ESRA 2.6 Static Fire Report for COPV Analysis

February 23th, 2020

Propulsion Hardware Team Members:	**Role:**
Jon Campillo	Sub-Team Lead
Mathew Van Gordon	FE and Internal Components
Carter Hazen	Testing / Analysis
Harjot Saran	Configuration Control Lead

1 Overview

The purpose of this document is to outline the data collected during the 2020 ESRA test fires that is relevant to producing a COPV motor casing in the future. This will include the hardware components used in the test fires; the pressure, thrust and thermal data collected and the simulations and data produced by the COPV subteam.

2 Static Fire Methods

2.1 Motor Assembly

The two full-scale motor assemblies were identical for each fire, aside from how the grains were spaced in the thermal liner. The forward enclosure was secured with a snap-ring identical to the one used on the nozzle. The thermal liner was 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. New o-rings, snap rings, thrust ring, and thermal liner, and nozzle were used. The forward enclosure, and motor tube were re-used for the 2nd fire. The

fiberglass thermal liner is filled under part number 10-007A, and the drawing is shown in figure 1.

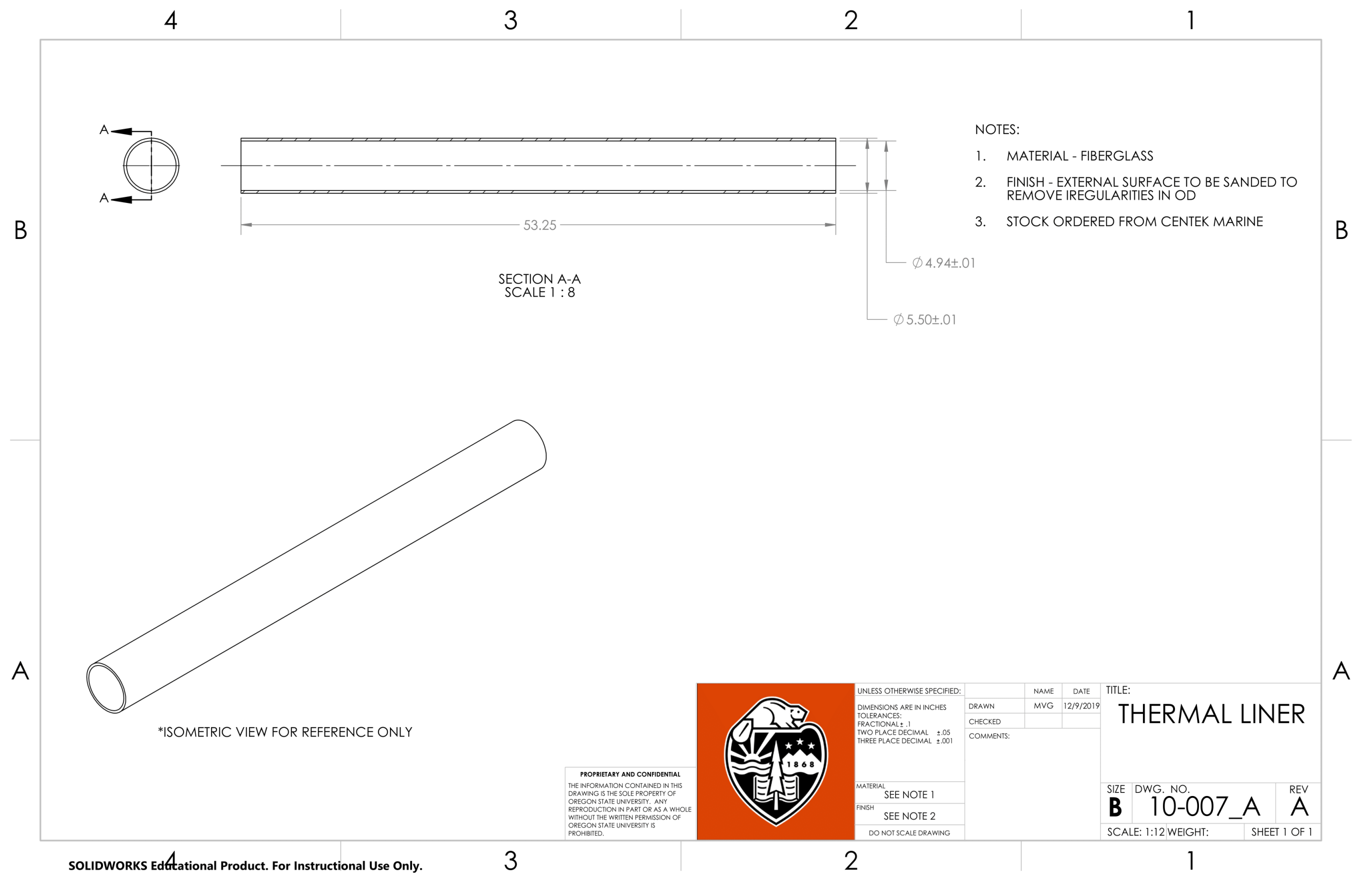


Figure 1: Thermal liner drawing

The forward enclosure was constructed from aluminum 6061, and filed under part number 10-003B shown in figure 2.

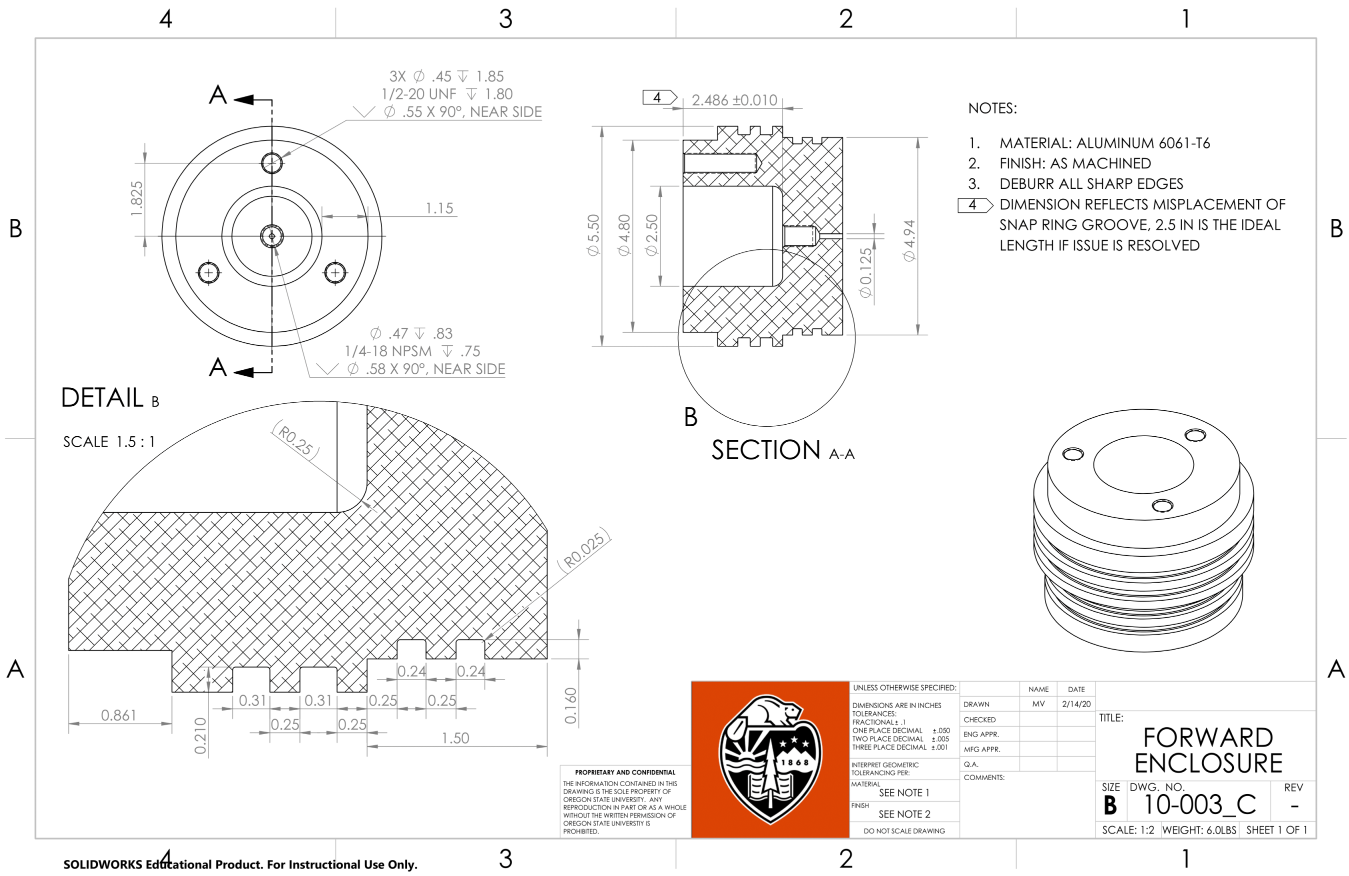


Figure 2: Forward enclosure drawing

The motor tube was constructed from aluminum 6061, and filed under part number 10-002C shown in figure 3.

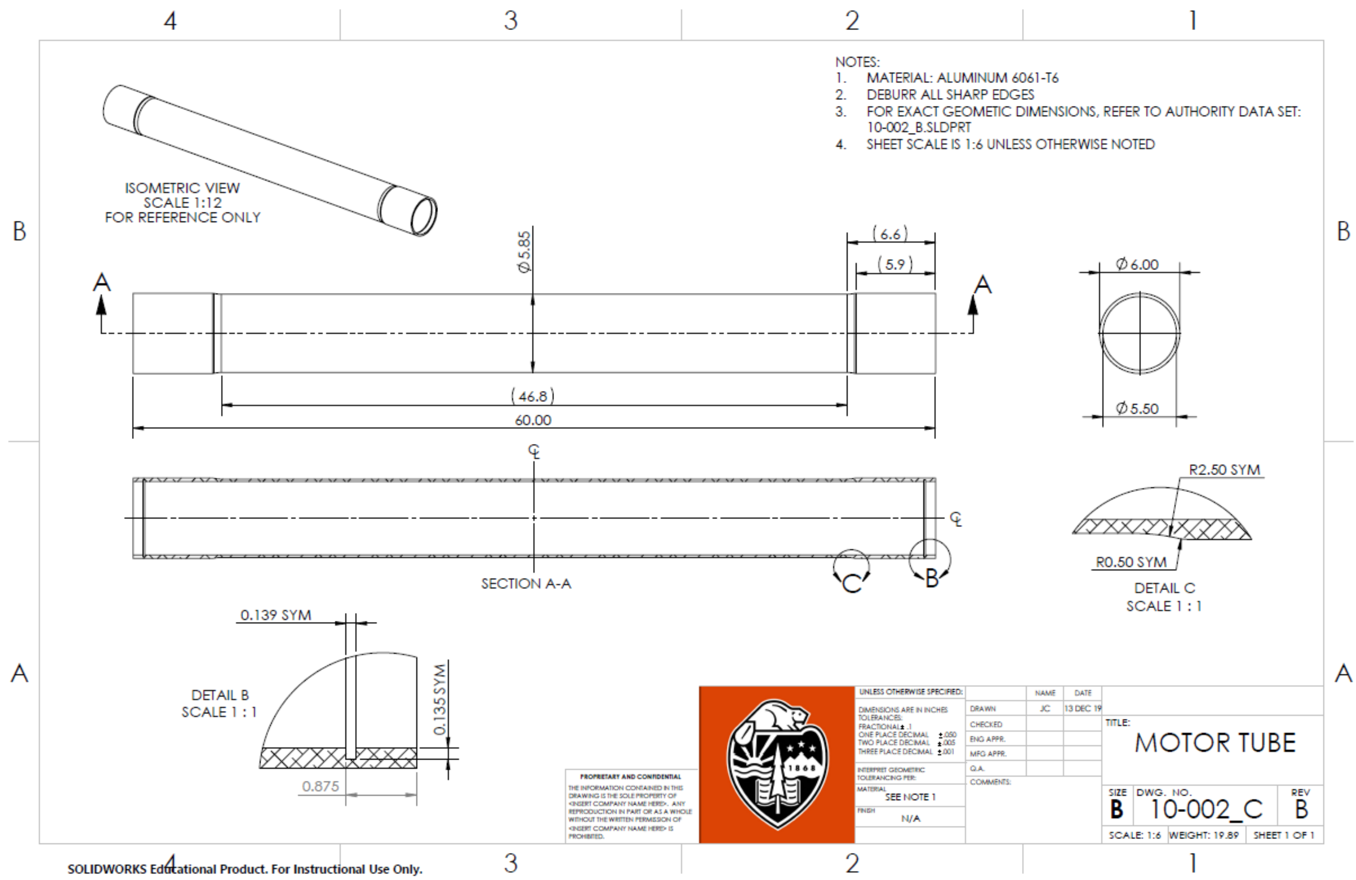


Figure 3: Motor tube drawing

The top level motor assembly is shown in figures 4, 5, 6, and 7.

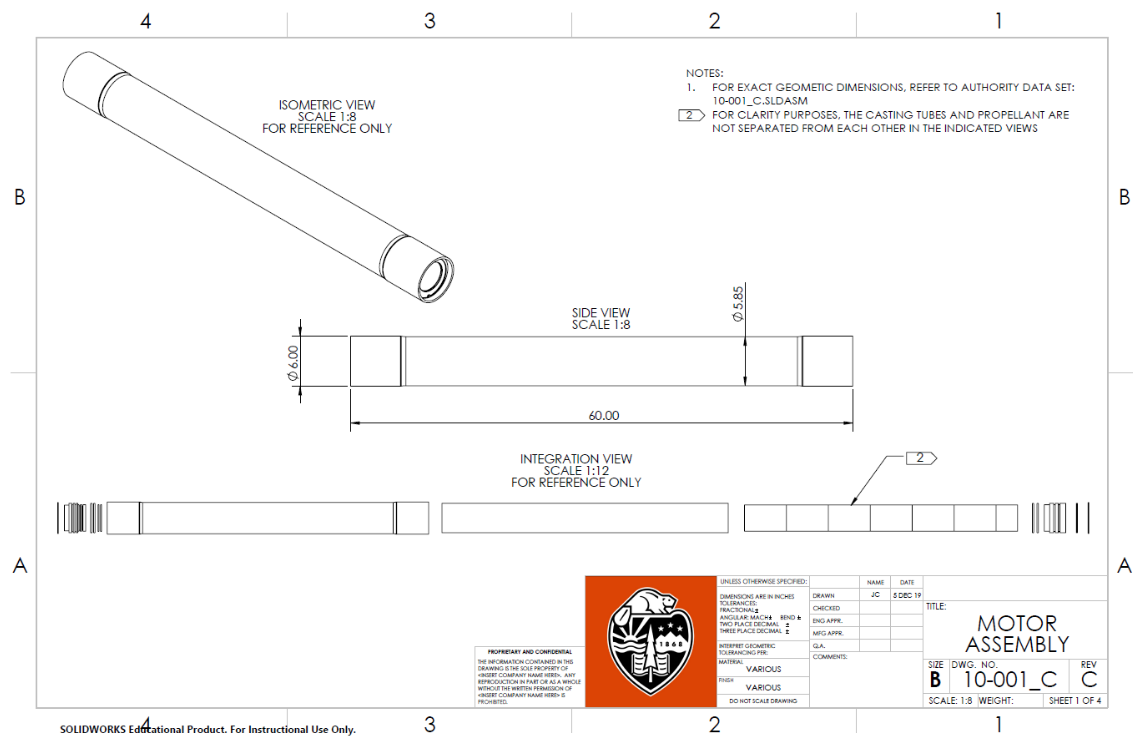


Figure 4: Motor assembly drawing page 1

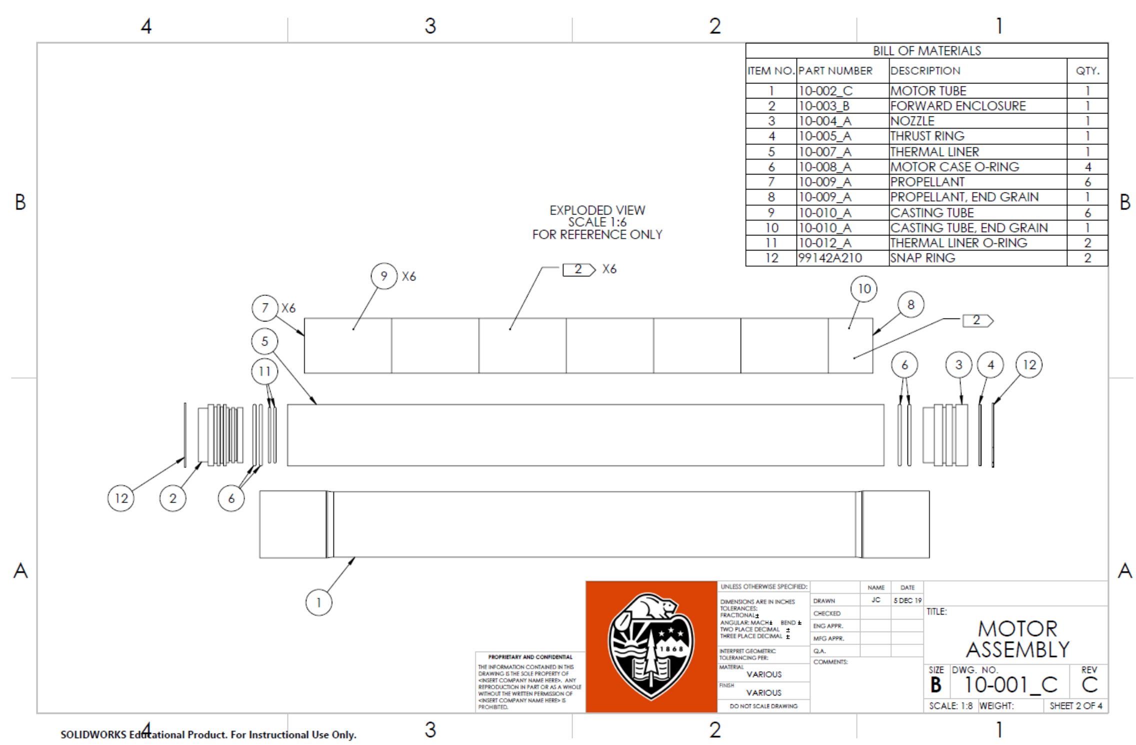


Figure 5: Motor assembly drawing page 2

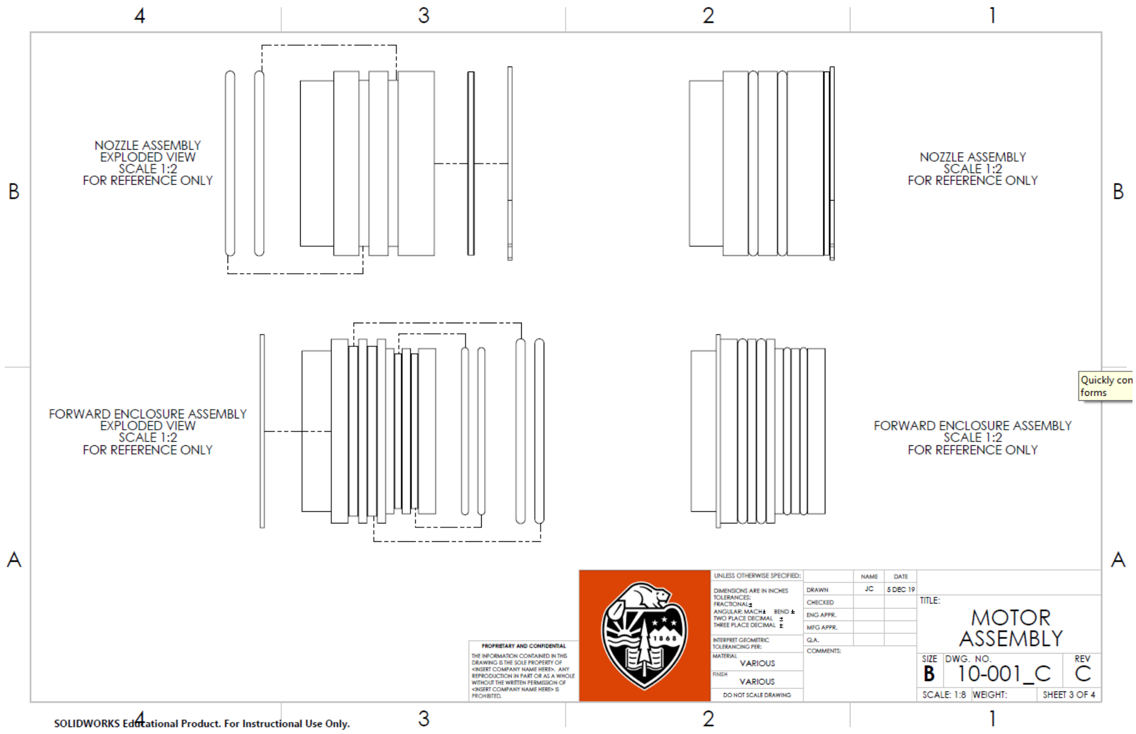


Figure 6: Motor assembly drawing page 3

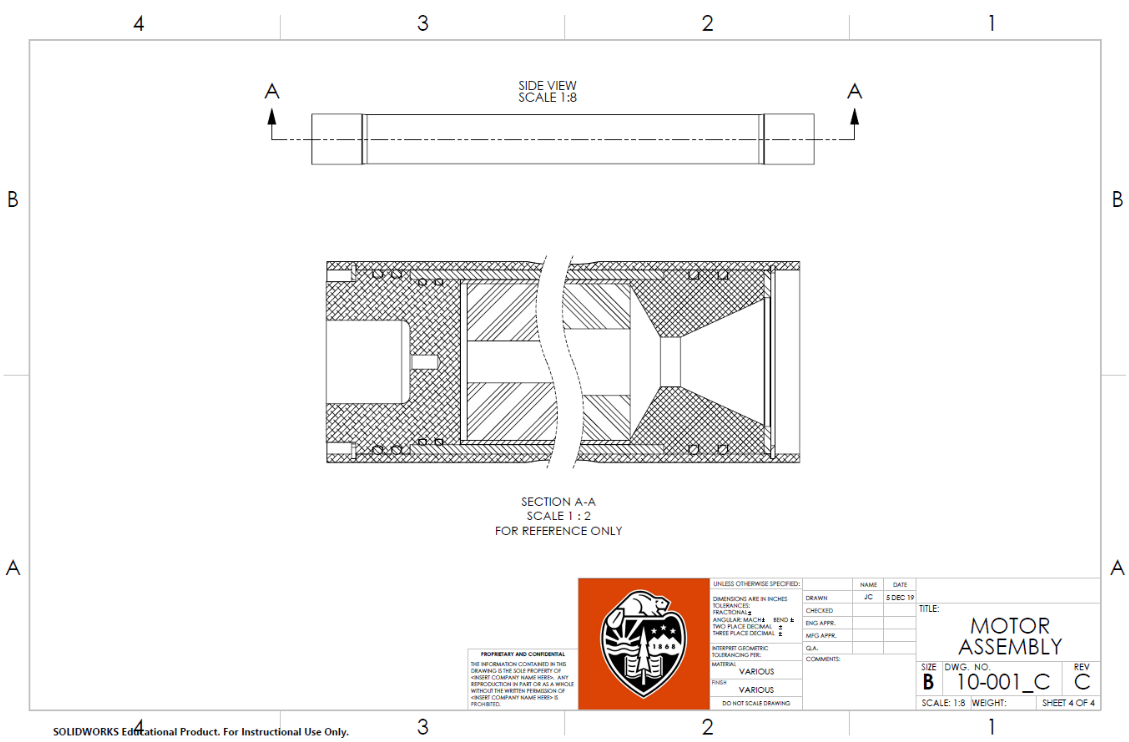


Figure 7: Motor assembly drawing page 4

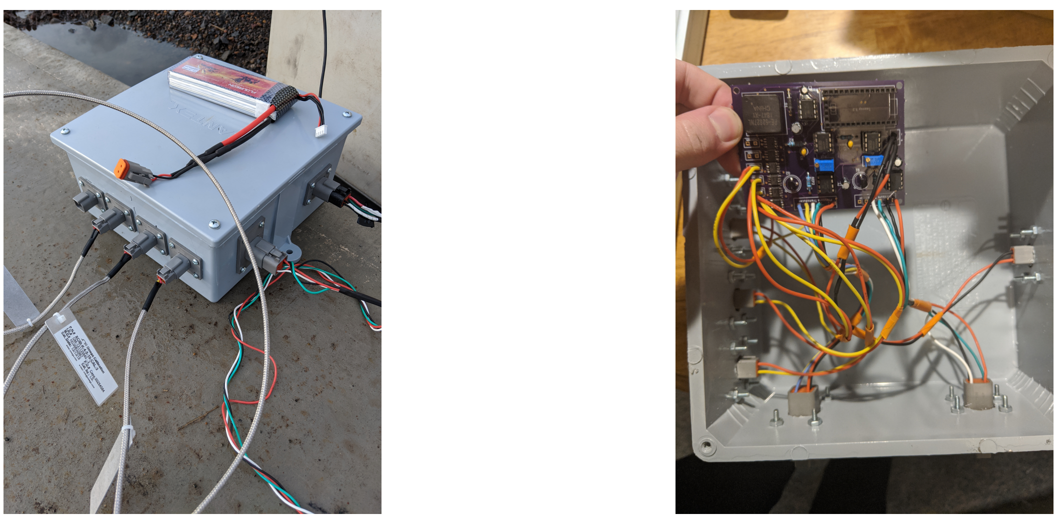
2.2 DAQ Test Stand

The motor was held in the same test stand as the prior static fire (shown in figure 8a). 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. Pressure data was recorded using a FUTEK PFP350 pressure transducer connected to the forward enclosure by a 18” copper pipe, as shown in figure 8b. 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. Three OMEGA XCIB-K-4-5-10 thermocouples were attached to the near the nozzle end of the motor tube by hose clamps painted with thermocouple putty shown in figure8c. The umbrella hat was secured to the top of the motor for tactical purposes.

(a) Test stand setup (b) Load and pressure setup (c) Thermocouple setup

Figure 8: Pressure

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 9: DAQ setup

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

3 Results

The pressure peaked at 650 psi with a burn time of 8.3028s.

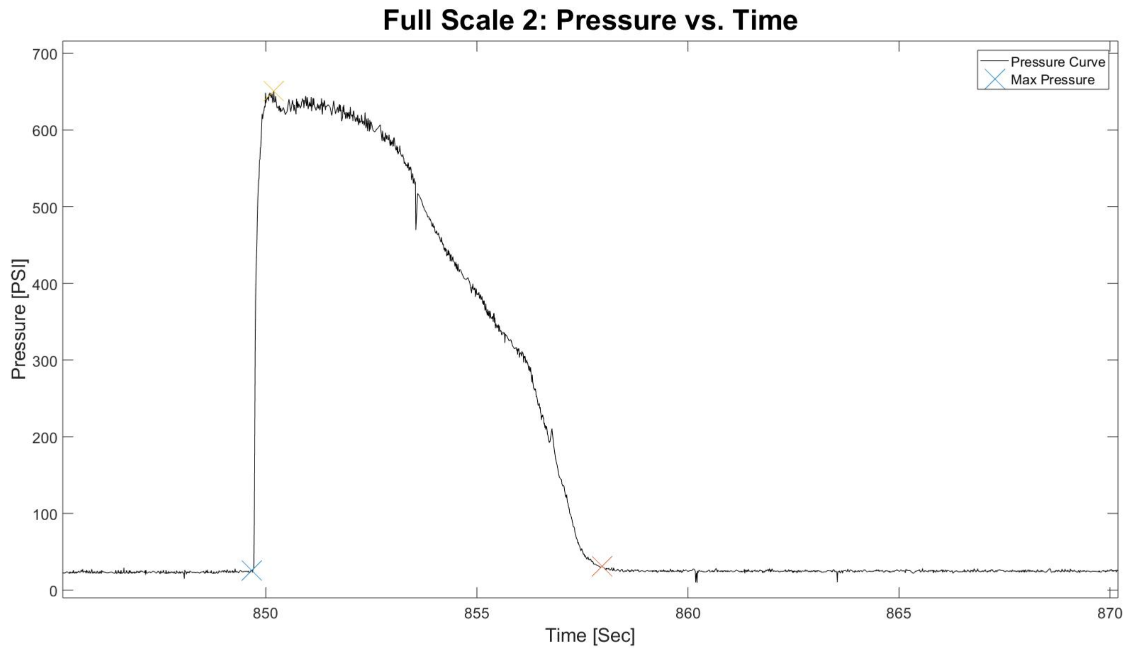


Figure 10: Pressure curve

Thrust data closely followed pressure displaying a maximum of 1545 lbf .

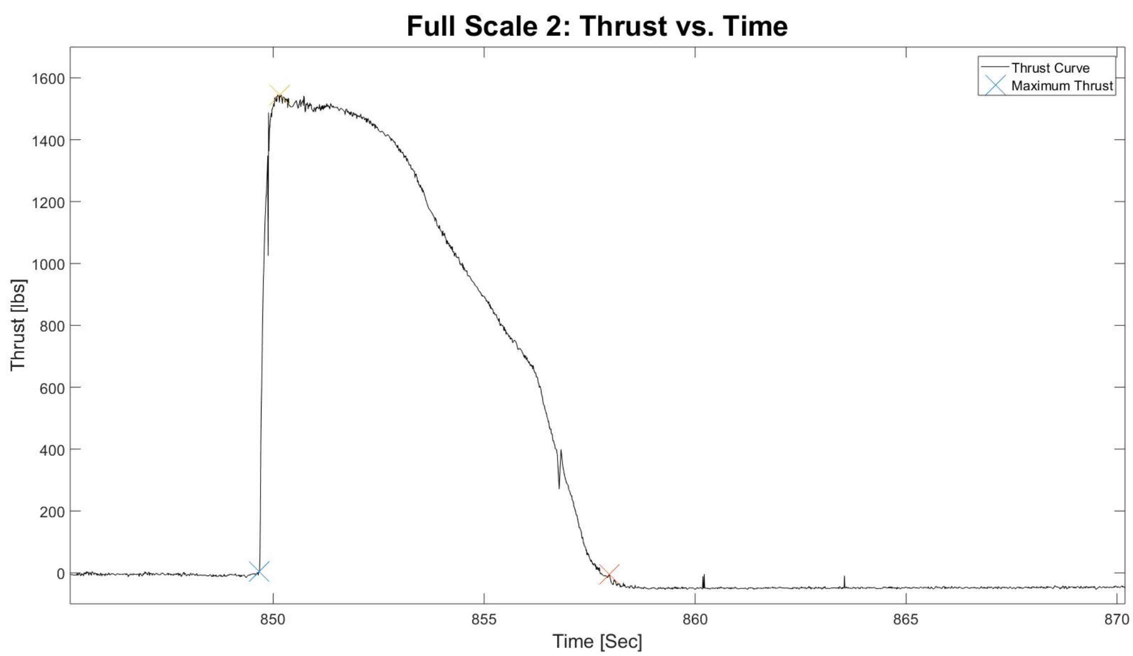


Figure 11: Thrust curve

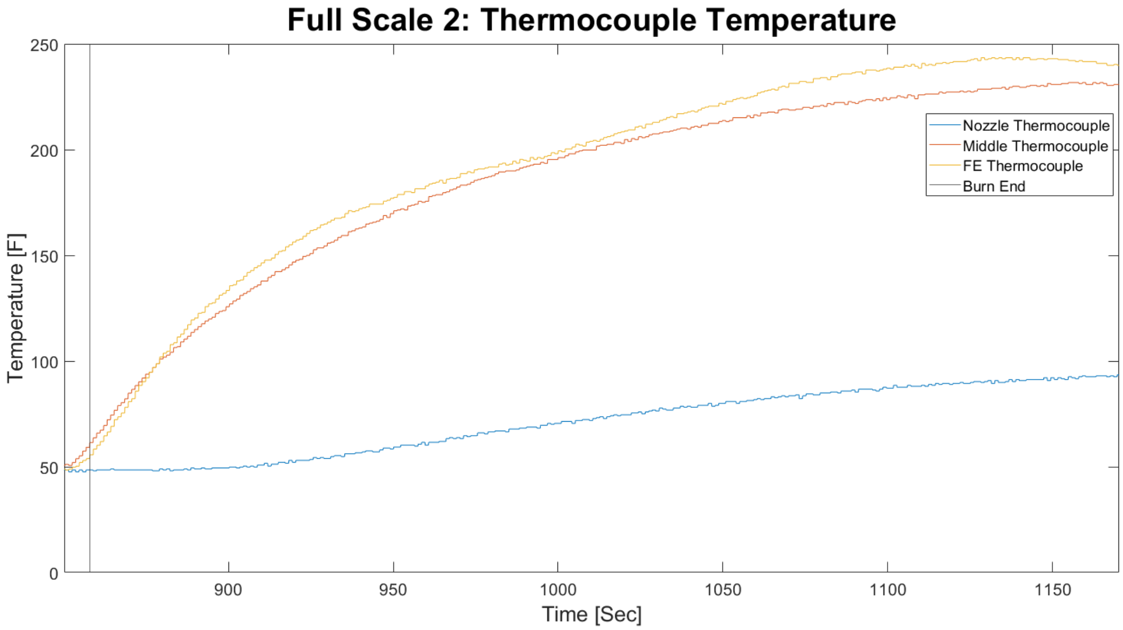
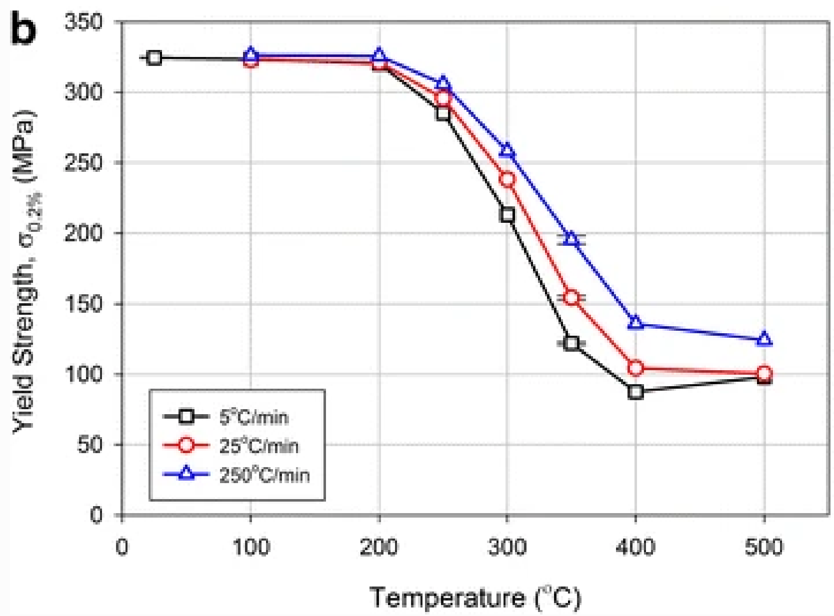


Figure 12: Motor tube temperature

Temperatures were measured at 6", 9" and 22" from the nozzle end of the motor. These locations were chosen to measure first where we believed temperature would be the highest, second the location where we believed factor of safety would be the lowest and third a reference location that we were confident would have a low temperature.The thermocouple located 6" from the nozzle opening reached a maximum temperature of 60F during the fire and 244F after sitting on the test stand for 3min. At 9" from the nozzle opening the thermocouple saw very similar temperatures at 55F during fire and 231F after resting. The reference thermocouple located near the center of the motor at 22" found to have no increase in temperature during the fire and only reached 94F after resting. This data is noticeably higher than the first fire where nozzle temperatures reached 183F, a 60 degree difference.

We have yet to determine the exact source of this increase. The factors that changed from the first fire were a decrease in propellant, decrease in pressure, quicker ignition, and shorter burn time. The most likely source of heat increase was an effective burn time increase as the quicker ignition and more steady burn lead to a burn time used for characterization of 8.3s while for the first fire the burn time was 7.5s. Figure 13 shows yield stress after heating at a defined rate and to a defined temperature. Note that due to the thickness of the aluminum (.175 in) temperature is assumed to be uniform radially in the motor tube.



(b) 6061-T651 after prior exposure at different heating rates.

Figure 13: Yield Strength vs. Annealing Temperatures
(Summers, P.T., Chen, Y., Rippe, C.M. et al. "Overview of alloy mechanical properties during and after fires")

There motor tube used in the first and second fire, dubbed "Ol faithful" has been reused twice and is planned to be reused again. Concerns of thermal damage to the motor casing arose. However from our thermal data we achieved a maximum heating rate of approximately 5C/min to a maximum temperature of approximate 150C. This should not have a substantial lasting effect on the motors strength according to the study seen in figure 13. Where our scenario falls into a region where no loss in yield strength is seen.

The motor tube's stress was calculated assuming steady state temperature values for a conservative approximation. Safety factor is plotted in figure 14.

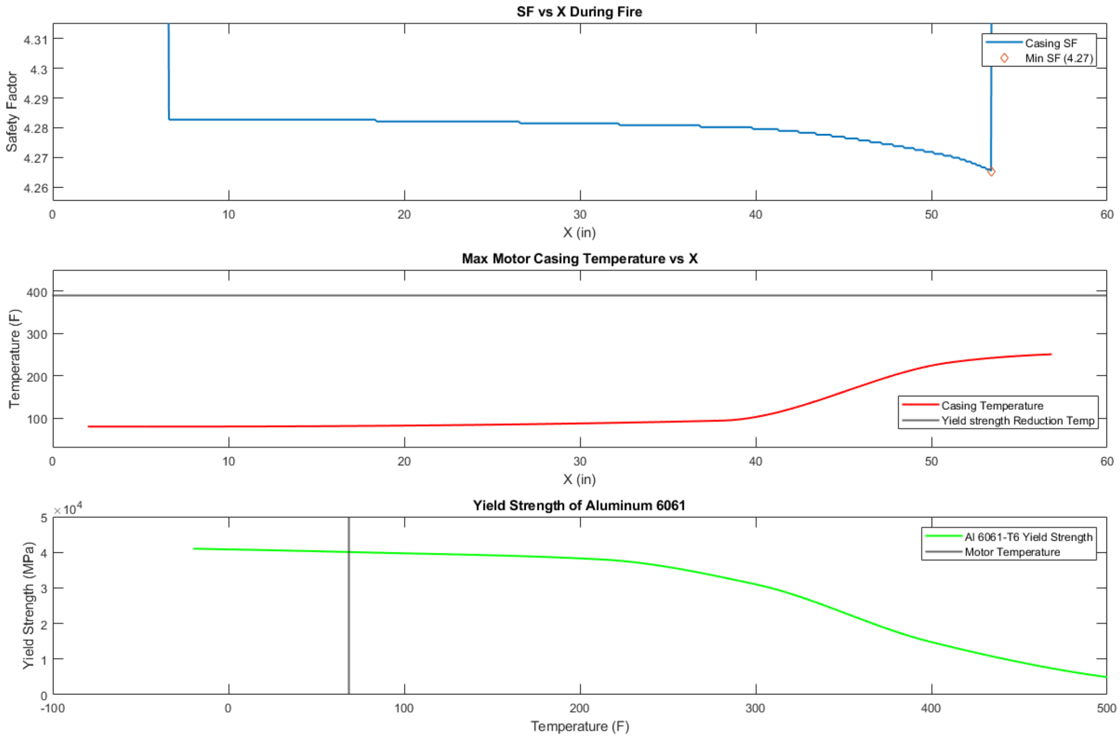


Figure 14: Safety Factor, Temperature, and Yield Strength of Motor Casing

Stress analysis was done using ductile failure theory (Von-Mises) and assuming that the motor tube was at max firing temperature during max pressure and it is a thin walled pressure vessel. This produces the lowest factor of safety and allows us to see where the highest risk lies. Through this analysis a minimum safety factor of 4.27 was found at the step down on the nozzle side. This safety factor however is very close to the nominal safety factor for the motor tube of 4.28 due to only small increase in temperature during the fire's duration.

- 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 15 summarizes the key data points.

MaximumPressure_Psi	MaximumThrust_lbs	BurnRate_in_per_sec	BurnTime	Max_T_to_M	TC1_F	TC2_F	TC3_F
650.88	1545	0.17909	8.3028	11.994	93.46	231.71	243.46

Figure 15: Peak test values

Figure 16: Motor on test stand

Figure 17: Ignition startup

4 Helius Composite Simulation

Simulations to determine optimal layup thickness's as well as schedule were done using helius composite. All simulations used a aluminum thickness of .1 in chosen because of difficulty of machining a motor tube with a smaller thickness. First simulations were done to decide an optimal layer thickness and number of layers to produce a significant weight savings and adequate safety factor. This can be seen in Figure 18.

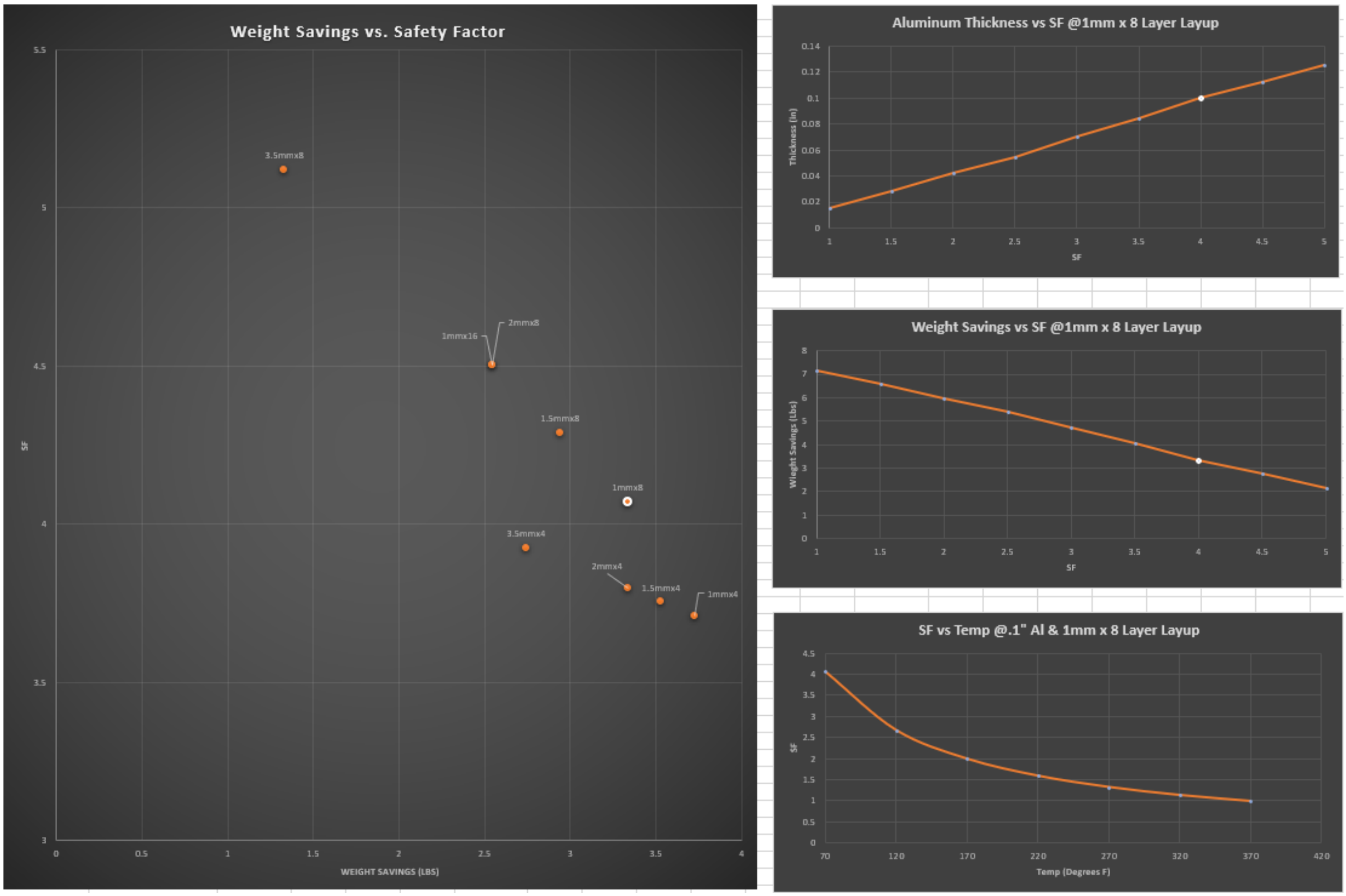


Figure 18: Composite thickness simulation data

After these simulations we ran into difficulty sourcing pre-preg kevlar-49 to produce the COPV motor and began to look into T-700 carbon fiber. This is due to the availability of T-700 at OSU from the GFR teams extensive use of this material. analysis of both this material and kevlar-49 were then preformed for a 5.5" inner diameter motor to simulate the current ESRA motor. This simulation data can be seen below in Figure 19.

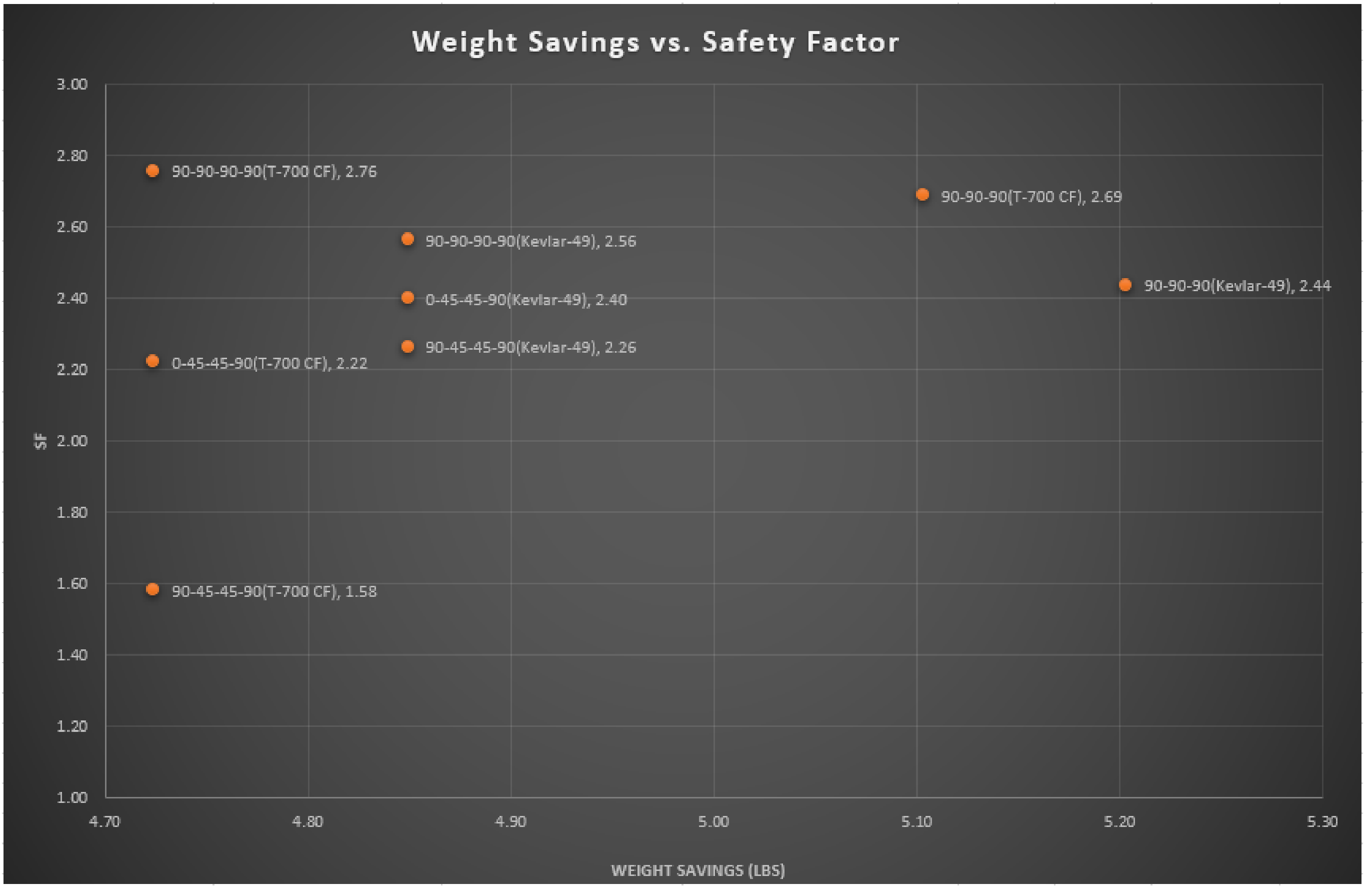


Figure 19: Composite schedule simulation data

	Weight Savings vs. Safety Factor		
Schedule/Material	**Weight Savings**	**Safety Factor Composite**	**Safety Factor Aluminum**
0-45-45-90(Kevlar-49)	4.85	4.92	2.40
90-45-45-90(Kevlar-49)	4.85	3.61	2.26
90-90-90-90(Kevlar-49)	4.85	6.42	2.56
90-90-90(Kevlar-49)	5.20	6.40	2.44
0-45-45-90(T-700 CF)	4.72	2.22	2.64
90-45-45-90(T-700 CF)	4.72	1.58	2.43
90-90-90-90(T-700 CF)	4.72	2.76	2.89
90-90-90(T-700 CF)	5.10	2.75	2.69

Figure 20: SF of designated material layups

Kevlar 1mm 90/45/-45/90/90/-45/45/90

Material	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.00132266	15938.6	2.3603
	2.8	0.00130022	15689.3	2.3978
	2.85	0.00127778	15440	2.4365
Kevlar-49 (.0315 in)	2.85	0.00127778	14267.9	6.8881
	2.85197	0.0012769	14258.1	6.8908
	2.85394	0.00127602	14248.3	6.8935
	2.85394	0.00127602	5308.21	4.9246
	2.85591	0.00127513	5305.2	4.9273
	2.85787	0.00127425	5302.18	4.93
	2.85787	0.00127425	5302.18	4.93
	2.85984	0.00127337	5299.17	4.9327
	2.86181	0.00127248	5296.15	4.9354
	2.86181	0.00127248	14209.1	6.9042
	2.86378	0.0012716	14199.3	6.9069
	2.86575	0.00127072	14189.5	6.9096
	2.86575	0.00127072	14189.5	6.9096
	2.86772	0.00126983	14179.7	6.9123
	2.86969	0.00126895	14169.9	6.915
	2.86969	0.00126895	5284.1	4.9463
	2.87165	0.00126807	5281.08	4.949
	2.87362	0.00126718	5278.07	4.9517
	2.87362	0.00126718	5278.07	4.9517
	2.87559	0.0012663	5275.05	4.9544
	2.87756	0.00126542	5272.04	4.9572
	2.87756	0.00126542	14130.7	6.9258
	2.87953	0.00126453	14120.9	6.9285
	2.8815	0.00126365	14111.1	6.9312

Relevant Info:
Minimum Safety Factor of Kevlar
4.92
Minimum Safety Factor of Aluminum
2.40
Number of Kevlar Layers
8.00
Weight Savings (Lbs)
4.85

Kevlar 1mm 0/45/-45/90/90/-45/45/0

Material	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.00142646	16889	2.2275
	2.8	0.00140226	16620.2	2.2635
	2.85	0.00137806	16351.3	2.3007
Kevlar-49 (.0315 in)	2.85	0.00137806	1189.7	3.6144
	2.85197	0.00137711	1188.93	3.6167
	2.85394	0.00137616	1188.16	3.619
	2.85394	0.00137616	5494.32	4.7917
	2.85591	0.00137521	5491.07	4.7944
	2.85787	0.00137425	5487.82	4.7972
	2.85787	0.00137425	5487.82	4.7972
	2.85984	0.0013733	5484.57	4.8
	2.86181	0.00137235	5481.32	4.8027
	2.86181	0.00137235	15301.7	7.1008
	2.86378	0.00137139	15291.1	7.1039
	2.86575	0.00137044	15280.6	7.1069
	2.86575	0.00137044	15280.6	7.1069
	2.86772	0.00136949	15270	7.11
	2.86969	0.00136854	15259.4	7.1131
	2.86969	0.00136854	5468.32	4.8138
	2.87165	0.00136758	5465.07	4.8166
	2.87362	0.00136663	5461.81	4.8193
	2.87362	0.00136663	5461.81	4.8193
	2.87559	0.00136568	5458.56	4.8221
	2.87756	0.00136473	5455.31	4.8249
	2.87756	0.00136473	1178.94	3.6474
	2.87953	0.00136377	1178.17	3.6497
	2.8815	0.00136282	1177.4	3.6521

Relevant Info:
Minimum Safety Factor of Kevlar
3.61
Minimum Safety Factor of Aluminum
2.26
Number of Kevlar Layers
8.00
Weight Savings (Lbs)
4.85

Kevlar 1mm 90/90/90/90/90/90/90/90

Material	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.00119675	14900.4	2.5248
	2.8	0.00117644	14674.9	2.5636
	2.85	0.00115614	14449.3	2.6036
Kevlar-49 (.0315 in)	2.85	0.00115614	12945.4	6.4153
	2.85197	0.00115534	12936.6	6.4174
	2.85394	0.00115454	12927.7	6.4195
	2.85394	0.00115454	12927.7	6.4195
	2.85591	0.00115374	12918.8	6.4216
	2.85787	0.00115294	12910	6.4237
	2.85787	0.00115294	12910	6.4237
	2.85984	0.00115214	12901.1	6.4258
	2.86181	0.00115135	12892.2	6.4279
	2.86181	0.00115135	12892.2	6.4279
	2.86378	0.00115055	12883.4	6.4301
	2.86575	0.00114975	12874.5	6.4322
	2.86575	0.00114975	12874.5	6.4322
	2.86772	0.00114895	12865.6	6.4343
	2.86969	0.00114815	12856.8	6.4364
	2.86969	0.00114815	12856.8	6.4364
	2.87165	0.00114735	12847.9	6.4385
	2.87362	0.00114655	12839	6.4406
	2.87362	0.00114655	12839	6.4406
	2.87559	0.00114575	12830.2	6.4427
	2.87756	0.00114495	12821.3	6.4448
	2.87756	0.00114495	12821.3	6.4448
	2.87953	0.00114415	12812.4	6.447
	2.8815	0.00114335	12803.6	6.4491

Relevant Info:
Minimum Safety Factor of Kevlar
6.42
Minimum Safety Factor of Aluminum
2.56
Number of Kevlar Layers
8.00
Weight Savings (Lbs)
4.85

Kevlar 1mm 90/90/90/90/90/90

Material	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.0012746	15680.2	2.3992
	2.8	0.00125288	15439	2.4367
	2.85	0.00123117	15197.8	2.4754
Kevlar-49 (.0315 in)	2.85	0.00123117	13771.4	6.3977
	2.85197	0.00123032	13762	6.3999
	2.85394	0.00122946	13752.5	6.4022
	2.85394	0.00122946	13752.5	6.4022
	2.85591	0.00122861	13743	6.4044
	2.85787	0.00122776	13733.5	6.4067
	2.85787	0.00122776	13733.5	6.4067
	2.85984	0.0012269	13724	6.4089
	2.86181	0.00122605	13714.5	6.4111
	2.86181	0.00122605	13714.5	6.4111
	2.86378	0.00122519	13705.1	6.4134
	2.86575	0.00122434	13695.6	6.4156
	2.86575	0.00122434	13695.6	6.4156
	2.86772	0.00122348	13686.1	6.4179
	2.86969	0.00122263	13676.6	6.4201
	2.86969	0.00122263	13676.6	6.4201
	2.87165	0.00122177	13667.1	6.4224
	2.87362	0.00122092	13657.7	6.4246

Relevant Info:
Minimum Safety Factor of Kevlar
6.40
Minimum Safety Factor of Aluminum
2.44
Number of Kevlar Layers
6.00
Weight Savings (Lbs)
5.20

Carbon Fiber 1mm 90/45/-45/90/90/-45/45/90				
	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.00118572	14456.5	2.6023
	2.8	0.00116561	14233	2.6432
	2.85	0.00114549	14009.5	2.6853
Kevlar-49 (.0315 in)	2.85	0.00114549	20687.1	3.1074
	2.85197	0.0011447	20672.9	3.1085
	2.85394	0.00114391	20658.7	3.1096
	2.85394	0.00114391	7979.9	2.2198
	2.85591	0.00114311	7975.41	2.221
	2.85787	0.00114232	7970.93	2.2221
	2.85787	0.00114232	7970.93	2.2221
	2.85984	0.00114153	7966.44	2.2233
	2.86181	0.00114074	7961.95	2.2245
	2.86181	0.00114074	20601.8	3.1138
	2.86378	0.00113995	20587.6	3.1149
	2.86575	0.00113915	20573.4	3.116
	2.86575	0.00113915	20573.4	3.116
	2.86772	0.00113836	20559.2	3.117
	2.86969	0.00113757	20545	3.1181
	2.86969	0.00113757	7943.99	2.2292
	2.87165	0.00113678	7939.5	2.2304
	2.87362	0.00113599	7935.02	2.2316
	2.87362	0.00113599	7935.02	2.2316
	2.87559	0.00113519	7930.53	2.2328
	2.87756	0.0011344	7926.04	2.234
	2.87756	0.0011344	20488.1	3.1224
	2.87953	0.00113361	20473.9	3.1235
	2.8815	0.00113282	20459.7	3.1246

Relevant Info:
Minimum Safety Factor of CF
2.22
Minimum Safety Factor of Aluminum
2.64
Number of Layers
8.00
Weight Savings (Lbs)
4.72

Carbon Fiber 1mm 0/45/-45/90/90/-45/45/0				
	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.00132779	15743.9	2.3895
	2.8	0.00130526	15493.6	2.4281
	2.85	0.00128274	15243.4	2.468
CF (.0315 in)	2.85	0.00128274	1651.96	1.5804
	2.85197	0.00128185	1650.88	1.5814
	2.85394	0.00128096	1649.81	1.5824
	2.85394	0.00128096	8417.49	2.1372
	2.85591	0.00128008	8412.47	2.1384
	2.85787	0.00127919	8407.44	2.1397
	2.85787	0.00127919	8407.44	2.1397
	2.85984	0.0012783	8402.41	2.1409
	2.86181	0.00127741	8397.39	2.1421
	2.86181	0.00127741	23026.2	3.2964
	2.86378	0.00127653	23010.2	3.2977
	2.86575	0.00127564	22994.3	3.2991
	2.86575	0.00127564	22994.3	3.2991
	2.86772	0.00127475	22978.4	3.3004
	2.86969	0.00127387	22962.5	3.3018
	2.86969	0.00127387	8377.28	2.147
	2.87165	0.00127298	8372.25	2.1483
	2.87362	0.00127209	8367.23	2.1495
	2.87362	0.00127209	8367.23	2.1495
	2.87559	0.00127121	8362.2	2.1507
	2.87756	0.00127032	8357.17	2.152
	2.87756	0.00127032	1636.92	1.5949
	2.87953	0.00126943	1635.84	1.5959
	2.8815	0.00126855	1634.77	1.597

Relevant Info:
Minimum Safety Factor of CF
1.58
Minimum Safety Factor of Aluminum
2.43
Number of Layers
8.00
Weight Savings (Lbs)
4.72

Carbon Fiber 1mm 90/90/90/90/90/90/90/90				
	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.00103136	13229.8	2.8436
	2.8	0.00101386	13035.4	2.886
	2.85	0.00099636	12841	2.9297
CF (.0315 in)	2.85	0.00099636	18058.9	2.756
	2.85197	0.00099567	18046.5	2.7568
	2.85394	0.00099498	18034.1	2.7575
	2.85394	0.00099498	18034.1	2.7575
	2.85591	0.0009943	18021.8	2.7582
	2.85787	0.00099361	18009.4	2.7589
	2.85787	0.00099361	18009.4	2.7589
	2.85984	0.00099292	17997.1	2.7597
	2.86181	0.00099223	17984.7	2.7604
	2.86181	0.00099223	17984.7	2.7604
	2.86378	0.00099154	17972.3	2.7611
	2.86575	0.00099085	17960	2.7619
	2.86575	0.00099085	17960	2.7619
	2.86772	0.00099016	17947.6	2.7626
	2.86969	0.00098947	17935.2	2.7633
	2.86969	0.00098947	17935.2	2.7633
	2.87165	0.00098878	17922.9	2.7641
	2.87362	0.0009881	17910.5	2.7648
	2.87362	0.0009881	17910.5	2.7648
	2.87559	0.00098741	17898.1	2.7655
	2.87756	0.00098672	17885.8	2.7663
	2.87756	0.00098672	17885.8	2.7663
	2.87953	0.00098603	17873.4	2.767
	2.8815	0.00098534	17861.1	2.7677

Relevant Info:
Minimum Safety Factor of CF
2.76
Minimum Safety Factor of Aluminum
2.89
Number of Layers
8.00
Weight Savings (Lbs)
4.72

Carbon Fiber 1mm 90/90/90/90/90/90				
	Location (in)	Hoop Strain (in/in)	Hoop Stress (PSI)	SF
Aluminum 6061-T6 (.1 in)	2.75	0.0011293	14216.4	2.6462
	2.8	0.00111006	14002.7	2.6866
	2.85	0.00109082	13789	2.7283
CF (.0315 in)	2.85	0.00109082	19744.3	2.7537
	2.85197	0.00109007	19730.7	2.7545
	2.85394	0.00108931	19717.1	2.7553
	2.85394	0.00108931	19717.1	2.7553
	2.85591	0.00108855	19703.5	2.7561
	2.85787	0.0010878	19689.9	2.7569
	2.85787	0.0010878	19689.9	2.7569
	2.85984	0.00108704	19676.3	2.7577
	2.86181	0.00108628	19662.7	2.7585
	2.86181	0.00108628	19662.7	2.7585
	2.86378	0.00108552	19649.2	2.7593
	2.86575	0.00108477	19635.6	2.7601
	2.86575	0.00108477	19635.6	2.7601
	2.86772	0.00108401	19622	2.7609
	2.86969	0.00108325	19608.4	2.7617
	2.86969	0.00108325	19608.4	2.7617
	2.87165	0.00108249	19594.8	2.7625
	2.87362	0.00108174	19581.2	2.7633

Relevant Info:
Minimum Safety Factor of Kevlar
2.75
Minimum Safety Factor of Aluminum
2.69
Number of Layers
6.00
Weight Savings (Lbs)
5.10

5 Summary

The COPV motor design will continue by creating a subscale motor to test the effectiveness of laying up on a aluminum casing as well as testing the accuracy of our simulations. To do so we need to determine correct schedule for layup and material that will be not only effective but obtainable for and economically viable price. We are currently sourcing pre-preg kevlar 49 as well as sourcing T-700 carbon fiber from other OSU capstone teams. This will most likely be used on the subscale layup to reduce wait time for testing. To do this a yardage of 10 with a length of 60" is needed to complete a full ESRA motor and 1 with a length of 8" for a subscale motor.