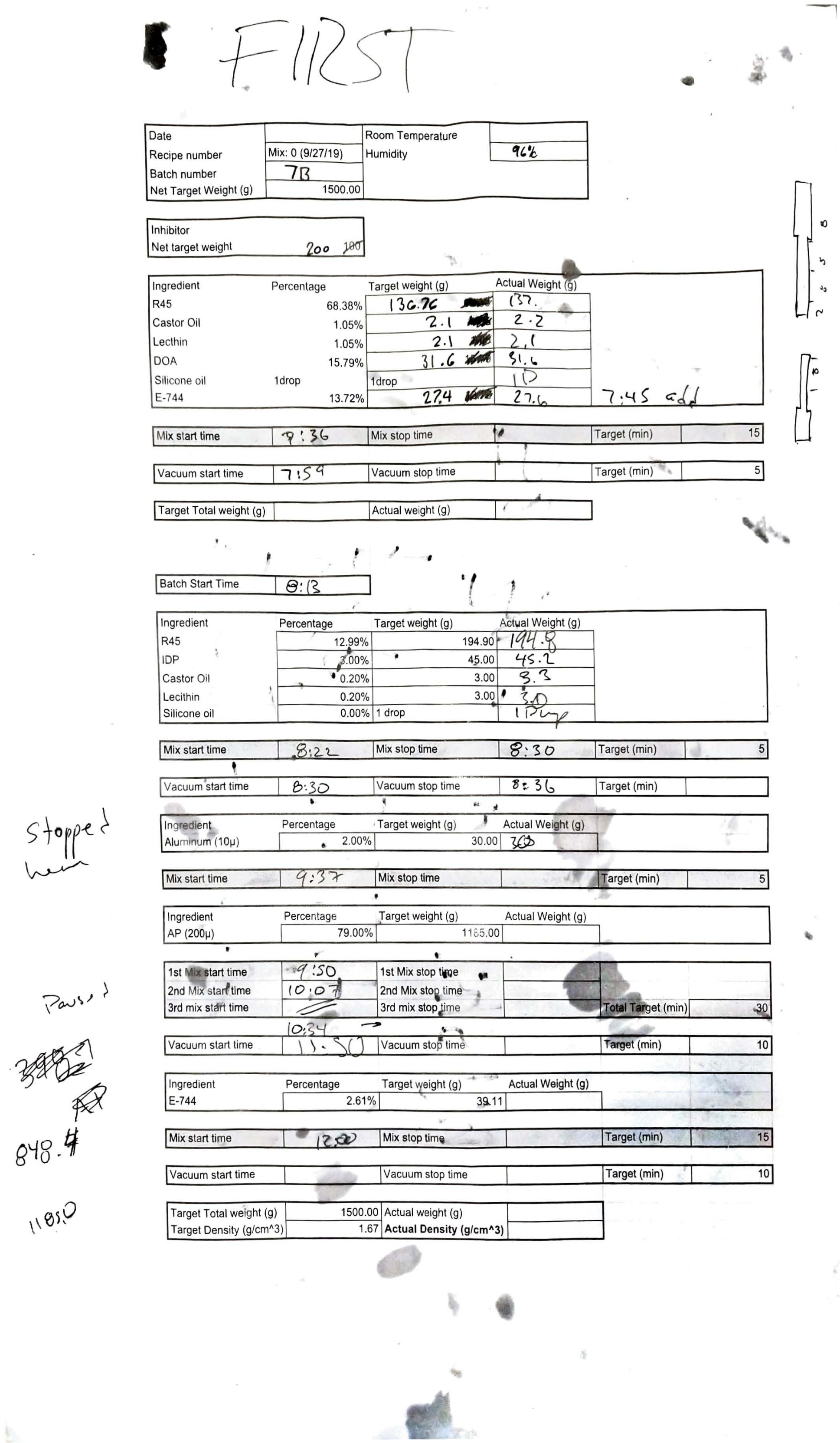
It is worth noting that propellant density in sub-scale was between 88 and 91%. However using new packing fixtures, the density was increased to around 95% on this motor. Additionally, ignitions in sub-scale had slow startups which possibly could have altered a and n values.

3 Methods

The following section outlines the propellant chemistry and mixing process, motor hardware, data acquisition system, and ignition system used on this fire.

3.1 Propellant

The motors from this fire used propellant from batches 7b, 8b, and 9b. Mix sheets are shown in figures 1, 2, and 3. The mix was conducted in 96% humidity. The mix followed formulation 0 with 79% ammonium perchlorate by weight. The grains used inhibitor on the inside of the casting tubes before the propellant was packed. The grains were left to cure in Graf. The grains were clamped using 3d printed fixtures shown in figure 4.



FIRST

Date		Room Temperature	
Recipe number	Mix: 0 (9/27/19)	Humidity	96%
Batch number	7B		
Net Target Weight (g)	1500.00		

Inhibitor	
Net target weight	200 ~~100~~

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
R45	68.38%	136.76 [redacted]	137.
Castor Oil	1.05%	2.1 [redacted]	2.2
Lecthin	1.05%	2.1 [redacted]	2.1
DOA	15.79%	31.6 [redacted]	31.6
Silicone oil	1drop	1drop	1D
E-744	13.72%	27.4 [redacted]	27.6

7:45 add

Mix start time	7:36	Mix stop time		Target (min)	15
Vacuum start time	7:59	Vacuum stop time		Target (min)	5
Target Total weight (g)		Actual weight (g)			

Batch Start Time	8:13

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
R45	12.99%	194.90	194.8
IDP	3.00%	45.00	45.2
Castor Oil	0.20%	3.00	3.3
Lecithin	0.20%	3.00	3.0
Silicone oil	0.00%	1 drop	1 Drop

Mix start time	8:22	Mix stop time	8:30	Target (min)	5
Vacuum start time	8:30	Vacuum stop time	8:36	Target (min)	

Stopped here

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
Aluminum (10µ)	2.00%	30.00	30

Mix start time	9:37	Mix stop time		Target (min)	5

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
AP (200µ)	79.00%	1185.00	

Paused

1st Mix start time	9:50	1st Mix stop time			
2nd Mix start time	10:07	2nd Mix stop time			
3rd mix start time	~~[illegible]~~ 10:34	3rd mix stop time		Total Target (min)	30
Vacuum start time	11:50	Vacuum stop time		Target (min)	10

~~398~~ 321

848.4

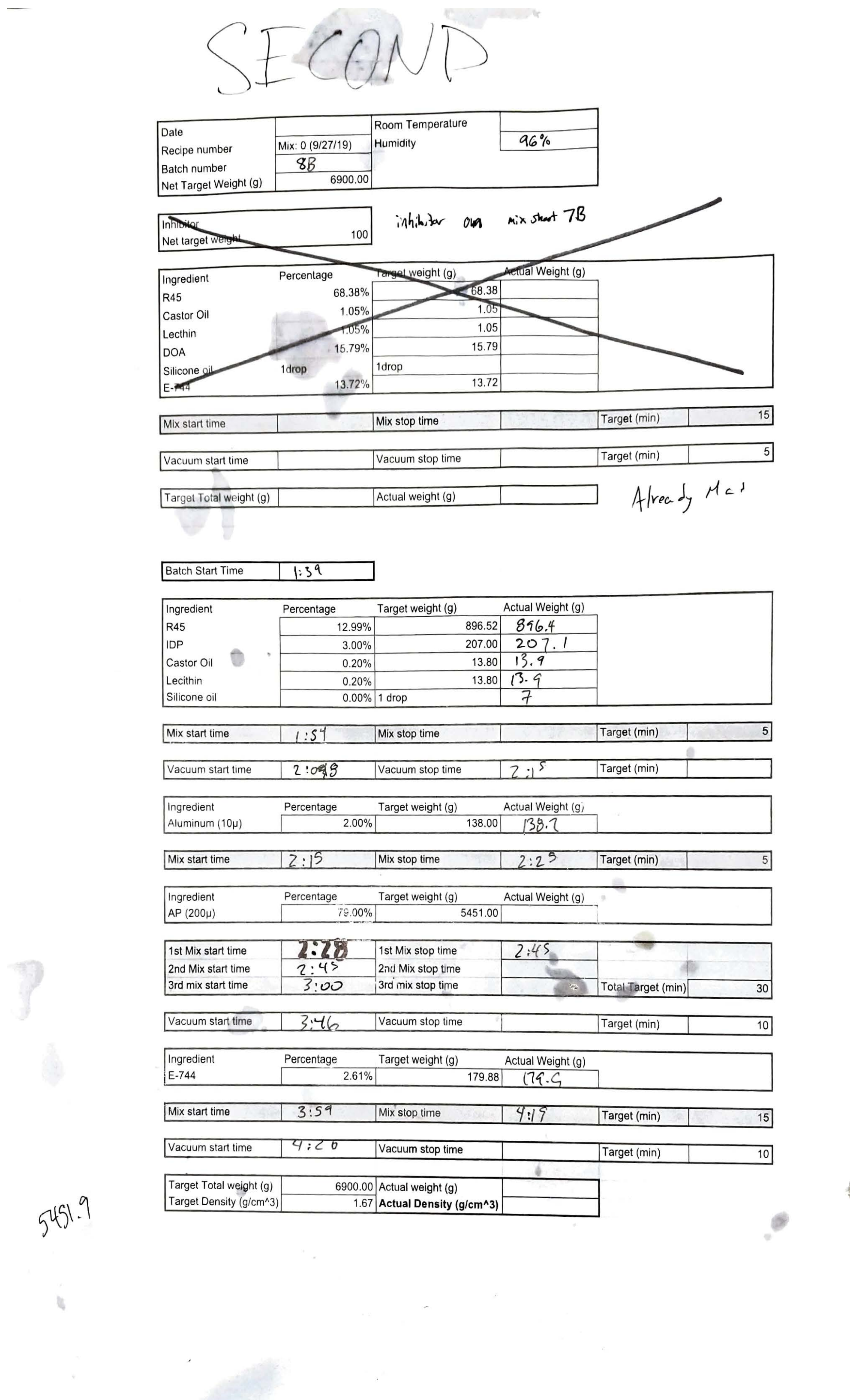
1185.0

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
E-744	2.61%	39.11	

Mix start time	12:00	Mix stop time		Target (min)	15
Vacuum start time		Vacuum stop time		Target (min)	10

Target Total weight (g)	1500.00	Actual weight (g)	
Target Density (g/cm^3)	1.67	**Actual Density (g/cm^3)**	

Figure 1: Mix Sheet 7b



SECOND

Date		Room Temperature	
Recipe number	Mix: 0 (9/27/19)	Humidity	96%
Batch number	8B		
Net Target Weight (g)	6900.00		

inhibitor on mix sheet 7B

Inhibitor	
Net target weight	100

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
R45	68.38%	68.38	
Castor Oil	1.05%	1.05	
Lecthin	1.05%	1.05	
DOA	15.79%	15.79	
Silicone oil	1drop	1drop	
E-744	13.72%	13.72	

Mix start time		Mix stop time		Target (min)	15
Vacuum start time		Vacuum stop time		Target (min)	5
Target Total weight (g)		Actual weight (g)			

Already Mad

Batch Start Time	1:39

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
R45	12.99%	896.52	896.4
IDP	3.00%	207.00	207.1
Castor Oil	0.20%	13.80	13.9
Lecithin	0.20%	13.80	13.9
Silicone oil	0.00%	1 drop	7

Mix start time	1:54	Mix stop time		Target (min)	5
Vacuum start time	2:08	Vacuum stop time	2:15	Target (min)	

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
Aluminum (10μ)	2.00%	138.00	138.2

Mix start time	2:15	Mix stop time	2:25	Target (min)	5

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
AP (200μ)	79.00%	5451.00	

1st Mix start time	2:28	1st Mix stop time	2:45		
2nd Mix start time	2:45	2nd Mix stop time			
3rd mix start time	3:00	3rd mix stop time		Total Target (min)	30
Vacuum start time	3:46	Vacuum stop time		Target (min)	10

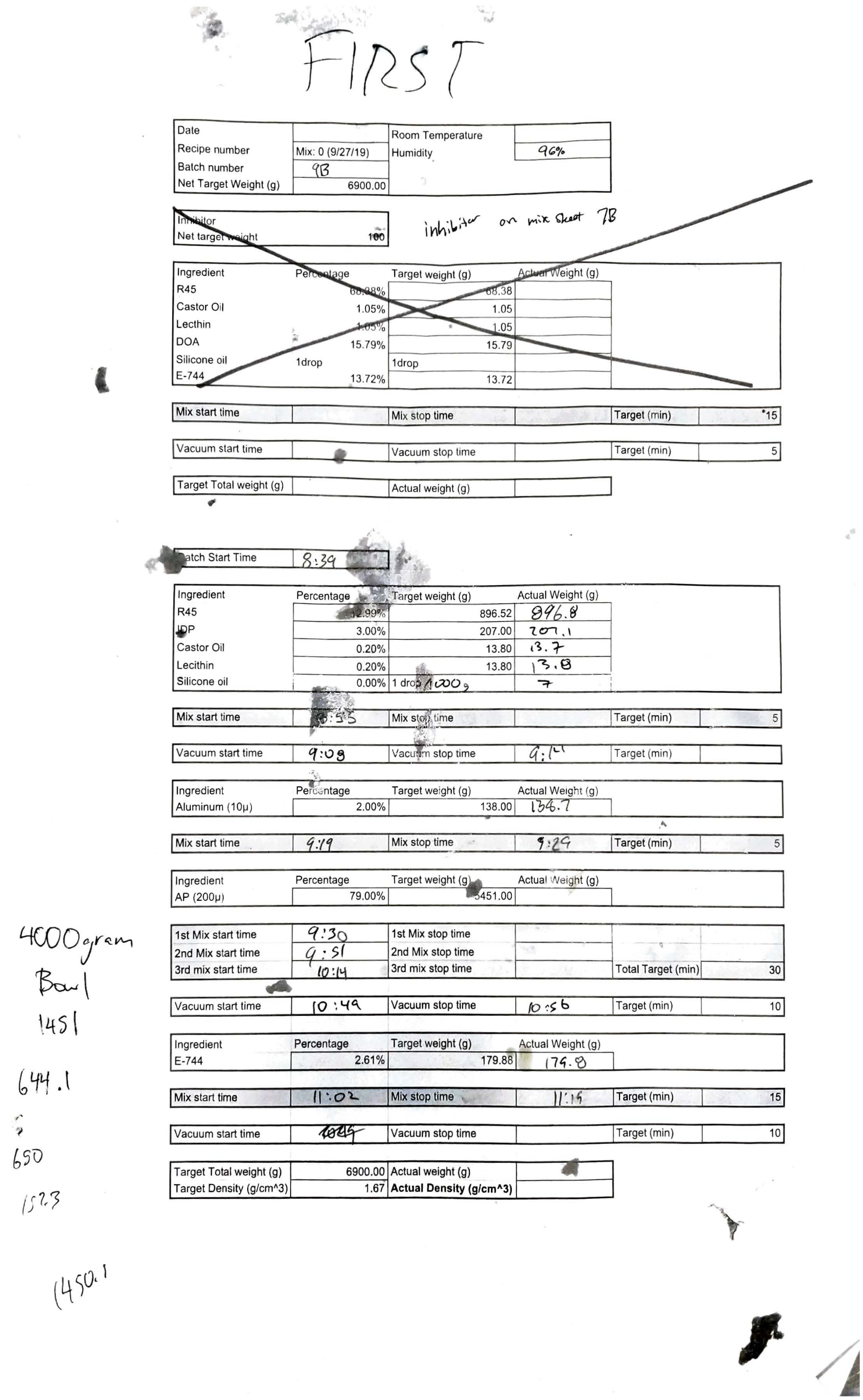
Ingredient	Percentage	Target weight (g)	Actual Weight (g)
E-744	2.61%	179.88	179.5

Mix start time	3:59	Mix stop time	4:19	Target (min)	15
Vacuum start time	4:20	Vacuum stop time		Target (min)	10

Target Total weight (g)	6900.00	Actual weight (g)	
Target Density (g/cm^3)	1.67	**Actual Density (g/cm^3)**	

5451.9

Figure 2: Mix Sheet 8b



FIRST

Date		Room Temperature	
Recipe number	Mix: 0 (9/27/19)	Humidity	96%
Batch number	9B		
Net Target Weight (g)	6900.00		

Inhibitor	
Net target weight	100

inhibitor on mix sheet 7B

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
R45	68.38%	68.38	
Castor Oil	1.05%	1.05	
Lecthin	1.05%	1.05	
DOA	15.79%	15.79	
Silicone oil	1drop	1drop	
E-744	13.72%	13.72	

Mix start time		Mix stop time		Target (min)	15
Vacuum start time		Vacuum stop time		Target (min)	5
Target Total weight (g)		Actual weight (g)			

Batch Start Time	8:39

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
R45	12.99%	896.52	896.8
IDP	3.00%	207.00	207.1
Castor Oil	0.20%	13.80	13.7
Lecithin	0.20%	13.80	13.8
Silicone oil	0.00%	1 drop 1000g	7

Mix start time	8:55	Mix stop time		Target (min)	5
Vacuum start time	9:09	Vacuum stop time	9:14	Target (min)	

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
Aluminum (10μ)	2.00%	138.00	136.7

Mix start time	9:19	Mix stop time	9:29	Target (min)	5

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
AP (200μ)	79.00%	5451.00	

1st Mix start time	9:30	1st Mix stop time			
2nd Mix start time	9:51	2nd Mix stop time			
3rd mix start time	10:14	3rd mix stop time		Total Target (min)	30
Vacuum start time	10:49	Vacuum stop time	10:56	Target (min)	10

Ingredient	Percentage	Target weight (g)	Actual Weight (g)
E-744	2.61%	179.88	179.8

Mix start time	11:02	Mix stop time	11:19	Target (min)	15
Vacuum start time	~~1045~~	Vacuum stop time		Target (min)	10

Target Total weight (g)	6900.00	Actual weight (g)	
Target Density (g/cm^3)	1.67	**Actual Density (g/cm^3)**	

4000 gram Bowl
1451
644.1
650
1523
1450.1

Figure 3: Mix Sheet 9b

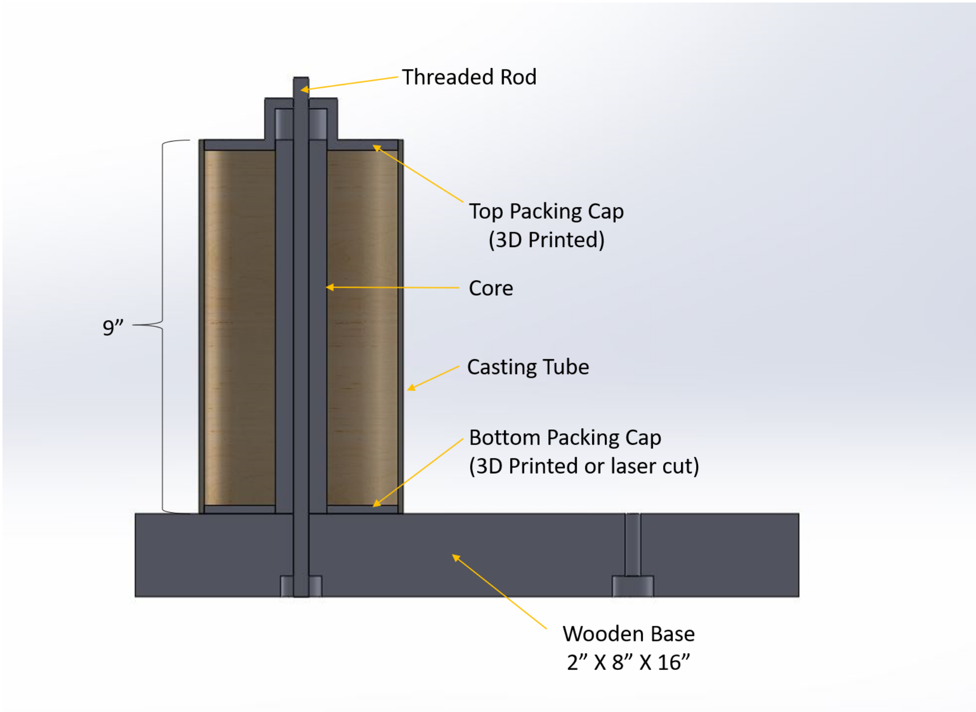


Figure 4: Grain Clamping Fixture

With the use of clamping fixtures while the grains were curing, densities reached around 95% with the exception of grain 5, which needed to be repacked. Densities of each grain are shown in figure 5. Grains were each 8 inches long, with the exception for grain 5, which was 4 inches long.

Casting Tube #	Propellant Density (lbs/in^3)	Density % Theoretical (lbs/in^3)
1	0.0557	95.1
2	0.0553	94.4
3	0.0562	95.8
4	0.0552	94.2
5	0.0540	92.1
6	0.0563	96.1
7	0.0559	95.3

Figure 5: Propellant Grain Densities

Propellant grains were glued into the fiberglass thermal liner using rocket epoxy. O-rings were disposably used as spacers between grains. The epoxy dried for a few days before the static fire. Figure 6 shows the thermal liner with grains glued in.

Figure 6: Propellant grains glued into thermal liner

The thermal liner and grains were integrated into the motor tube the day of the static fire.

3.2 Motor Assembly

The full-scale motor tube this year included many changes to previous revisions. The forward enclosure is secured with a snap-ring identical to the one used on the nozzle, instead 12 radial bolts to save weight and simplify manufacturing. The thermal liner was changed from a phenolic tube to a 0.25" thick fiberglass liner under the brand name vernatube. Casting tubes were sourced from a custom spiral tubing company Spiral Paper Tube & Core in order to fit the fiberglass tube. O-rings were added to the shoulder of the forward enclosure to seal the forward end of the thermal liner to mitigate hot gas circulation. O-rings were not placed on the nozzle's shoulder to avoid pressurizing the thermal liner.

The fiberglass thermal liner is filled under part number 10-007A, and the drawing is shown in figure 7.

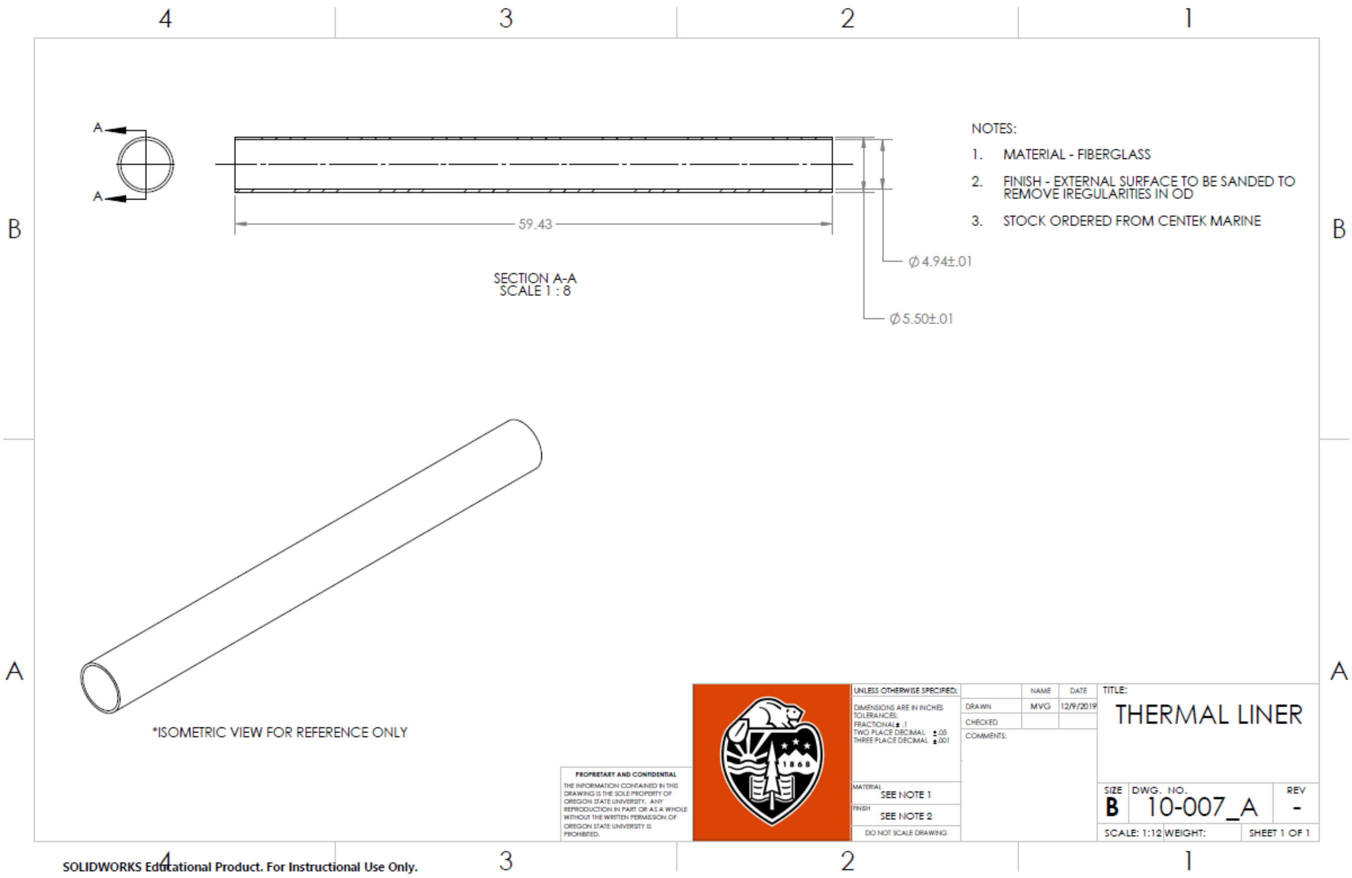


Figure 7: Thermal liner drawing

The forward enclosure was constructed from aluminum 6061, and filed under part number 10-003B shown in figure 8.

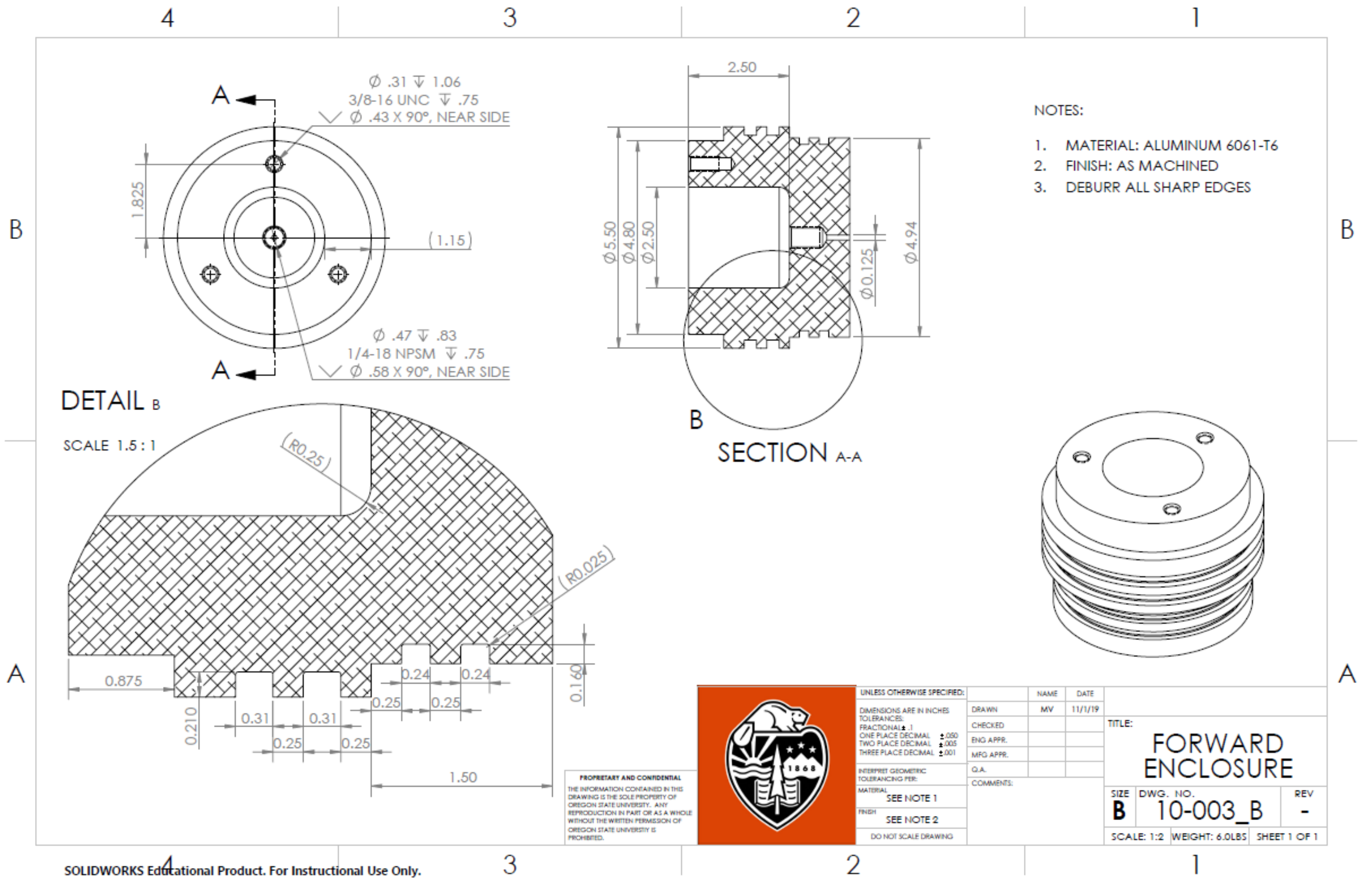


Figure 8: Forward enclosure drawing

The motor tube was constructed from aluminum 6061, and filed under part number 10-002C shown in figure 9.

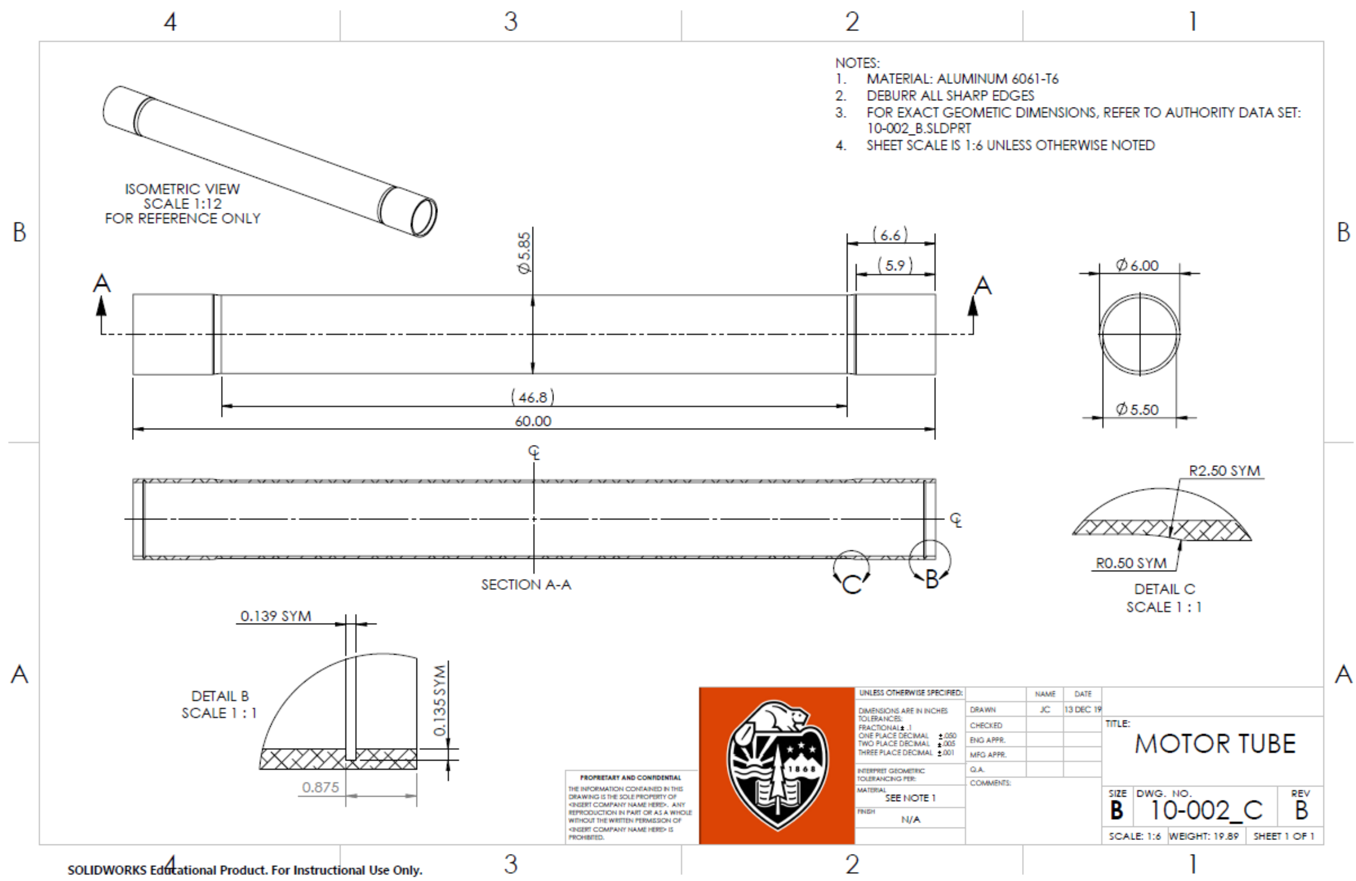


Figure 9: Motor tube drawing

The top level motor assembly is shown in figures 10, 11, 12, and 13.

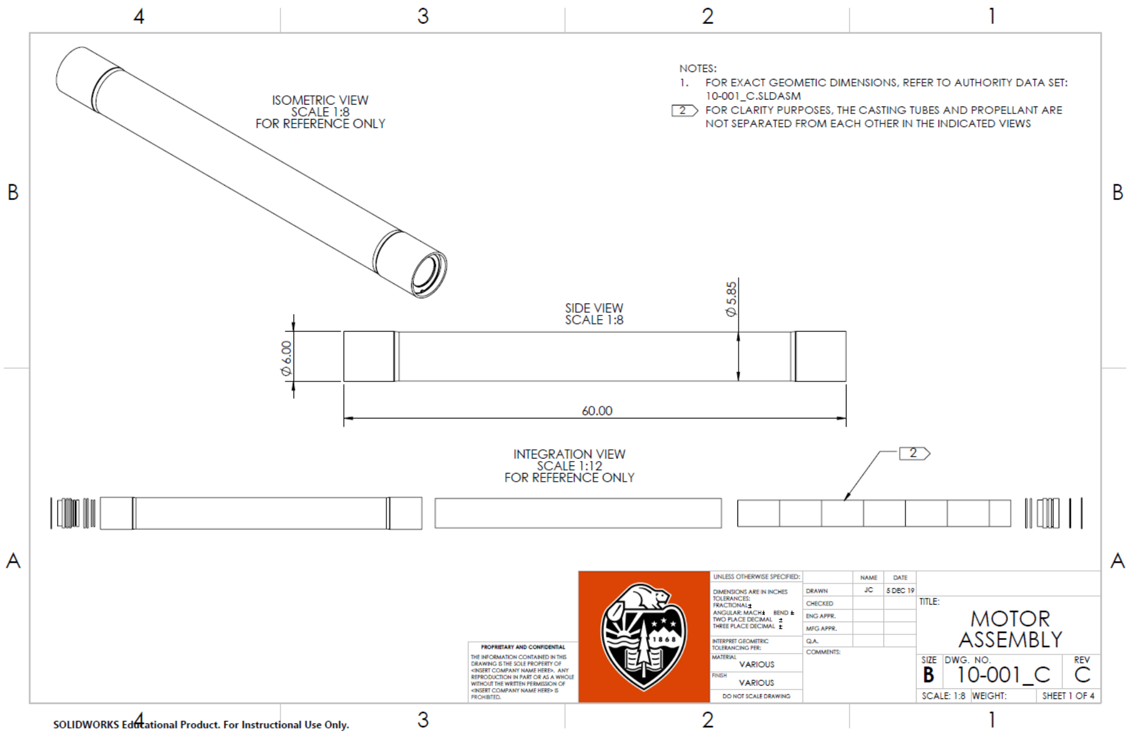
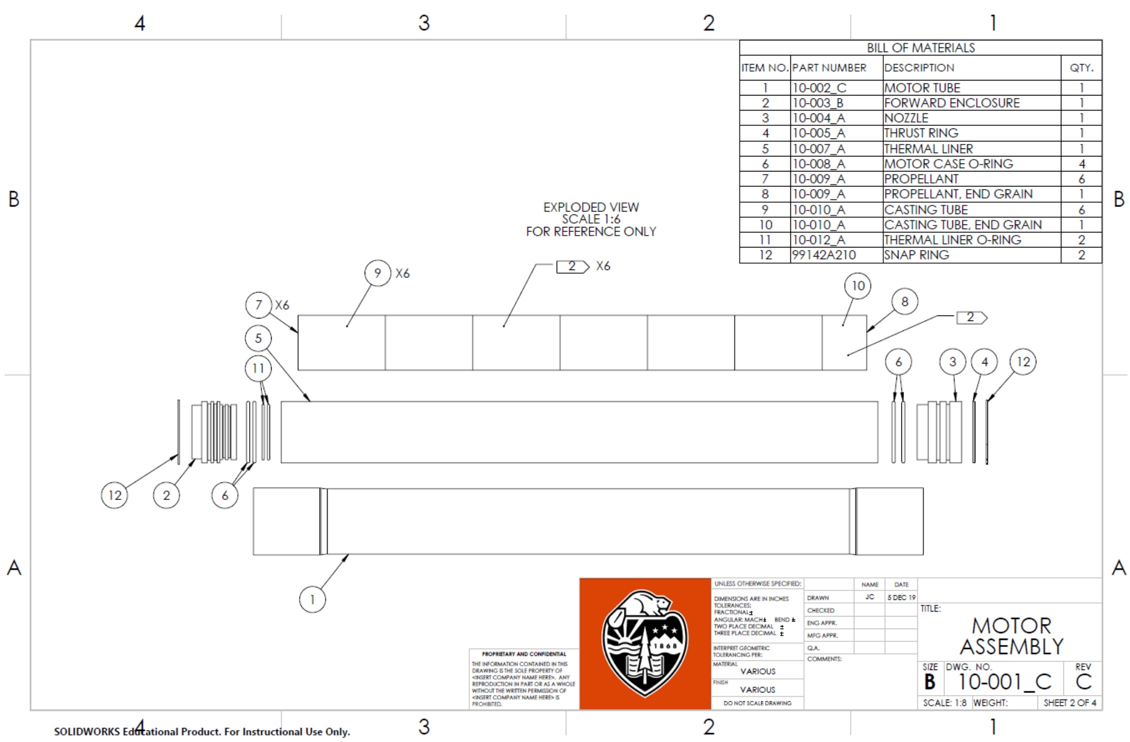


Figure 10: Motor assembly drawing page 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10-002_C	MOTOR TUBE	1
2	10-003_B	FORWARD ENCLOSURE	1
3	10-004_A	NOZZLE	1
4	10-005_A	THRUST RING	1
5	10-007_A	THERMAL LINER	1
6	10-008_A	MOTOR CASE O-RING	4
7	10-009_A	PROPELLANT	6
8	10-009_A	PROPELLANT, END GRAIN	1
9	10-010_A	CASTING TUBE	6
10	10-010_A	CASTING TUBE, END GRAIN	1
11	10-012_A	THERMAL LINER O-RING	2
12	99142A210	SNAP RING	2

Figure 11: Motor assembly drawing page 2

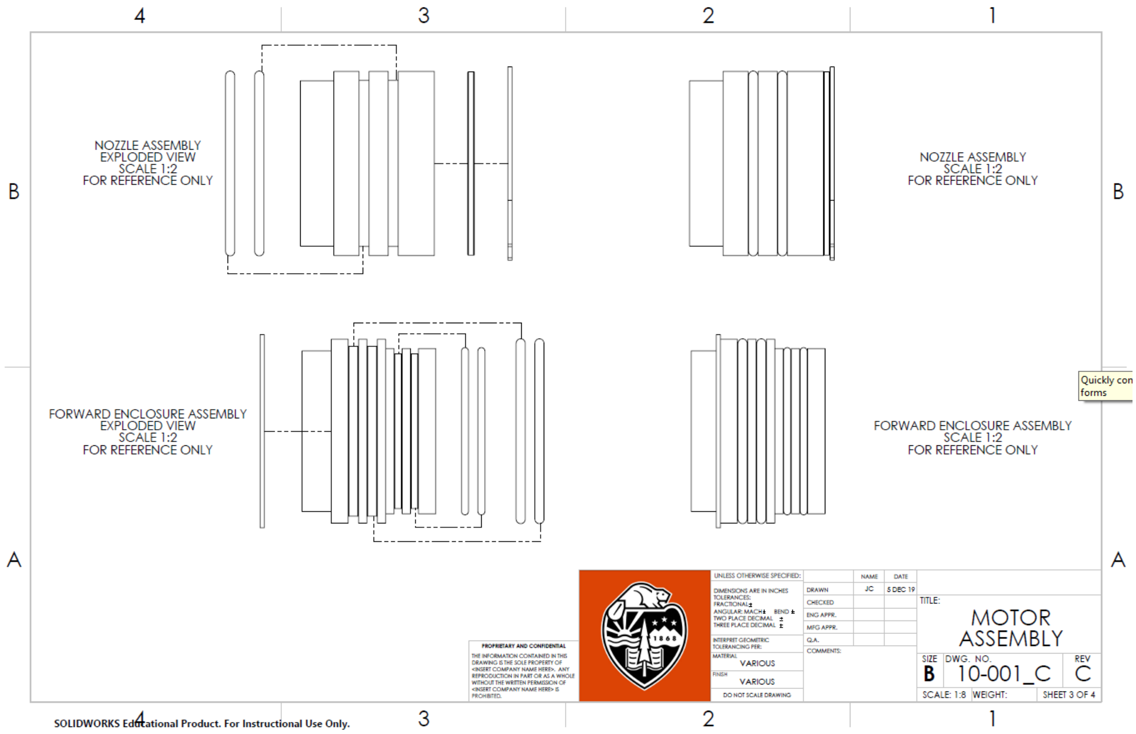


Figure 12: Motor assembly drawing page 3

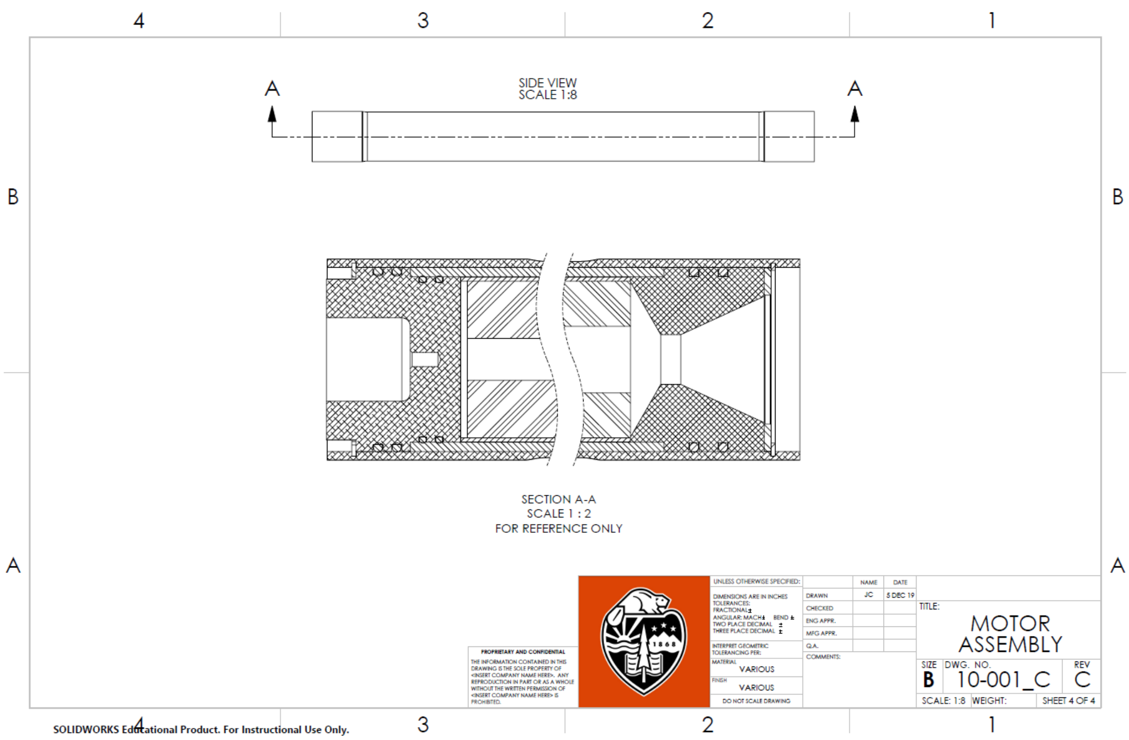


Figure 13: Motor assembly drawing page 4

3.3 Nozzle

The graphite De Laval Nozzle has a converging angle of 60 degrees and a diverging angle of 20.44 degrees. The nozzle throat diameter is 1.478 inches. A drawing of the full-scale nozzle design can be seen in figure 14. Further, photographs of the finished design can be seen in figures 15a and 15b. The nozzle was manufactured on OSUs Summit Lathe in the Engineering Machine Shop. The geometry of the nozzle is determined by the performance expectations set by the ESRA team. BurnSim is a software that aids in calculating theoretical nozzle geometry and performance characteristics of a solid-rocket propellant motor. BurnSim allows you to tweak rocket motor parameters to pinpoint an optimal nozzle design. Refer to figure 16 for the Burnsim Simulations.

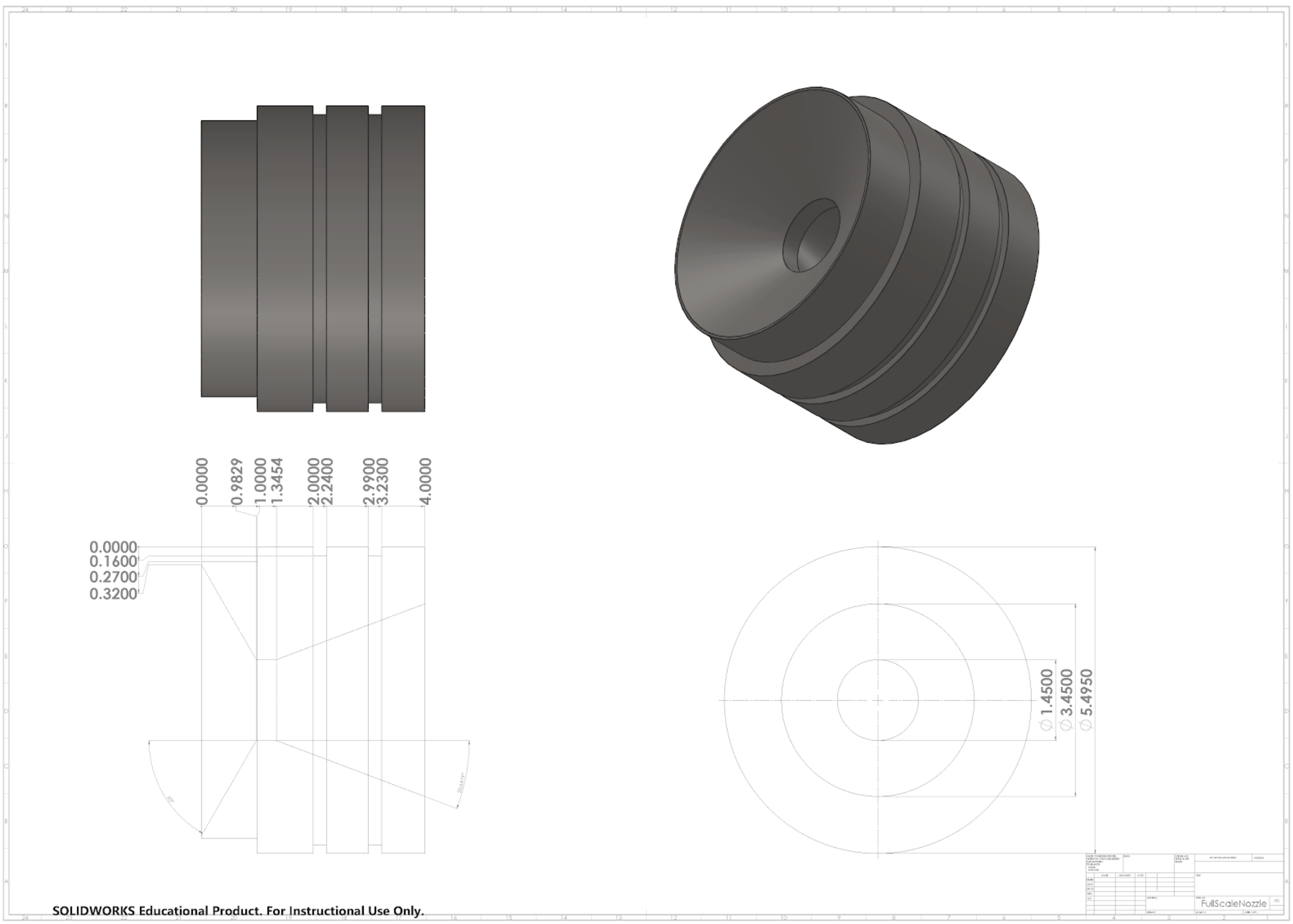
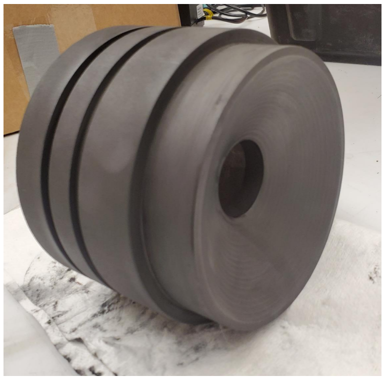
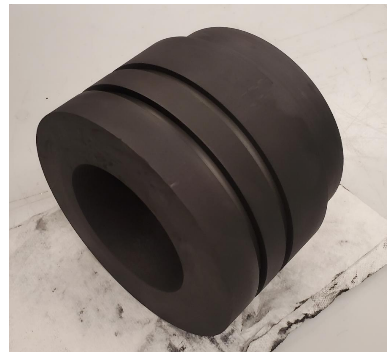


Figure 14: Nozzle Drawing



(a) View 1



(b) View 2

Figure 15: Manufactured nozzle

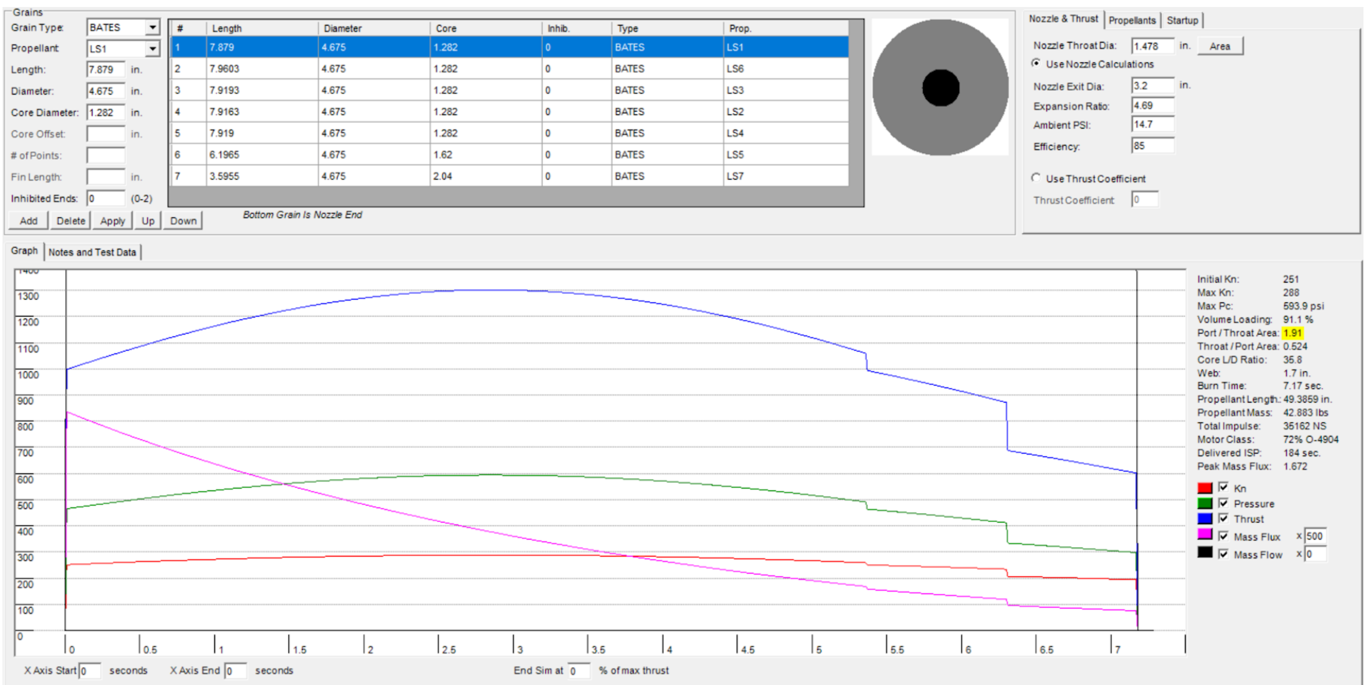


Figure 16: Burnsim Simulation

3.4 DAQ Test Stand

A new test stand was built (shown in figure 17a and 17b) to hold the motor tube in place securely while minimizing unnecessary clamping force that could alter load data. The motor is held by 80/20 Inc.'s extruded aluminum and custom machined brackets and with gasket material to minimize scratches. All bolts were torqued to 25 ft-lbs as per the maximum suggested by 80/20 Inc.

(a) Test fit

(b) Day of static fire

Figure 17: Test stand setup

Pressure data was recorded using a FUTEK PFP350 pressure transducer connected to the forward enclosure by a 18" copper pipe. The orifice on the sensor was filled with lithium grease. The copper tube was empty. Load data was collected using an OMEGA LCM305-10KN load cell. This load cell had a max measuring capacity of 2248 lbf and the projected maximum thrust was 1250 lbf.

Figure 18: Load-cell and pressure transducer setup

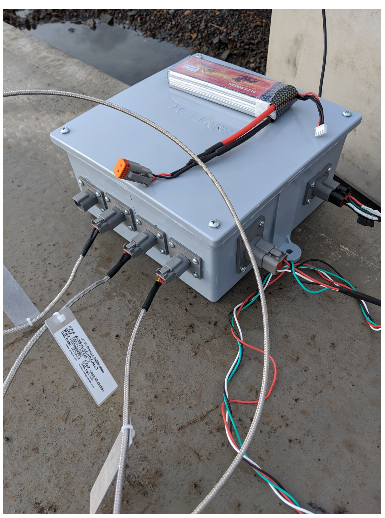
This was the first static fire in the history of OSU's ESRA program where temperature data was recorded succesfully. Three OMEGA XCIB-K-4-5-10 thermocouples were attached to the forward enclosure end, center, and nozzle end of the motor tube by hose clamps painted with thermocouple putty (shown in figures 18, 19a, and 19b). The umbrella hat was secured to the top of the motor to keep water out of the nozzle while waiting to fire, as well as make it look cool.

(a) Center of motor tube body

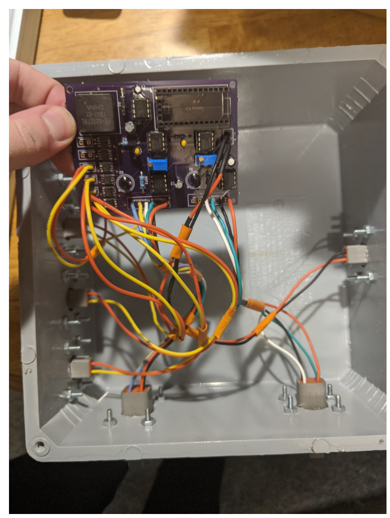
(b) Nozzle end motor tube body

Figure 19: Therocouple setup

The DAQ used Texas Instruments REF102CP chips to supply excitation, Texas Instruments INA122PA amplifiers for the pressure transducer and load cell signals, and Maxim Integrated MAX6675ISA+ cold junction compensated k thermocouple to digital converts to read the thermocouples. Analog and digital signals from the sensors were read using a Teensey 3.2 at 50Hz for the load and pressure, and 10Hz for the temperature data.



(a) DAQ sensor connections



(b) DAQ internals

Figure 20: DAQ setup

The data was logged over USB serial from the Teensey to a computer running Putty.

3.5 Ignition

The ignition system is composed of a wireless transmitter, a microcontroller, and a yard stick with eight igniters attached to it and wired in parallel. The wireless transmitter sends out a signal to a microcontroller near the motor which operates like a switch and allows the current from a 12V battery to flow through the igniters. The yard stick is placed within the motor through the nozzle throat to rest on the forward enclosure. Eight igniters were used to light each grain.

Figure 21: Igniter

4 Results

The pressure and thrust both had two significant peaks. The pressure initially peaked at 883 psi, and later at 740 psi. This exceed the anticipated 594 psi. The initial spike was not simulated in burnsim.

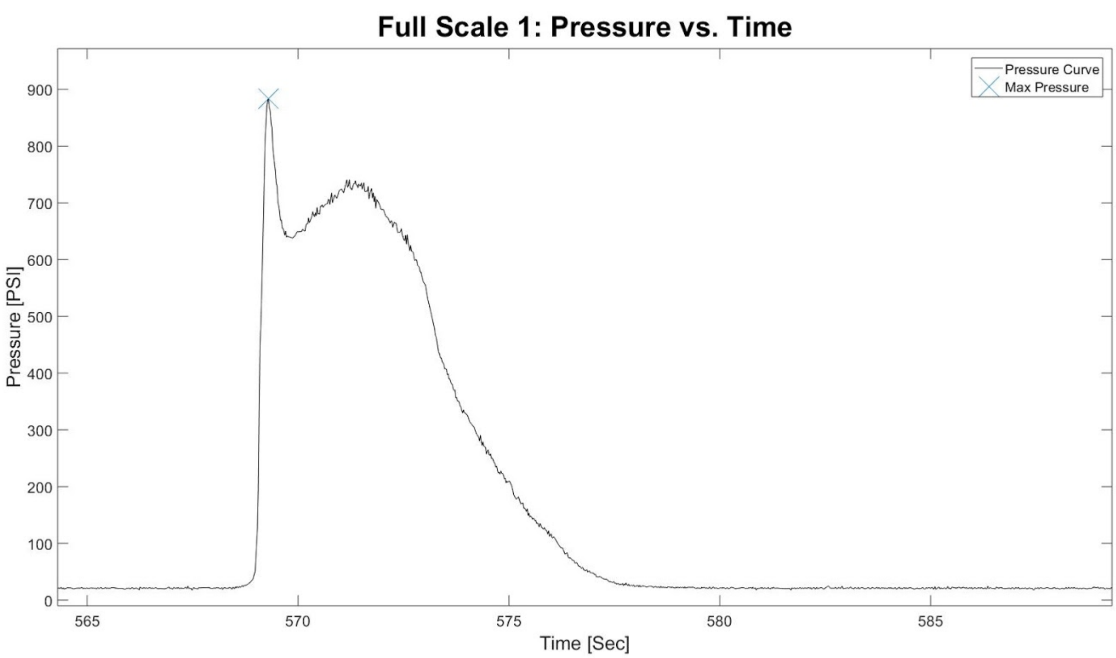


Figure 22: Pressure curve

Thrust data closely followed pressure displaying an initial maximum of 1976 lbf and a second maximum of 1767 lbf later.

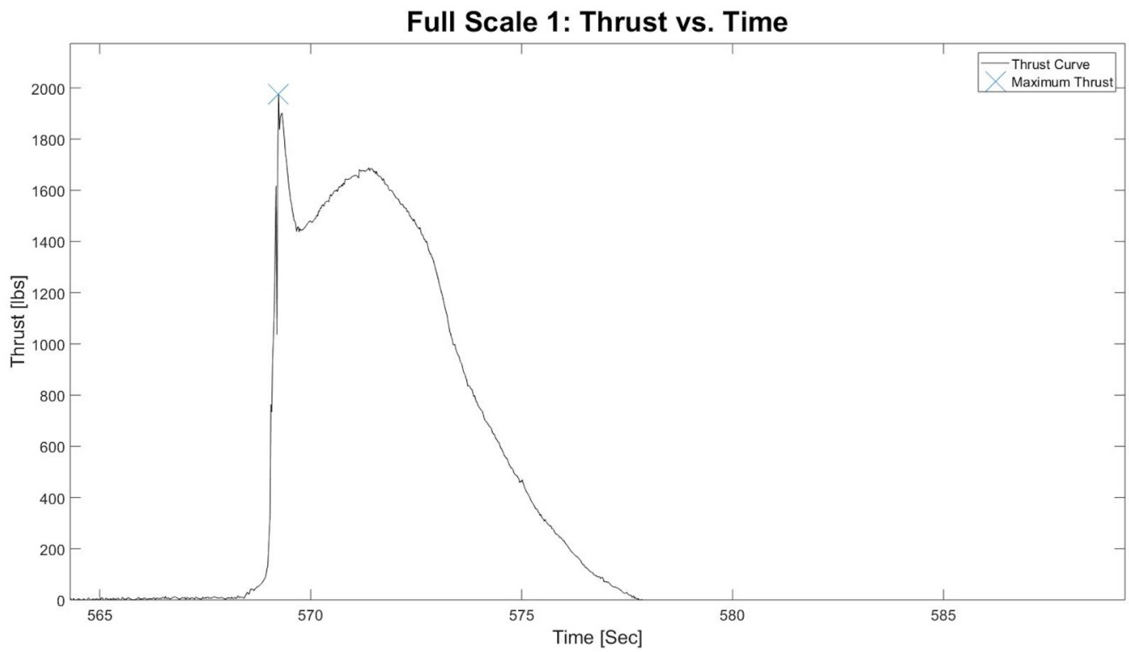


Figure 23: Thrust curve

The temperature of the nozzle reached a much greater temperature than the middle section of the motor tube body or the forward enclosure end. The nozzle end reached a maximum temperature of 183F, while the section only reached 80F and the forward end reached 77F.

The burntime of this static fire was estimated to be 7.5 seconds. Due to the slow descent of the pressure curve and a lack of methods to estimate the burn end time with this type of behavior, the burn time value could range anywhere from 7.3 to 7.7 seconds. However, at the estimated burn time the propellant achieved a burn rate of 0.217 in/sec.

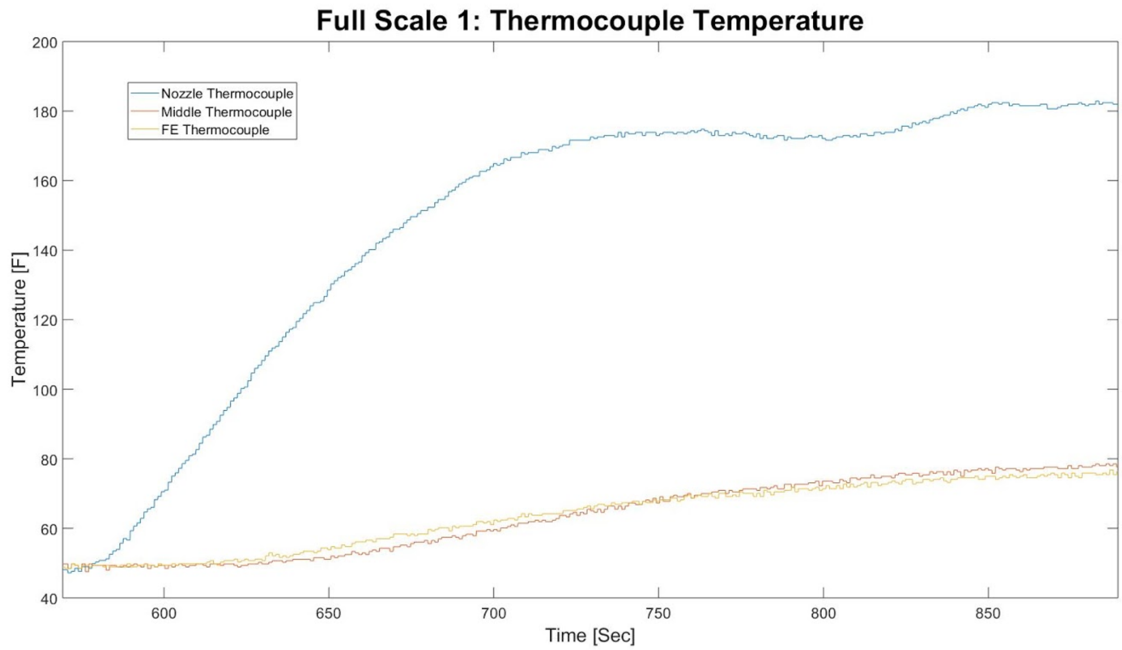


Figure 24: Motor tube temperature

However the end did not heat up measurably until long after the burn. Figure 25 shows max temperature, pressure and min safety factor along the motor tube during the fire. Note that due to the thickness of the aluminum (.175 in) temperature is assumed to be uniform radially in the motor tube.

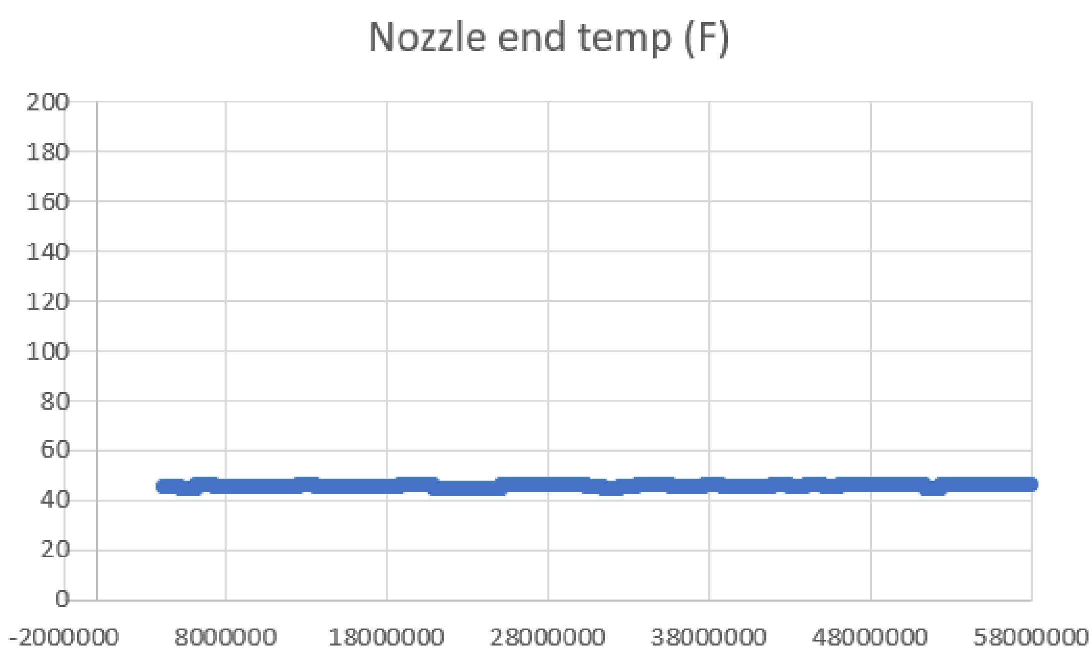


Figure 25: Motor tube temperature during burn time

The motor tube's stress was calculated assuming steady state temperature values for a conservative approximation. Safety factor is plotted in figure 26.

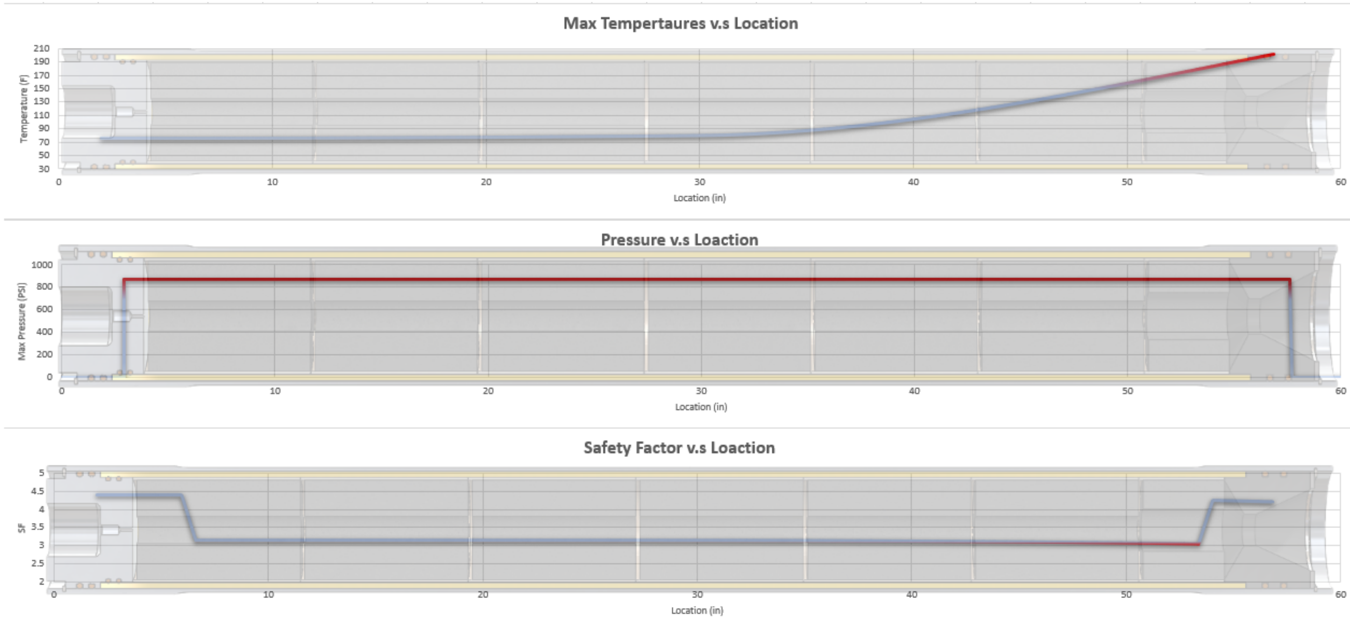


Figure 26: Temperature, pressure, and safety factor across motor tube

Stress analysis was done using ductile failure theory (Von-Mises) and assuming that the motor tube was at max temperature during max pressure. This produces the lowest factor of safety and allows us to see where the highest risk lies. Through this analysis a minumum safety factor of 3.11 was found.

- r = Mean Radius
- P = Max Pressure
- Th = Wall Thickness

$HoopStress = \frac{Pr}{\text{th}}$
$AxialStress = \frac{\text{Hoop stress}}{2}$
Principal Stress = Eigenvalues of stress matrix.
$VonMisesStress = \sqrt{((PS1 - PS2)^2 + (PS2 - PS3)^2 + (PS3 - PS1)^2)/2}$
$SafetyFactor = \frac{YieldStrength(T)}{VonMises}$

Figure 27 shows aluminum 6061's yeild strength change with temperature.

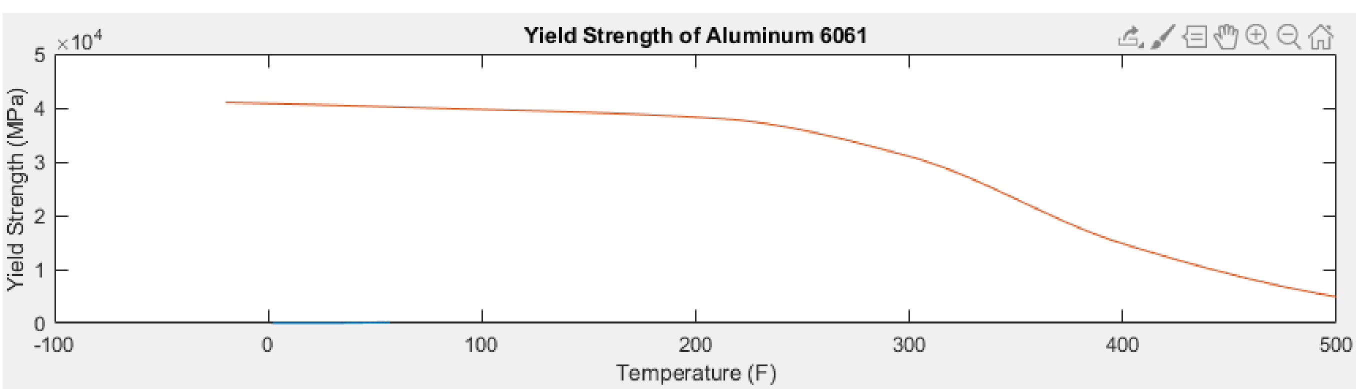


Figure 27: Aluminum strength Vs. Temperature(F)

Figure 28 summarizes the key data points.

PEAK VALUES						
FIRST PRESSURE MAXIMUM [PSI]	SECOND PRESSURE MAXIMUM [PSI]	FIRST THRUST MAXIMUM [LBS]	SECOND THRUST MAXIMUM	MAXIMUM NOZZLE TC [°F]	MAXIMUM MIDDLE TC [°F]	MAXIMUM FE TC [°F]
883	741	1975	1767	183	80	77

Figure 28: Peak test values

Figure 29 shows an image of the burn.

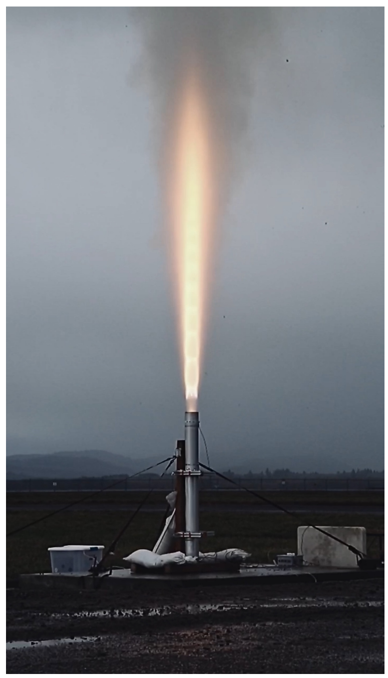


Figure 29: Motor burn

While it isn't apparent in the pressure and thrust plots, ignition lag on this burn was fairly high. It took about 10 seconds after ignition before all of the grains lit. This is shown best in figure 30.

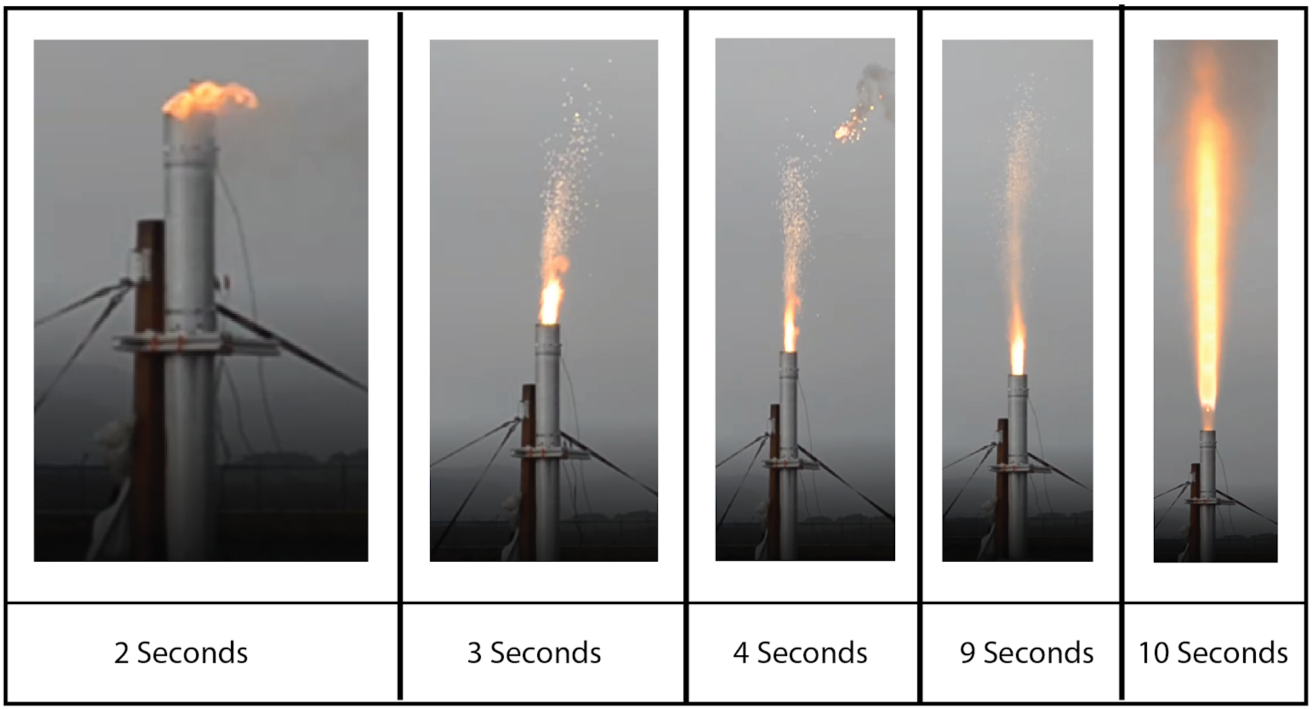


Figure 30: Ignition startup

Moments during the burn you can also witness brief flashes in the flame. This is believed to be when chunks of o-rings used as spacers between grains were ejected out the nozzle throat. However there are no pressure spikes in the data recorded during such events. It appears that there may not have been a pressure spike during that time, or the data was not sampled quickly enough to detect it. Some of these rejected o-rings were recovered as shown in figure 31.

Figure 31: Rejected o-ring

The thermal liner appeared to have endured minimal thermal stress from the static fire compared to phenolic liners in the past. The majority of the stress appeared to be located at the nozzle end. Figure 32 shows this in greater detail.

Figure 32: Damage to thermal liner

Figure 33 shows damage to the casting tubes after they were pulled out with pliers.

Figure 33: Damage to casting tube

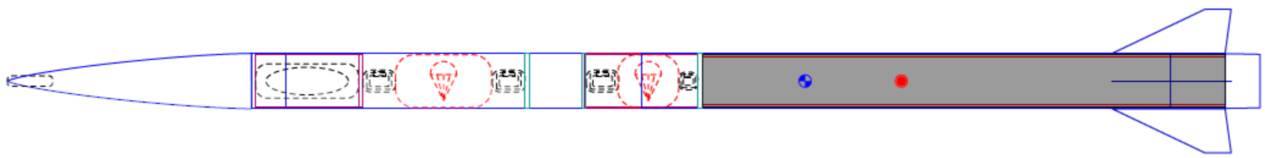
5 Discussion

The motor burned at a higher pressure and thrust than anticipated from burnsim based on sub-scale data. The initial peak was not expected either, but is not uncommon in motors beyond certain sizes according to OSU ESRAs Oregon Rocketry Mentor(OROC) Jim Baker. It is also not necessarily problematic, and can sometimes be useful getting the rocket off the rail initially. The slow ignition is clearly an issue however. Standard propellant did not burn fast enough when sparked with an e-match. Two ideas to try for the next static fire include either using a new formulation specifically for igniters with a higher aluminum content (12-18%) or using boron potassium nitrate granulates.

The raw data was converted to a motor file (.eng file type). The file was started at the large spike at startup. The file was then ended at the point at which the load cell reading returned to a starting value. This length however was around 11 seconds long. This seemed longer than the visible useful thrust that was seen in the video clip. This long tail off adds a substantial amount of impulse. When put into OpenRocket the motor is shown to have a 97% O impulse. The largest allowed at competition is an O-classified motor. Small adjustments in simulations and motor files seem to have substantial effects on simulated apogees. The propulsion team is working with Aero and recovery to find the settings and motor file that will best represent the rocket and its conditions when launching.

	Name	Configuration	Velocity off rod	Apogee	Velocity at depl...
!	Simulation 2	[11Seconds-0]	172 ft/s	47317 ft	45.8 ft/s

Figure 34: Open Rocket simulation



Rocket

Stages: 1

Mass (with motor): 120 lb

Stability: 1.74 cal

CG: 91.551 in

CP: 103 in

Altitude	41677 ft
Flight Time	669 s
Time to Apogee	48.5 s
Optimum Delay	41 s
Velocity off Pad	101 ft/s
Max Velocity	2098 ft/s
Velocity at Deployment	56.6 ft/s
Landing Velocity	13.7 ft/s

Motor	Avg Thrust	Burn Time	Max Thrust	Total Impulse	Thrust to Wt	Propellant Wt	Size
ESRAFullRealData	5058 N	7.46 s	9144 N	37788 Ns	9.45:1	43.3 lb	5.98/60 in

Figure 35: Open Rocket diagram

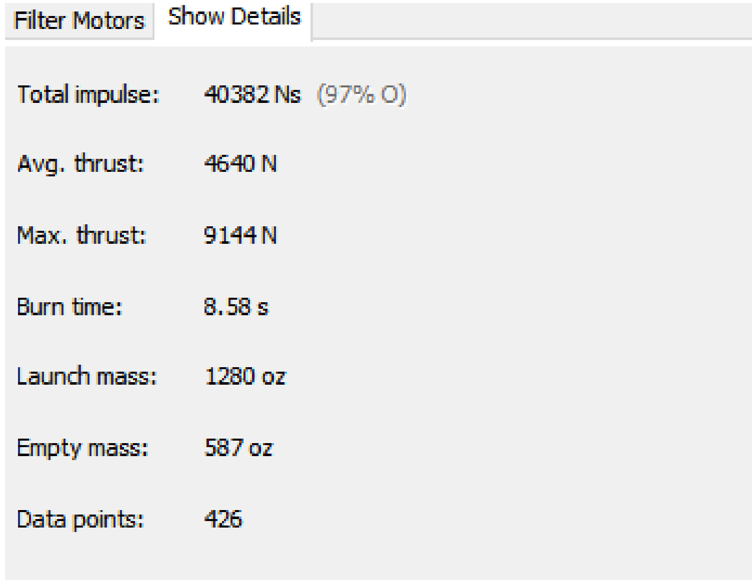


Figure 36: Open Rocket projected numbers

In conclusion, the OSU ESRA team validated their full scale motor design, however, encountered one major issue: the ignition of motor. The slow ignition may have altered the performance of the motor and in result, the data collected has been deemed inconclusive. To mitigate a potential ignition failure, we will be testing a new method recommended by Jim Baker. The motor will be ignited using approximately 1 gram of Boron Potassium Nitrate (BKNO3). BKNO3, burns well above the flash-point temperature of our solid rocket propellant and is used as an industry standard.