PSAS COMPOSITE ROCKET AIRFRAME

ME 493 Final Report - Year 2014

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Executive Summary

The composite rocket airframe capstone team was tasked with designing the next generation rocket airframe for Portland State Aerospace Society (PSAS). PSAS has developed highly sophisticated avionics systems and needs a next-gen airframe to enable their growing capabilities. The primary deliverables for this capstone project were the tools, processes, and knowledge required for manufacturing lightweight airframe modules. Additionally, the capstone team had to deliver at least one complete airframe module.

Composite materials became the obvious choice for the airframe structure because of their high specific strength properties. Because of its manufacturability and exceptional performance, pre-impregnated carbon fiber was chosen as the primary airframe material. This was combined with a honeycomb sandwich structure and bonded aluminum coupling rings to complete the airframe module design. The final design was evaluated by extensive testing and iteration, and ultimately surpassed the project requirements.

Our sponsor, PSAS, has been satisfied with the results of the project. Most importantly, the capstone team has thoroughly documented all design and manufacturing processes. With this documentation and minimal training, PSAS is confident that it will be able to continue manufacturing carbon airframe modules into the future. However, there is still room for improvements. Investigations should be made into the use of a variety of carbon fabrics and layup schedules. There are also ample opportunities for PSAS to build on this project's composites knowledge to continue integrating composite structures into the rest of the airframe.

Contents

1. Introduction and Background Information

Portland State Aerospace Society (PSAS) is an educational aerospace program at Portland State University (PSU) that builds small sounding rockets. PSAS is currently planning a 100 km launch vehicle that requires a new airframe module design that is much lighter than the current fiberglass/aluminum modules. The PSAS team has spent nearly a decade developing the rocket's avionics and communications equipment using a robust and reliable airframe. In order to achieve their goal to put a CubeSat in orbit, PSAS needs an optimized mechanical airframe design that is capable of efficiently reaching higher altitudes.

2. Mission Statement

The composite rocket airframe project will provide PSAS with the tools, processes, and knowledge necessary for repeatable manufacturing of composite airframe modules using existing aerospace solutions. Extensive documentation will ensure that PSAS will be able to independently manufacture modules in the future. The capstone team must also deliver at least one complete airframe module including the coupling mechanism necessary for integration with the rest of the rocket.

3. Main Design Requirements

Based on the full project PDS, provided in Table A.1, the most critical design considerations were buckling strength, manufacturing repeatability, and bending stiffness. Because the rocket is subjected to high compression loading during launch, the cylindrical structure is particularly susceptible to buckling failure. The module design would have to be able to withstand at least the full 800 lb_f thrust of the motor.

Because PSAS will continue to manufacture modules in the future, it was important that the manufacturing process for the modules be relatively simple and repeatable. Variation in strength between modules should be minimized.

The bending stiffness of the rocket is also a major concern, as it contributes to the natural frequency of the rocket and resists the potentially large aerodynamic stresses caused by changes in direction.

Table 3.1 shows additional major requirements in terms of priority and final outcome.

Table 3.1. General design requirements as specified by PSAS, indicating priority as well as outcome.

Category	Specification	Priority	Metric	Result
Airframe Modules	Weigh less than 1.5lbf per module	Must	lbf	1.25
	Strong enough to withstand 100km launch	Must	Yes/No	Yes
	Stiff enough to avoid resonant frequencies below 5000hz	Must	Yes/No	Yes
	Customizable end flanges for module coupling and internal structures	Must	Yes/No	Yes
	Have varying lengths from 100mm to 2000mm	Must	Yes/No	Yes
	Have a single target ID of 300mm	Must	Yes/No	Yes
	Use inexpensive materials	Should	Yes/No	No
Tooling	Be portable and operational in a standard garage/workshop	Must	Yes/No	Yes
	Be able to be rebuilt or adapted to alternative module diameters	Must	Yes/No	Yes
	Have documentation in order to be replicated and modified	Must	Yes/No	Yes
	Be able to make variable wall thickness modules from .25" to .375"	Should	Yes/No	Yes
	Take into account windows and holes in the modules	Should	Yes/No	Yes
	Use inexpensive materials	Should	Yes/No	No
	Be adaptable for nosecone design and construction	May	Yes/No	Yes
	Be automated	May	Yes/No	No
Process	Deliver a well-documented work instruction on using tooling to make airframe modules	Must	Yes/No	Yes
	Be inexpensive to run	Must	Yes/No	Yes

	Minimize time and resources necessary	Should	Yes/No	No
	Minimize training requirements	Should	Yes/No	No

4. Design Concepts Overview

4.1 Module Section Design

Several different module structure designs were considered. These include: honeycomb sandwich, reinforced core sandwich, integral blade sandwich, integral blade stiffened, and bonded hat, as seen in Fig.4.1.1. Due to the relative simplicity of the fabrication process, honeycomb sandwich construction was selected for the module sections.

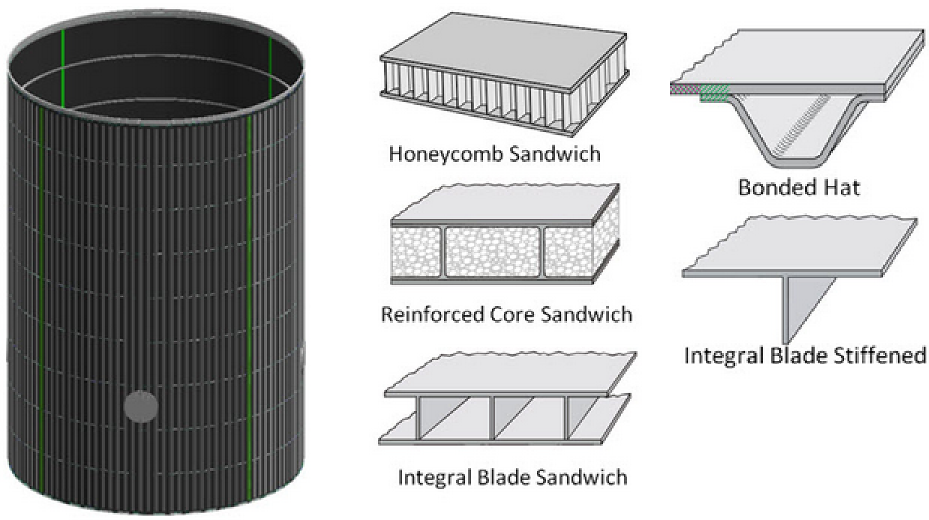


Figure 4.1.1. Composite structure cross-section design concepts.

4.2 Coupling Ring Design

Several different module coupling methods were considered including a quick-release type mechanism similar to a camera lens or hydraulic/pneumatic coupling. Examples of these are shown in Fig.4.2.1. Double and single shear lap joints were also investigated. A single shear lap joint was chosen because it was significantly easier to manufacture than the other coupling joints discussed above.

Figure 4.2.1. Coupling mechanism design concepts. A quick-release camera lens attachment (left) and a quick-release pneumatic hose connector (right) are shown.

4.3 Materials and Fabrication Process

Composite materials are well-known for high strength-to-weight ratios, and many different types were considered for this application. The most common aerospace composites are fiberglass, Kevlar, and carbon fiber. Fiberglass and Kevlar are relatively inexpensive but carbon fiber excels in strength. Additionally, the fabric may be dry, with an epoxy resin applied, or pre-impregnated. Pre-preg is much easier to work with but is significantly more expensive.

Composites can utilize a wide variety of manufacturing processes depending on the materials being used and the desired product. The manufacturing process and tooling costs are heavily influenced by mold type. A female mold would provide a very good outside surface finish, but would be more expensive and harder to work with. Alternatively, a male mold, or mandrel in this case, would be less expensive and easier to work with, but would sacrifice surface finish quality.

Most composites require pressure and sometimes elevated temperatures in order to cure properly. Deciding on the method for this will also influence quality and manufacturability of the part. An autoclave oven is capable of very high pressure and provides a controlled temperature environment, but the equipment is hard to access and very expensive to use. The pressure can also be applied using a vacuum bag system or shrink tape. Shrink tape's performance excels in the case of simple, cylindrical geometry.

5. Final Design

Final design choices were driven primarily by manufacturability. This strategy would ensure maximum repeatability and knowledge transfer by greatly simplifying the process. A carbon fiber and aluminum composite structure was chosen as the final module design concept. The use of expensive composite materials was enabled by generous sponsor donations and the potential for PSAS to maintain these sponsor relationships.

Based on these factors, the final design utilized high-temperature cure pre-impregnated carbon fiber. The module structure consists of a carbon fiber, sandwich core construction which is bonded to aluminum coupling rings using aerospace grade structural adhesive film. The module design can be seen in Fig.5.1, and Fig.5.2 demonstrates its integration with the rest of the rocket. This design proved to exceed strength and weight performance expectations. See Fig.C.1 for an exploded module assembly schematic.

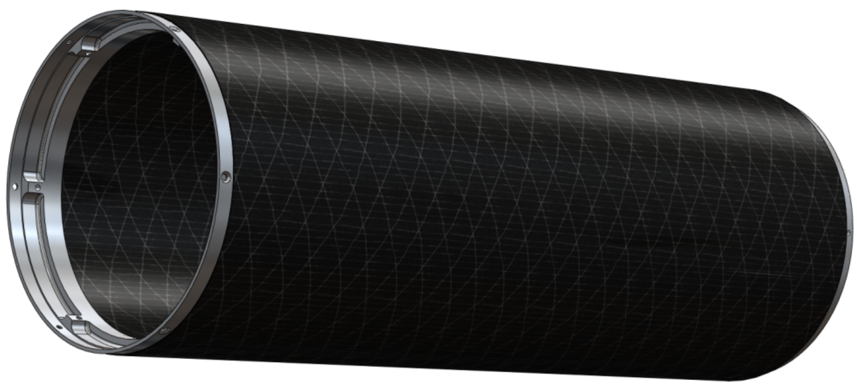


Figure 5.1. Final module design. Aluminum rings are bonded to composite structure using aerospace grade structural adhesive.

Figure 5.2. Full rocket model, showing integration of standard module design into rocket assembly

5.1 Composite Structure

External research showed that the primary failure mode of rocket airframes is buckling. In this case, it was important that the modules be sufficiently resistant to buckling failure. A carbon fiber, honeycomb sandwich structure was chosen for the module's composite structure. The structure consists of two layers of carbon fiber, two layers of film adhesive, and a layer of ¼ in. thick, over-expanded honeycomb core. The carbon plies provide strength while the honeycomb core creates sufficient structure thickness to resist buckling without adding excess mass. Figure 5.1.1 shows a sectioned view of the layers composing the composite structure.

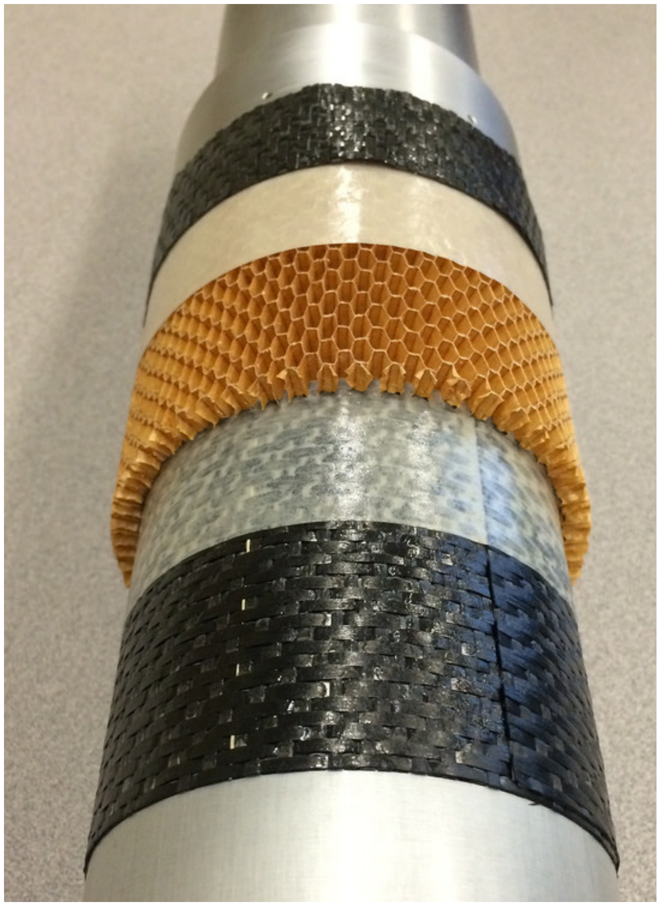


Figure 5.1.1. Photo showing sectioned view of composite layers. A narrow adhesive layer bonds the inside carbon ply to the coupling rings (not shown), then a layer of carbon, adhesive, core, adhesive, and the outside layer of carbon are added.

5.2 Aluminum Joint Design

The airframe modules are connected by aluminum coupling rings. The assembly consists of male and female rings which mate by sliding together. The joint is fastened using six countersunk #4-40 screws. Figure 5.2.1 shows a sectioned view of two mated modules and a pair of assembled rings. For more detailed coupling ring drawings, see Appendix B. The rings have been designed so that the compression load during launch is taken through the mating surfaces rather than the fasteners. As can be seen in Fig.5.2.1, the mass of the rings has been optimized by removing as much material as possible. As a result, a pair of rings (one pair per module) weighs only 0.3 lb. It was critical to reduce the mass of the rings because even at 0.3 lb, they still comprise 25% of the weight of a single module.

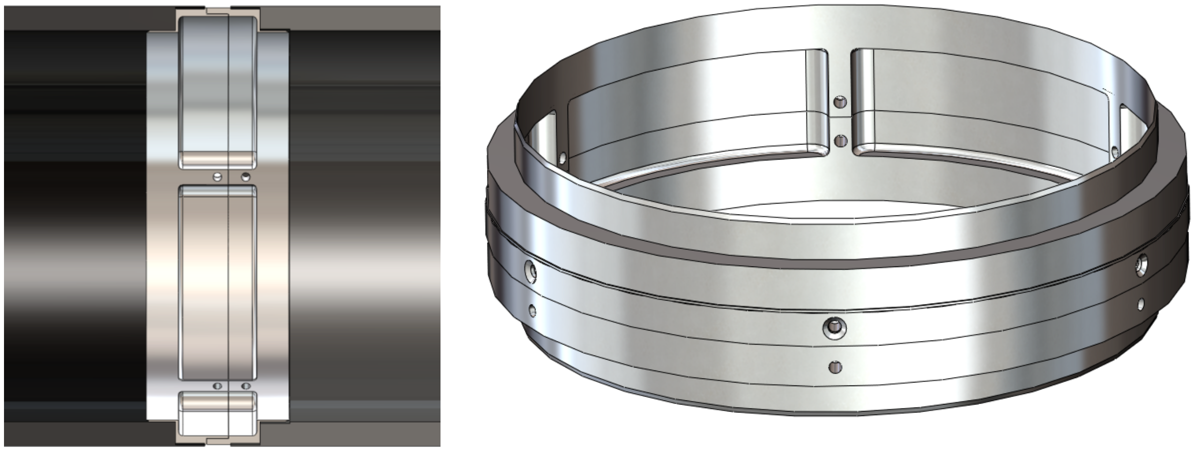


Figure 5.2.1. Sectioned view of module connection (left), and assembled coupling rings (right).

5.3 Tooling and Layup Process

The tooling and layup processes were carefully selected and tested to guarantee simplicity and repeatability for PSAS to continue manufacturing modules in the future. The tooling, shown in Fig.C.2, consists of two brackets which hold a male mandrel. The coupling rings are fixtured on the mandrel by a pair of corresponding ‘dummy’ rings, which mate to the coupling rings and are fastened to the mandrel. Detailed drawings of the dummy rings and layup mandrel are provided in Appendix B.

Templates were created using laser-cut acrylic to guarantee dimensional accuracy when cutting out composite materials. Layers of carbon, adhesive, and core are cut using the templates and are carefully wrapped around the mandrel in a specific order. This process is relatively simple for composites manufacturing because the geometry of the material patterns is very simple, and the geometry of the tooling is very simple. This minimizes the complexity of the layup process. Additionally, the cost and difficulty of making the tooling (the male mandrel) is relatively low.

Once the layup is complete, the assembly is wrapped with perforated shrink tape. The perforated shrink tape contracts during cure at high temperature, applying near-autoclave pressure to the structure during cure while also allowing excess resin to escape through the perforations. The assembly is then placed in a controlled oven that cures the carbon fiber and adhesive based on manufacturer specifications.

6. Verification of PDS Requirements

Because of the complexity and variability of composite materials, especially in buckling failure modes, physical testing was utilized to verify design requirements rather than theoretical analysis.

To verify buckling strength of the module, compression tests were carried out on both scale and full size module prototypes. The type of motor used by PSAS is capable of up to 2400 lb_f thrust, so the module was designed to handle this thrust with a large factor of safety. The verification was carried out with a compression test machine. The scale modules consistently demonstrated a critical buckling load of approximately 7000 lb_f. The full scale module withstood up to 5000 lb_f, at which point the limit of the testing machine was reached. Therefore, the ultimate buckling strength of the full size module is unknown.

In conjunction with these buckling tests, repeatability was tested by manufacturing several modules, each by a different person. The compression testing verified that the variability in strength between each module was minimal. This proves that the process is simple enough that the chances for variability during manufacturing are minimal.

Using the same compression testing machine, a bending test verified that the ultimate strength of the aluminum joint and the stiffness of an assembled structure greatly exceeded flight requirements. The joint failed at 1100 lb_f in a three-point bending test over a distance of 27 in. Minimal deflection in bending demonstrated high stiffness and natural frequency of the structure.

7. Conclusions and Recommendations

The capstone team has exceeded the requirements of the project and has provided a solid foundation for PSAS to manufacture future carbon fiber airframe modules. The feedback the team has received from PSAS has been very positive. The major design requirements were verified through extensive testing, and the capstone team is confident that the modular structure of the rocket can withstand launch conditions.

The manufacturing process for the modules has been thoroughly documented and verified to be repeatable by a variety of people with varying levels of composites manufacturing skill. Additionally, training with PSAS is underway to guarantee that the manufacturing knowledge is passed on.

The support provided by the team's industry advisor, Andrew Greenberg, was critical to the success of the capstone project. His enthusiasm for the project and trust in our team allowed us to take risks that eventually paid off very well.

There is a lot of potential to improve the composite module design. Obvious improvements could be made with respect to surface finish and improved manufacturing tools. These could include an automated shrink tape winder and more reliable mandrel removal system after the part has cured. There is also much room for improvement by testing and utilizing various types of carbon fabrics and fiber orientations to optimize strength. Also, more advanced curing methods such as autoclave curing could significantly increase strength and reduce weight. The use of 3D printing could be better utilized in the future to decrease the complexity of manufacturing coupling rings and other components. It would also be beneficial to investigate the possibility of post-bonding in order to utilize a wider variety of structures.

As the rocket project evolves, it could also include such improvements as a structurally integrated composite fuel tank by building on the composites knowledge passed on by this capstone project. This would allow for drastic weight reduction in conjunction with an expected liquid fuel propulsion system. This integrated fuel tank design is not out of reach for a subsequent mechanical capstone project.

Appendix A – Product Design Specifications Table

Table A.1 shows the full engineering product design specifications for the composite airframe capstone project.

Table A.1. PSAS product design specifications for the composite rocket airframe.

Airframe Modules						
Priority	**Requirement**	**Customer**	**Metric**	**Target**	**Target Basis**	**Verification**
	Weight	PSAS	*Grams*	200-500	Customer requirement	Measurement
	Yield Strength	PSAS	*Pa*	7.00E+10	Customer requirement	Testing
	Stiffness	PSAS	*Pa*	1.10E+08	Customer requirement	Testing
	Customizable Flanges / Couplers	PSAS	*Assemble / Disassemble Time (min)*	< 1 min per Module	Customer requirement	Testing
	Customizable Length	PSAS	*mm*	305, 457, 914	Customer requirement	Measurement
	Inside Diameter	PSAS	*mm*	152, 203, 254, 305	Customer requirement	Measurement
	Materials	PSAS	*Dollars*	0-150 per module	Customer requirement	BOM
	Wall thickness	PSAS	*mm*	1-15	Customer requirement	Measurement

Tooling						
Priority	**Requirement**	**Customer**	**Metric**	**Target**	**Target Basis**	**Verification**
	Allows for variable length	PSAS	*mm*	100-2000	Customer requirement	Design
	Portability	PSAS	*Number of people required to transport*	1 person	Customer requirement	Design
	Design must be adaptable to variable module diameters	PSAS	*mm*	152, 203, 254, 305	Customer requirement	Measurement
	Documentation w/ instruction	PSAS	*Yes/No & Electronic / Physical*	Yes & Both	Customer requirement	Design is repeatable
	Accommodate module access ports	PSAS	*Yes/No*	Yes	Customer requirement	Design
	Uses commercial off-the-shelf components	PSAS	*% of parts used*	50-100	Customer requirement	Manufacturing
	Adaptable for nose cone manufacturing	PSAS	*Yes/No*	Yes	Customer requirement	Design
	Automated	PSAS	*Yes/No*	Yes	Customer requirement	Design

Process

Priority	Requirement	Customer	Metric	Target	Target Basis	Verification
	Documentation w/ instruction	PSAS	*Yes/No & Electronic / Physical*	Yes & Both	Customer requirement	Process is repeatable
	Cost	PSAS	*Dollars*	< 150 per module	Customer requirement	BOM
	Minimize manufacturing time	PSAS	*Hours*	< 24 per module	Customer requirement	Manufacturing
	Training required	PSAS	*Hours*	< 24	Customer requirement	Manufacturing

Cost

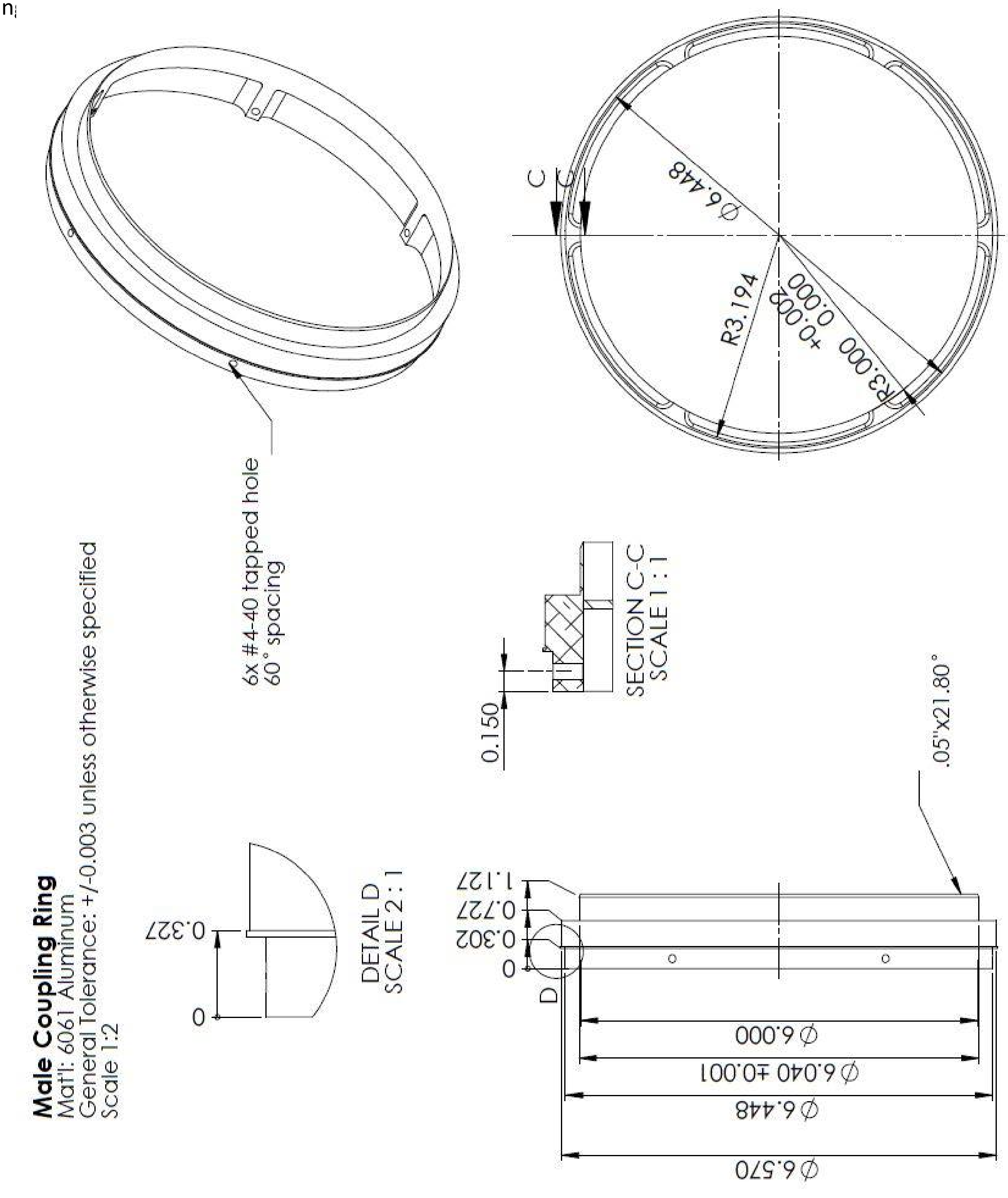
Priority	Requirement	Customer	Metric	Target	Target Basis	Verification
	Total cost	PSAS	*USD*	< $4000	Customer requirement	BOM

Schedule

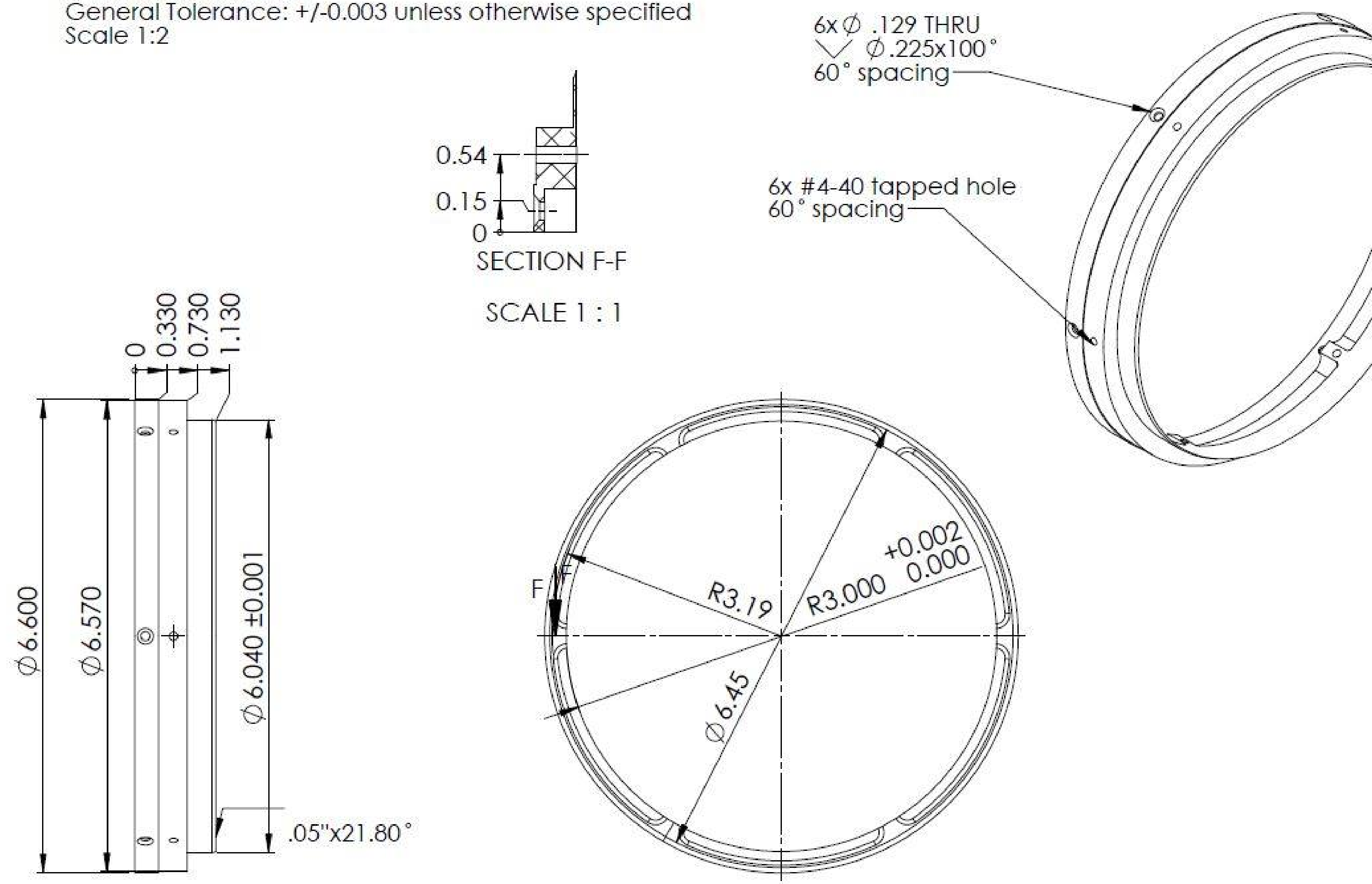
Priority	Requirement	Customer	Metric	Target	Target Basis	Verification
	PDS Report	Sung Yi	*Date*	2/4/2014	Customer requirement	Grade
	Progress Report	Sung Yi	*Date*	3/13/2014	Customer requirement	Grade
	Sounding Launch	PSAS	*Date*	6/16/2014	Customer requirement	Testing

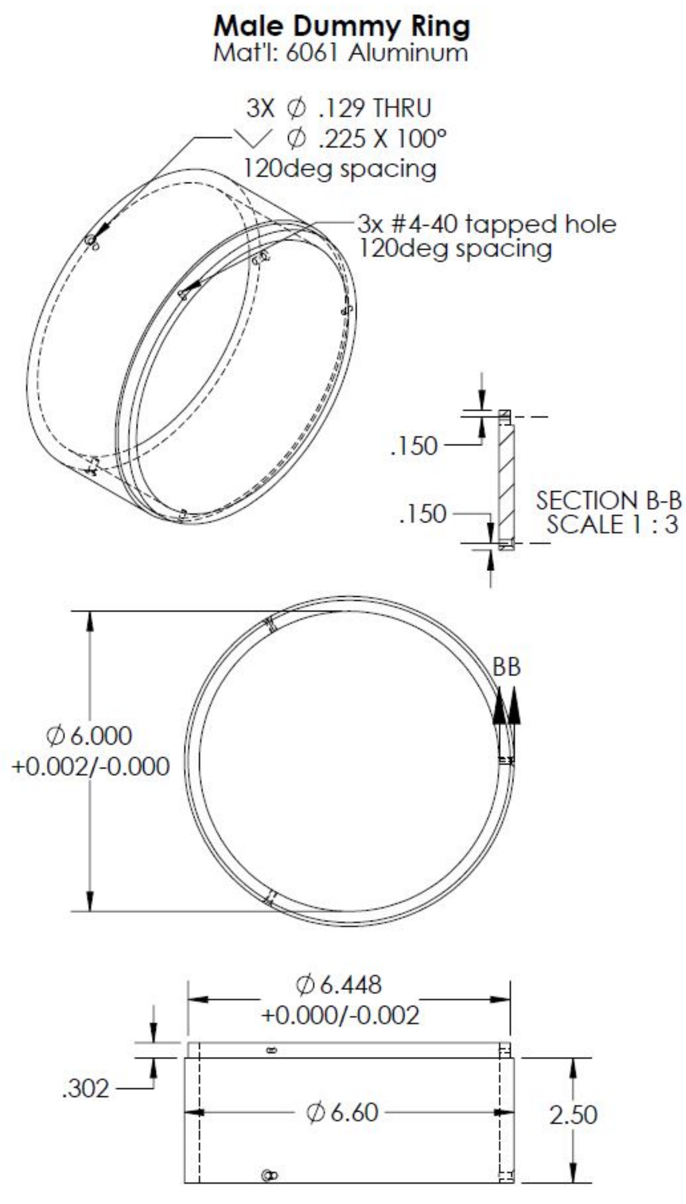
Appendix B – Detailed Part Drawings

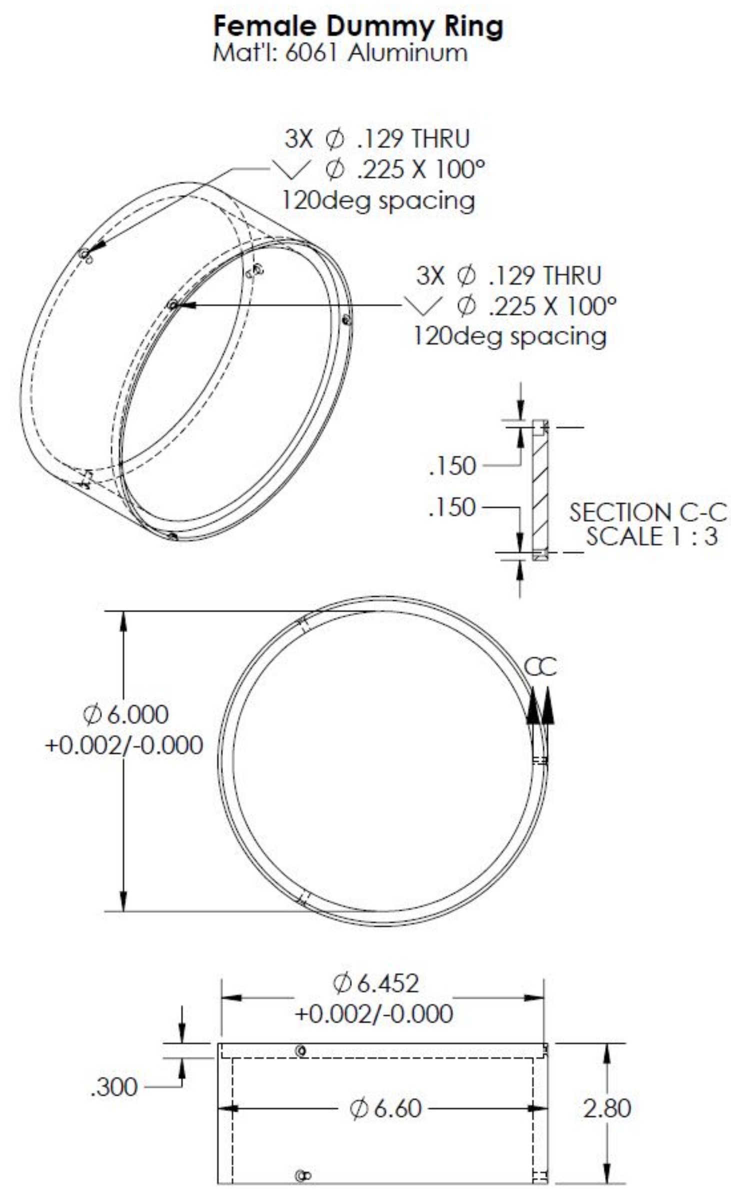
Part drawin

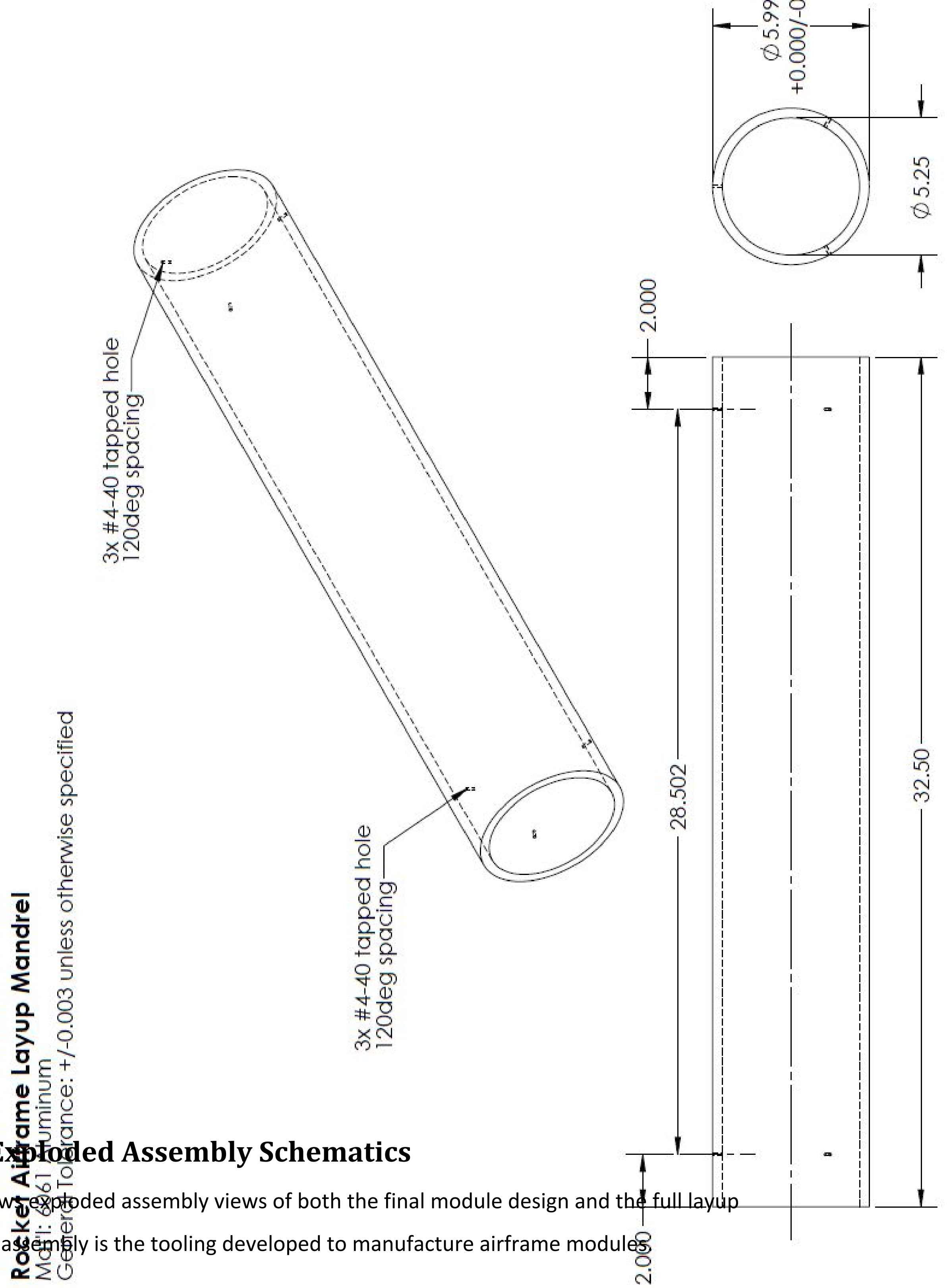


Female Coupling Ring
Mat'l: 6061 Aluminum
General Tolerance: +/-0.003 unless otherwise specified
Scale 1:2



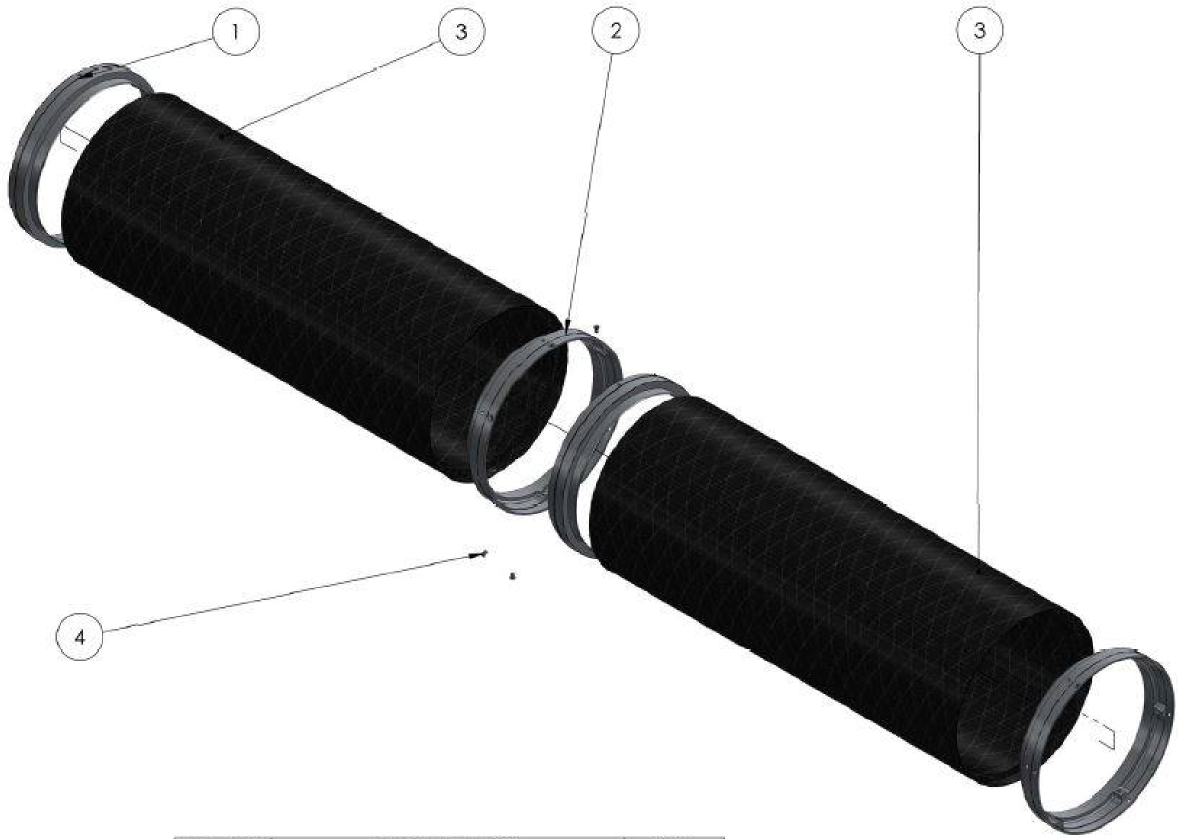

Male Dummy Ring
Mat'l: 6061 Aluminum
3X ∅ .129 THRU
∅ .225 X 100°
120deg spacing
3x #4-40 tapped hole
120deg spacing
.150
.150
SECTION B-B
SCALE 1 : 3
BB
∅ 6.000
+0.002/-0.000
∅ 6.448
+0.000/-0.002
.302
∅ 6.60
2.50


Female Dummy Ring
Mat'l: 6061 Aluminum
3X ∅ .129 THRU
∅ .225 X 100°
120deg spacing
3X ∅ .129 THRU
∅ .225 X 100°
120deg spacing
.150
.150
SECTION C-C
SCALE 1 : 3
CC
∅ 6.000
+0.002/-0.000
∅ 6.452
+0.002/-0.000
.300
∅ 6.60
2.80



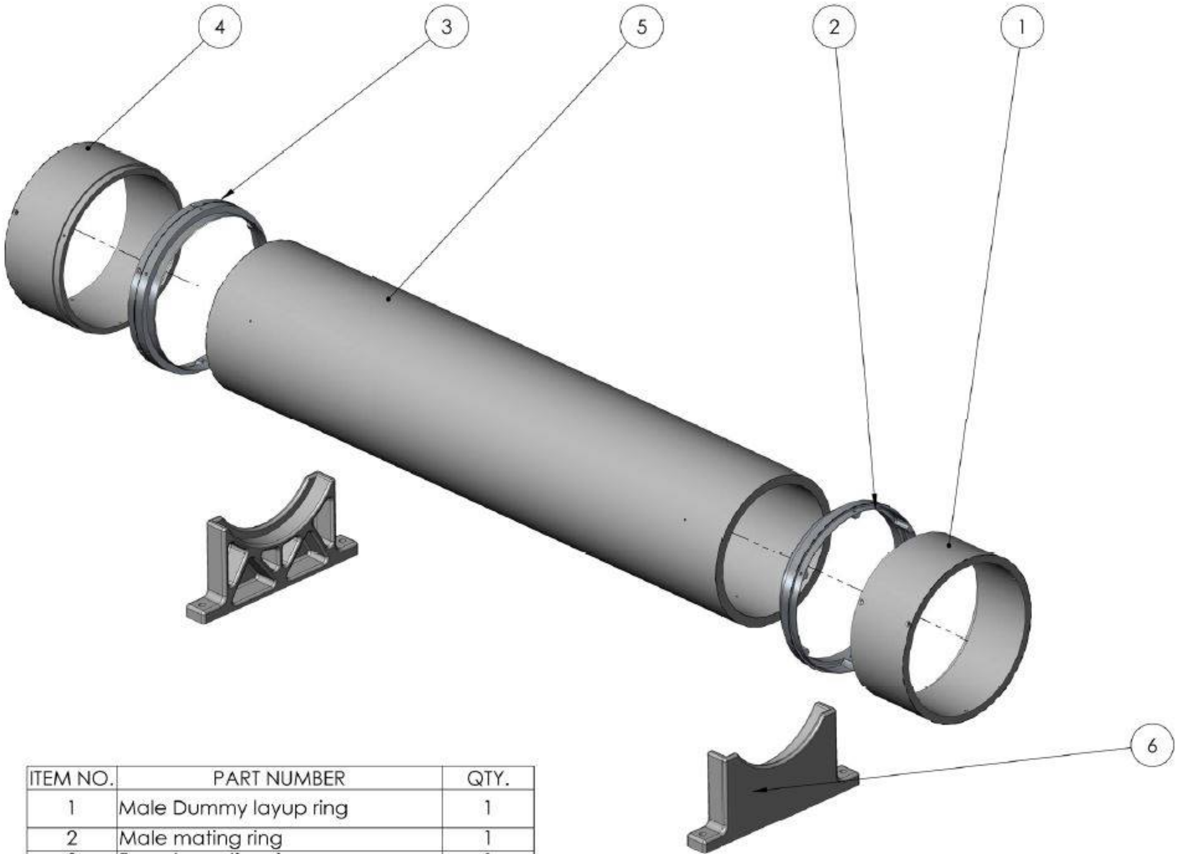
Appendix C – Exploded Assembly Schematics

This attachment shows exploded assembly views of both the final module design and the full layup assembly. The layup assembly is the tooling developed to manufacture airframe modules.



ITEM NO.	PART NUMBER	QTY.
1	Male aluminium ring	2
2	Female aluminium ring	2
3	Carbon Tube	2
4	Screws40x0.188x0.188-N	6

Figure C.1. Exploded assembly of two airframe modules. Aluminum coupling rings are bonded to a carbon honeycomb sandwich structure. The modules are connected using six #4-40 countersunk screws.



ITEM NO.	PART NUMBER	QTY.
1	Male Dummy layup ring	1
2	Male mating ring	1
3	Female mating ring	1
4	Female Dummy layup ring	1
5	Layup Mandrel	1
6	Mandrel support base	2

Figure C.2. Exploded view of layup assembly. Two brackets are used to hold the layup mandrel. Two coupling rings are fixture to the mandrel using two corresponding dummy rings.

Appendix D – Airframe Module Bill of Materials

The bill of materials lists all parts and materials necessary to manufacture an airframe module.

Table D.1. Airframe module BOM. Table includes module materials as well as manufacturing tools and materials.

Item #	Item	Part #	Qty	Source	Cost/Unit	Description
	Standard Module BOM					
1	3M Scotch-Weld, 20"x16.85"	AF30	1	Pacific Coast Composites	Donation	Inner layer adhesive film
2	3M Scotch-Weld, 22"x17.65"	AF30	1	Pacific Coast Composites	Donation	Outter layer adhesive film
3	3M Scotch-Weld, 21"x.35"	AF30	2	Pacific Coast Composites	Donation	Coupling rign adhesive film
4	CYCOM 934 EPOXY PREPREG (5 Harness), 20"x16.85"	N/A	1	Pacific Coast Composites	Donation	Inner prepreg carbon fiber ply
5	CYCOM 934 EPOXY PREPREG (5 Harness) , 22"x17.56"	N/A	1	Pacific Coast Composites	Donation	Outter prepreg carbon fiber ply
6	Female Mating Rings	N/A	1	Machine sicence	Donation	Aluminum
7	Male Mating Rings	N/A	1	Machine sicence	Donation	Aluminum
8	Honeycomb Core	N/A	1	Pacific Coast Composites	Donation	1lb density,21.25"x16.94"x.25"
9	Assemble Screws	93085A105	6	Tacoma Screw	$8.01/100	#4 40 100 deg countersunk screws 3/16 length
	Layup Tools					
10	Layup Mandrel	N/A	1	Machined by Arrow	$350.00	27"x6"OD
11	Dummy Layup Rings	N/A	2	Machined in house	$180.00	Aluminum
12	Mandrel Screws	93085A105	6	Tacoma Screw	$8.01/100	#4 40 100 deg countersunk screws 3/16 length
13	Perforated Shrink Tape	V-24A	900"	ACP Composites	$21.63/roll	1" Shrink Tape - Perforated/Release Coated
14	Flash Tape	NA	10"	ACP Composites	20.01/roll	1" Flash Breaker Tape 72 yd Roll
15	Cutout Templates	NA	4	Laser cut in house	NA	See description in steps 1 through 6 instruction
16	Heat Gun	96289	1	Harbor Freight	$14.95	1500 Watt Dual Temperature Heat Gun
17	Tongue Depressors	NA	2	Fred Meyer	5/bag	Wood
	Treatment Chemicals					
18	ORCA Clean	252202	.25 cups	Fiberlay	$94.21/gal	Mold cleaner
19	3M Surface Pre-Treatment	AC-130	25 mL	Pacific Coast Composites	Donation	Aluminum surface treatment
20	ORCA Seal	252203	.25 cups	Fiberlay	$128..88/gal	Mold sealer

Appendix E – Module Layup Instruction Manual

LV3 Airframe Module Layup Instructions

Tips and Tricks

1. Staying clean and organized is very important.
2. A heat gun is super useful for dealing with the adhesive film. However, be careful not to let it get too hot. A little bit goes a long way.
3. Adhesive film is hard to remove from its backing, especially with gloves on. You can use the tongue depressor against the edge after sticking it to the part to get the backing off. Leave the blue side of the adhesive on.
4. The carbon sticks to the adhesive film too well, don't stick it down unless you are sure it is in the correct spot.

Procedure

1. Clean all surfaces and the floor using acetone, brooms etc.
2. Put on gloves
3. Arrange 4 work surfaces, each with a specific task:

a. Layup

b. Tool treatment

c. Cutting pieces of composite material

d. Aluminum mating ring treatment

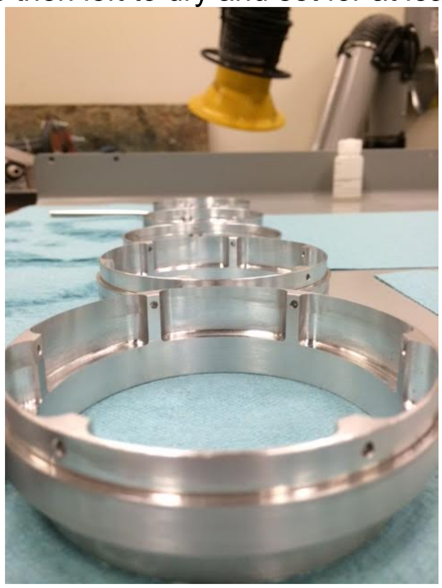
2. Clean all the metal tools and part surfaces using acetone. Each part should cleaned thoroughly so that it leaves no visible residue on the towel.

1. Wax the mandrels using Orca hybrid mold release according to the instructions on the can.

1. Similarly, wax the inside of the aluminum mating rings, making sure not to get any mold release on the carbon bond surfaces of the aluminum rings

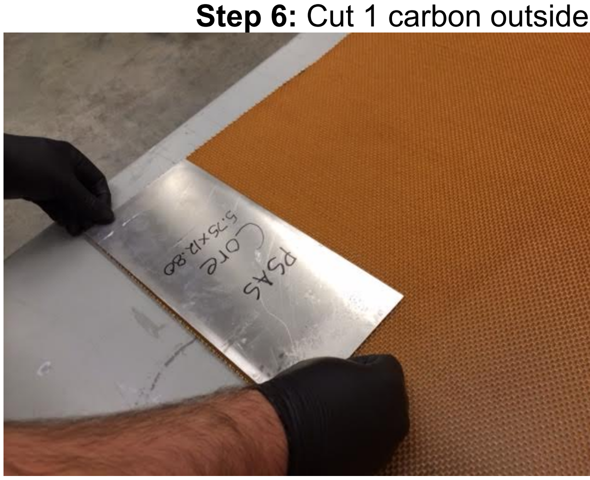
1. Thoroughly sand the carbon bond surfaces of each aluminum mating ring to remove the oxide layer. When you're finished sanding, the surfaces must be cleaned thoroughly with acetone.

1. Apply the 3M anti-galvanic corrosion agent to the bond surfaces by following the instructions on the package. In general, the solution should be applied with a brush constantly for about 3 minutes then left to dry and set for at least an hour.



1. Cut the following layers using a sharp razor (except the core) and the cutout templates. Templates are labeled as steps 1-6.

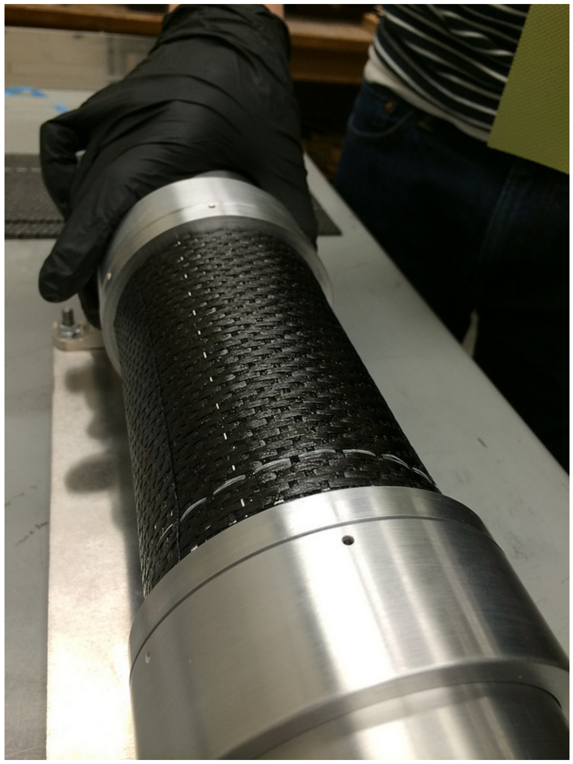
   Step 1: Cut 2 strips of aluminum step adhesive
   Step 2: Cut 1 carbon inside ply
   Step 3: Cut 1 inside film adhesive layer
   Step 4: Mark with sharpie the outline of the honeycomb core layer. Use scissors to cut the core
   Step 5: Cut 1 outside film adhesive layer
   Step 6: Cut 1 carbon outside ply



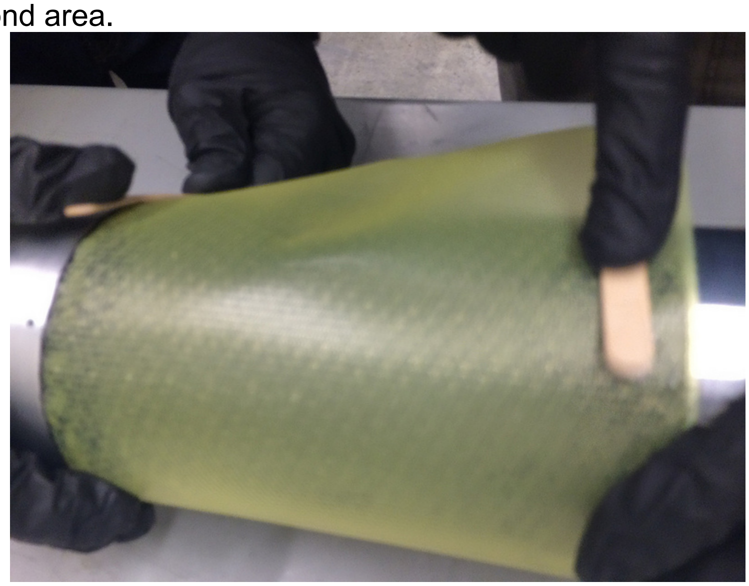
1. Lay everything out. ***If you need more than ~30minutes of time before laying up the module, the carbon and adhesive layers must be put back in the freezer until layup***.

1. Slide the aluminum mating rings over the mandrel, making sure the orientation is correct
1. Slide the dummy layup rings onto the mandrel and fasten them to the mating rings
1. Fasten the dummy rings to the mandrel

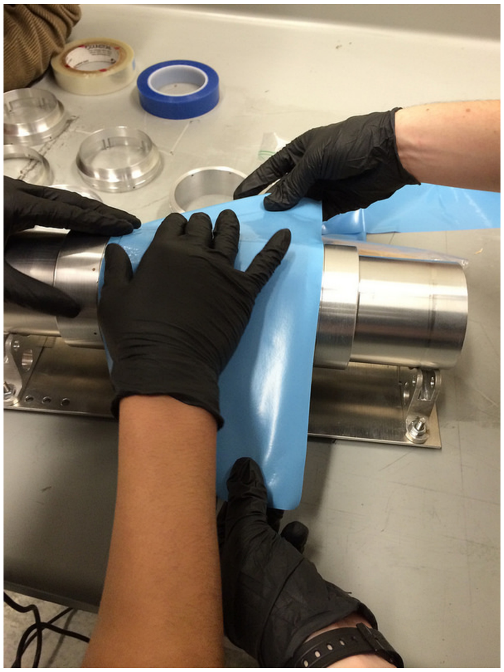
1. Wrap the two thin strips of adhesive around the lower bond surface of the mating rings.
1. Wrap the first layer of carbon. Make sure that the adhesive film layer underneath doesn’t move off of the step and onto the mandrel. It works best if one person does the aligning and the other rotates the mandrel. Wrap it snugly, but be sure to not introduce any warping of the fibers. Don't allow any air bubbles to remain.



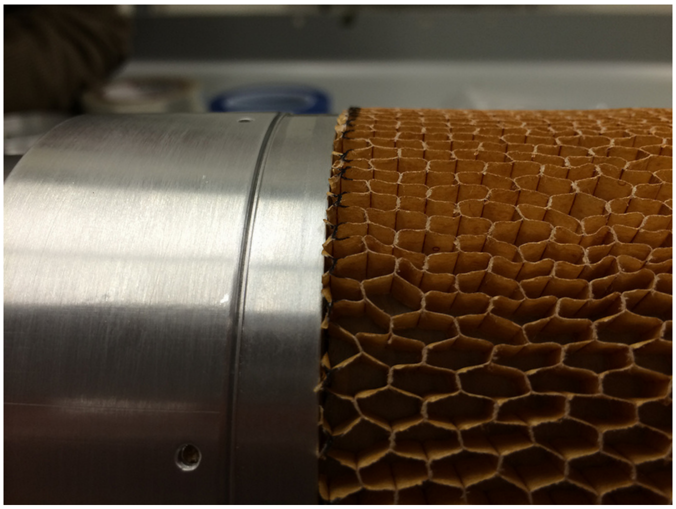
1. Use a tongue depressor in a rocking fashion (perpendicular to mandrel axis) to flatten out the carbon on top of the bond areas. This ensures good contact between the carbon and the bond area.



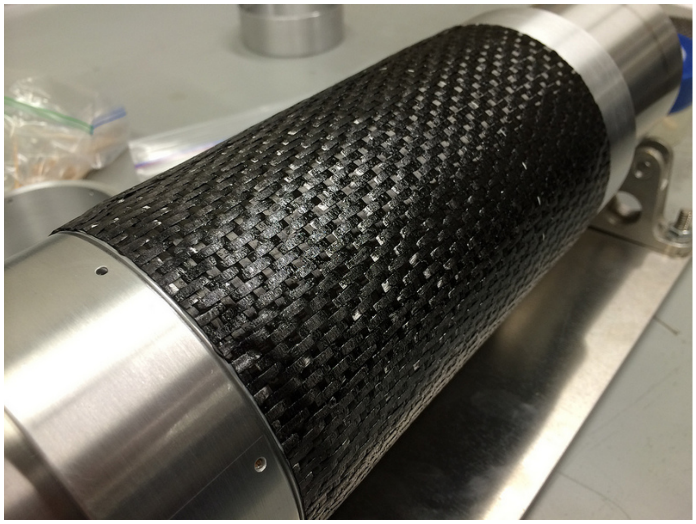
1. Wrap the inside layer of film adhesive on top of the carbon. Try to align the edges as well as possible, but it’s okay if there are wrinkles. The adhesive will melt and flow during cure.



1. Wrap the honeycomb core layer. Use the heat gun sparingly to warm the adhesive underneath and press the core onto the adhesive to make it stick.
1. When you get to the end of the core wrap, compress the excess length of core and force it up against the other side. This compressed area will prevent gaps from forming at the core seam during cure.

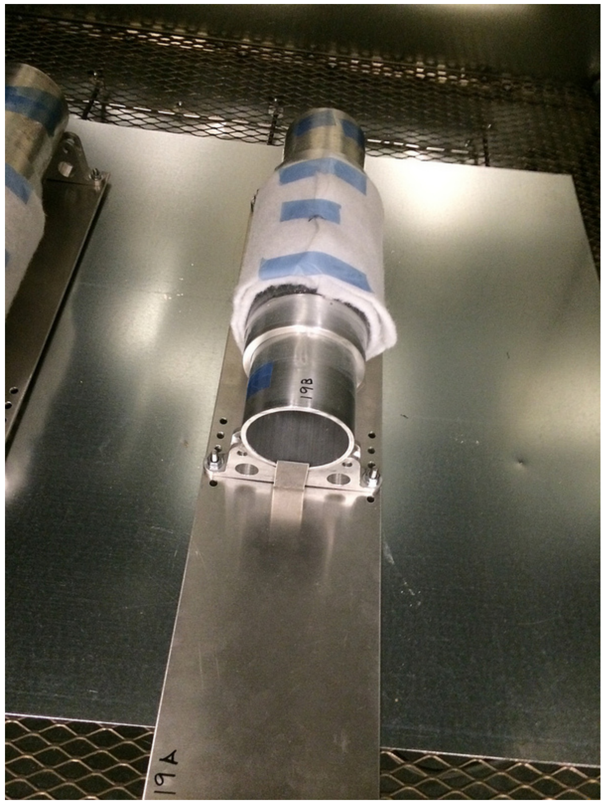


1. Wrap the outside layer of adhesive film. This one will go over both the core and rings. Try to align the edges of the adhesive with the step on the mating ring as well as possible.
1. Wrap the outside layer of carbon. Make sure that the lettering on the carbon does not end up on the outside of the module.



1. Wrap the perforated shrink tape across the length of the mandrel so that it overlaps itself 50% each time. Start the wrap on the dummy, taping it down well with the flash tape (clear blue). Then, have one person rotate the mandrel, one person hold the shrink tape roll, and one person align the tape as it is wrapped. The person aligning the shrink tape should also tension the tape so that it is taught as it is wrapped but not tight. End the shrink tape at the other dummy and secure it with flash tape.

1. Wrap a diaper made from the breather cloth and use flash tape to secure it.



1. Put The mandrel into the oven on the aluminum stands
1. Turn on bake cycle. 3deg/min ramp up to 350F, where it is held for 2 hours.
1. Let cool slowly. The part will crackle as it cools down. This is normal.
1. Sometimes you have to hammer the parts off the mandrel. Whatever method you use, be sure not to damage the aluminum rings