LSA INTEGRATION

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SENIOR DESIGN PROJECT

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ABSTRACT

With the recent addition of a Light Sport Aircraft (LSA) classification by the Federal Aviation Administration there has been an ongoing, missions-oriented project by Messiah College's Flying Club and various Senior Projects to design and create an airplane to take advantage of this new opportunity. This new aircraft will be able to operate out of small, unimproved airstrips while providing economical and practical air transportation for missionaries in remote locations. The aircraft has been designed from the start with simplicity and durability in mind to help it achieve this goal.

The scope of the engine integration project, made up of Joshua Joyce, Jonathan Shenk, and Tyler Miller, was to incorporate an engine into the already completed fuselage of the aircraft. Prior senior projects selected and tested a rotary engine made by Rotamax as the power plant for the aircraft. With the help of our advisor Dr. Pratt and Rotamax, we were able to procure an aircraft-quality engine and mount it to the fuselage of the aircraft. We also installed an exhaust and cooling system along with cockpit instrumentation and various accessories to make the engine operational.

ACKNOWLEDGMENTS

Listed below are people whose assistance in this project was vital to its completion:

Name:	Role:
Dr. Don Pratt	Project advisor
Mr. John Meyer	Shop technician and parts procurement
Tim Bourgeois	Project I & II team
Paul Gustafson	Project I & II team
David Smith	Project I & II team
Skip Gorman	RotaMax, inc.
Eric Barger	RotaMax, inc.

1 INTRODUCTION

The Messiah College Flying Club began work on designing a new aircraft in the spring of 2005. Over the past few years, they have developed various components for the aircraft as well as contracted work out to the Messiah Engineering Department and the Collaboratory. At the beginning of this year, work on the fuselage and work on engine/drive train were separate projects. The fuselage was largely the product of work done by engineering students in the Messiah College Flying Club. It is a tubular structure constructed from 4130 chromoly steel tubing with TIG-welded joints. The engine compartment of fuselage was designed as a strong platform for the weight of the engine and to provide a suitable location for the thrust of the engine to be directed.

The engine and drive train components were developed by previous senior engineering projects. The first of these projects selected a rotary engine made by Rotamax and constructed a test apparatus from which numerous tests were run on the engine. The second of these projects continued testing the engine and focused on developing instrumentation. As mentioned above, the challenge of our project was to take all of the past work done on the engine and integrate it into the aircraft itself.

1.1 Description

Essentially, the main goal of our project was to mount the engine into the aircraft and develop prototype designs for exhaust and cooling systems. In order to test and use our designs, we also installed some basic engine instrumentation in the cockpit of the aircraft. To help guide our project, we set specific, measurable objectives at the beginning of this year. Below is a list of these objectives:

1. Create an engine mount design able to support a 100lb engine, absorb 150 ft-lbs of torque and 500lbs of thrust.
2. Install a radiator with duct work capable of maintaining an engine temperature of 140-160^{o}F with ambient air temperatures at 110^{o}F.
3. Design an exhaust system to maintain sound levels less then 85 dB at a 25m distance. (Assume pilot and/or passenger have ear protection.)

4. Design engine mount system to allow engine removal from the fuselage in less than 60 minutes with common tools.
5. Require inspection of mounting design every 800 hours of flight.

1.2 Literature Review

Engine

Listed below is the compiled research of mainstream production aircraft engines that have specifications comparative to the Rotamax engine we are planning to install in the LSA fuselage.

AIRCRAFT ENGINE SPECIFICATIONS

		Source
Manufacturer	**Rotamax 650cc**	Communication with Rotamax, inc; Also www.rotamax.net
Model	**NA**	
Engine Type	Rotary	
Rated Horsepower	65	
Rated Torque (ft-lb)	60	
Weight (lbs)	85	
Fuel Cons. (gph at cruise)	~4	
TBO (hours)	unknown	
Cost (USD)	5500-6000	
Cost of Install	N/A	
Notes	none	
Manufacturer	**Rotax**	
Model	**503**	http://www.ultralightnews.ca/rotaxengineprices/3.html
Engine Type	2 stroke	http://www.ultralightnews.ca/rotaxengineprices/3.html
Rated Horsepower	50	http://www.ultralightnews.ca/rotaxengineprices/3.html
Rated Torque (ft-lb)	41	http://www.leadingedge-airfoils.com/pdf/503info.pdf
Weight (lbs)	79	http://www.theultralightplace.com/specifications.htm
Fuel Cons. (gph at cruise)	5.2	http://www.leadingedge-airfoils.com/pdf/503info.pdf
TBO (hours)	300	http://www.recreationalmobility.com/cgi-bin/recreation/RotaxFAQ.html
Cost (USD)	5400-6000	http://www.leadingedge-airfoils.com/services.htm

Cost of Install	1700	http://rans.com/s6sPricing.html
Notes		

Manufacturer	**Rotax**	
Model	**618**	
Engine Type	2 stroke	http://www.theultralightplace.com/specifications.htm
Rated Horsepower	74	http://www.theultralightplace.com/specifications.htm
Rated Torque (ft-lb)	55.3	http://www.theultralightplace.com/specifications.htm
Weight (lbs)	80	http://www.theultralightplace.com/specifications.htm
Fuel Cons. (gph at cruise)		
TBO (hours)	300	http://www.ultralightnews.com/rotaxinfo/rotax912-582.html
Cost (USD)	7500	http://www.ultralightnews.com/rotaxinfo/rotax912-582.html
Cost of Install		
Notes	No longer produced	http://www.theultralightplace.com/specifications.htm

Manufacturer	**Rotax**	
Model	**582**	http://www.ultralightnews.ca/rotaxengineprices/3.html
Engine Type	2 stroke	http://www.ultralightnews.ca/rotaxengineprices/3.html
Rated Horsepower	64.4	http://www.ultralightnews.ca/rotaxengineprices/3.html
Rated Torque (ft-lb)	55	http://www.leadingedge-airfoils.com/pdf/582info.pdf
Weight (lbs)	72	http://www.theultralightplace.com/specifications.htm
Fuel Cons. (gph at cruise)	5.8	http://www.leadingedge-airfoils.com/pdf/582info.pdf
TBO (hours)	300	http://www.ultralightnews.com/rotaxinfo/rotax912-582.html
Cost (USD)	7100-7700	http://www.leadingedge-airfoils.com/services.htm
Cost of Install	2100	
Notes	liquid cooled	

Manufacturer	**Rotax**	
Model	**912**	
Engine Type	4 stroke	http://www.theultralightplace.com/specifications.htm
Rated Horsepower	80	http://www.theultralightplace.com/specifications.htm
Rated Torque (ft-lb)	76	http://www.theultralightplace.com/specifications.htm
Weight (lbs)	123	http://www.zenithair.com/kit-data/zac-rtx912.html
Fuel Cons. (gph at cruise)	5	http://en.wikipedia.org/wiki/Rotax_912
TBO (hours)	1200	http://www.theultralightplace.com/specifications.htm
Cost (USD)	14250	http://www.zenithair.com/zodiac/6-price.html
Cost of Install	3500	http://www.zenithair.com/zodiac/6-price.html
Notes	none	

Manufacturer	**Jabiru**	
Model	**2200**	
Engine Type	4 stroke	http://suncoastjabiru.com/prices.htm
Rated Horsepower	80	http://suncoastjabiru.com/prices.htm
Rated Torque (ft-lb)		
Weight (lbs)	132	http://suncoastjabiru.com/prices.htm
Fuel Cons. (gph at cruise)	4	http://en.wikipedia.org/wiki/Jabiru_2200
TBO (hours)	2000	http://suncoastjabiru.com/prices.htm
Cost (USD)	12000	http://suncoastjabiru.com/prices.htm
Cost of Install		
Notes	none	

Summary of Engine Research

The two engines on this list that are most comparable to the Rotamax engine we are using are the Rotax 503 and 582 (the also comparable Rotax 618 is no longer produced).

The Rotax 503 engine can be purchased in the same price range as the Rotamax engine. However, it is rated at 15 less horsepower, and only 2/3 as much torque. Additionally, the 503 is a two-stroke engine, meaning that it will have to run faster, louder, and dirtier, and will vibrate a lot more than the Rotamax engine.

Looking at the Rotax 582, its power output is much closer to the Rotamax engine. However, it is also a two-stroke engine, plus it costs $1000-$1500 more. Higher up in the horsepower range are the Rotax 912 and Jabiru 2200, both rated at 80 horsepower. In short, both of these would be overkill for our airplane. Their high costs also go against our intentions of building an economical airplane.

Mounting and Cooling

We have looked different places for ideas of how to mount the engine and radiator onto our fuselage. One website that has a wealth of information is www.rotaryeng.net. Pictures of engine mounting methods and radiator locations from this website are located in Appendix 9.1A-C.

With respect to mounting the engine, the Lord and Barry Mount websites have provided a wealth of information on vibration isolation theory. Phone calls to Paul Snyder, a Lord engineer, informed us that though counter-intuitive, most small engine aircraft use “industrial” engine isolators (and not “aerospace” isolators), so we focused on industrial mounts when we made our selection.

We also checked a book out of the library titled How to Cool Your Wankel by Paul Lamar. Paul Lamar is also the publisher of www.rotaryeng.net. This book has a lot of good information and creative ideas despite some of the editorial shortcomings. According to this book, many recent developments have been made to air ducting design in an effort to improve the aerodynamics of water-cooled systems. The basic principle behind many recent designs dictates that air be slowed and pressurized through the use of a diffuser in order to enhance heat transfer and reduce drag produced by the cooling system. Two of the most notable modern designers are Kays & London as well as Kuchemann & Weber. Kuchemann & Weber have contributed in the area of diffuser design on the inlet side of the radiator. The basic idea behind a Kuchemann & Weber diffuser is that the inlet area does not increase linearly. Instead, the Kuchemann & Weber diffuser creates a trumpet like shape similar to that shown on the inlet of our Under-Belly Design shown Appendix 9.2A. This creates a very efficient air flow and it helps to distribute air evenly over the radiator surface.

Kays and London are responsible for a wedged-shaped diffuser. This type of diffuser is used to slow air and redirect it downward through the radiator. These diffusers are very useful in tight spaces where it is difficult to align a radiator with incoming air. Our Under-Engine Design shown in Appendix 9.2B utilizes a wedge-shaped diffuser to fit the cooling system into the engine compartment. According to How to Cool Your Wankel, a Kuchemann & Weber design is probably the most efficient diffuser shape however its geometric requirements (large size) make it somewhat impractical. With this in mind, Lamar suggests that a Kays & London design is probably the best choice.

Exhaust System

Tony Bingelis’s book Firewall Forward and www.rotaryengine.net both discuss ideas for installing exhaust systems.

Some ideas from Firewall Forward are:

- The muffler should be placed as close to the exhaust port of the engine as possible

- Mufflers should have a “good length of tail pipe downstream” (p111) to increase effectiveness.
- Exhaust system components should be braced to the engine so that everything vibrates together and connections do not develop cracks
- Tailpipes can be flared with the outlet pointed downstream into the slipstream to generate some thrust

Both Firewall Forward and www.rotaryengine.net focus on mufflers with the input on the side rather than the end of the muffler. These are known as tangential mufflers. Additionally, www.rotaryengine.net describes the concept of “fishtailing” tailpipes to further reduce sound levels (see Appendix 9.3 for picture)

1.3 Solution

As we discussed earlier, we selected a single-rotor Rotamax engine for our aircraft. Previous senior projects made this selection and our research validates their decision. The Rotamax engine offers a high level of torque through a wide range of RPMs due to its rotary design. This allows the engine to turn a larger propeller than a typical piston engine of similar size. The Rotamax engine also has the theoretical capability to run on a variety of fuels which makes it especially valuable in remote locations. For our project, we obtained an aircraft-specific engine from Rotamax. This engine is essentially the same engine that was originally tested by earlier senior projects with a few extra aircraft accessories such as dual ignition.

In order to mount the engine, we designed a two-mount system underneath the engine. Our design was partially inspired by designs we encountered during our research. This tubular, steel structure connects the engine block to two rubber mounts made by Barry Controls. The use of only two mounts to support the engine’s weight provides optimum vibration damping characteristics. It also does not constrain the engine at all in the fore and aft directions. This means that the majority of the engine’s thrust is directed to our thrust linkage at the top of the engine.

The thrust linkage is designed to transfer thrust from the engine to the fuselage. We choose a specific linkage dedicated to thrust transfer because we wanted to avoid unnecessary stress on the weight-bearing members of the mounting system. We observed this principle in our research of rotary powered aircraft.

For the cooling system, we designed a duct and radiator system that is mounted on the belly of the aircraft. We choose the belly of the aircraft as the location of our cooling system due to geometric considerations and system serviceability. In our research, we discovered that many ducting designs utilize a diffuser shape to aid airflow through the radiator. Therefore, we incorporated this type of shape into our design.

The exhaust system we choose to incorporate into our prototype was influenced by conversations we had with engineers at Rotamax. We selected the Hushpower II muffler by Flowmaster as a recommendation from Rotamax. They suggested this muffler for its resistance to high exhaust gas temperatures produced by the Rotamax engine.

For instrumentation, we chose to measure the following parameters: engine temperature, carburetor vacuum pressure, engine amperage, engine voltage, engine RPM, and engine run time (hour meter). We selected these instruments based on research and what we think the pilot should be able to monitor during flight. This portion of the project was largely completed by members of the Project I & II class, Timothy Bourgeois, Paul Gustafson, and David Smith. See Appendix 9.4 for a picture of the final control panel.

2 DESIGN PROCESS

<u>Engine Mount Design</u>

Our initial designs for the engine mount called for a thrust mount connecting the top of the engine to the fuselage and four rubber bushing mounts in the bottom corners of the fuselage engine compartment. A tube structure would be hard-mounted to the base of the engine connecting to the four bushings on the fuselage. For initial mounting designs see Appendix 9.5.

A major component of the engine mount design is isolating the vibrations from the engine and drive train. We initially determined four sources of such vibration. These are rotor rotation, driveshaft rotation, propeller rotation, and the blades of the propeller moving through the air. We determined that the first three in this list should not cause significant vibrations because they are balanced. However, as the propeller blades move through the air they encounter differing amounts of resistance. This is because at certain points a propeller blade has to push harder to move air past more protruding parts of the fuselage. This inconsistency is what causes the vibration.

We wanted to isolate this vibration throughout the entire engine speed range (approximately 2000-5500 revolutions per minute). Thus, we could not have any resonant frequencies occurring in this range. Appendix 9.6A shows a plot of vibration transmission based on frequency ratio (driving frequency divided by natural frequency). Because our driving frequencies were within a set range, the only thing we could change to control the amount of vibration isolation was the natural frequency.

The equation for the natural frequency is the square root of the spring rate (k) of the mount divided by the mass of the system (m): $\sqrt{(k/m)}$. With this relationship, having a heavier system or a softer mount leads to a lower natural frequency, a higher frequency ratio, and thus better vibration isolation.

With the mass of the engine and the range of frequencies known, the only variable in this system was the stiffness of the mount. The problem we initially encountered, however, was that we could not find mounts that were both soft enough to effectively isolate vibrations and strong enough to support the loads due to engine weight and torque.

Switching to a two-mount design allowed us to solve this issue. With two mounts instead of four, the mounting system is effectively softer. This allowed us to use fewer, stronger mounts. Another important advantage of the two mount design is that all the vibrations of the propeller blades moving through the air are transferred through the thrust link. Again, having these vibrations picked up only by the thrust link is much more effective than having them picked up by multiple mounts. See Appendix 9.6B for a plot of the calculated transmission of the vibration from the propeller blades moving through the air.

All of our designs were modeled in SolidWorks and combined with a model of the fuselage and engine. This allowed for accurate changes to be quickly made and new measurements taken off the software for inspection of the design. The final two mount design is shown in Appendix 9.7.

One problem we ran into was exactly how to mount the rubber bushings to the fuselage and also then how to connect our mounting tubes from the engine to the bushings. One important aspect was to get the mounts as wide as possible, increasing the moment arm and allowing the mounts to better pick up the torque from the engine. Also, the closer the mount attachment points are to a welded joint of the fuselage, the more crack resistance the structure has due to less bending loads. Our initial design had plates for the rubber bushings welded on top of the fuselage tubes. For our final design, we cut out a part of the diagonal fuselage tubes at the base of the engine compartment and welded a plate snug against the joint. This created a slightly larger moment arm for the mount. The plates for the rubber bushing mounts can be seen in Appendix 9.8.

The next challenge was the thrust mount design which also needed a rubber bushing system to absorb vibrations. For this we investigated using the same concept as a control arm for a car rear suspension. We decided to sandwich rubber hose with two metal sleeves, one through the inside and one encasing the outside of the rubber. The design has two yokes with one connected to the fuselage and the other to the top of the engine. The challenge was to determine the most efficient design of how to mount either side. Our final design was a dog bone configuration where the two outer sleeves were connected with a linkage tube and then the two yokes mounted on the fuselage and engine were connected to the inner sleeve of the joint. For thrust mount components and final construction see Appendix 9.9.

<u>Radiator and Duct Work</u>

The main design decisions that were made for the cooling system involved what type of radiator to purchase, how to shape the ducting surrounding the radiator, and where to mount the radiator.

Designing the duct dimensions and the radiator size was an iterative process because both components of the cooling system affect each other. The ducting for the radiator is designed to reduce the speed of the incoming air using a diffuser. By doing this, drag through the cooling system is lowered while still maintaining an acceptable rate of heat transfer from the radiator to the passing air. A nozzle has been placed on the backside of the duct to help reduce drag as well. The components of the design can be scene in Appendix 9.10A.

In order to dissipate heat from the engine, we selected a 20.5” x 12.5” Volkswagen radiator. This size radiator gave us an optimum combination of cooling power and low drag when housed in a duct. This decision was a result of a few competing variables.

If we used a straight duct (no diffuser), we could get away with a smaller radiator but there would have been a high drag penalty for trying to smash 100mph+ air through the system. The other extreme was using a diffuser that slows the air down to about 10% of its original speed. This reduces drag through the radiator significantly but requires a large radiator to make up for the lower heat transfer coefficient dictated by the slower air. A very large radiator was undesirable because it resulted in a large amount of drag on the outside of the ducting. Additionally, we needed a system that would allow sufficient mass flow rate of air to dissipate the heat of the radiator.

With all of these factors in mind, we decided on a duct that reduces incoming air speed to 30% of the original air speed which required a radiator of about 240 square inches. This size radiator/duct combination also allowed for a sufficient volume of air to pass through the radiator to cool it. To help us with the iterative process of selecting a radiator, we used an Excel spreadsheet published by the EAA as a reference. An example of this spreadsheet is shown in Appendix 9.10B.

To handle the fluid in the system, we used an overflow tank as a fill point as well as method of removing air from the system and accommodating volume changes in the hot fluid. To accomplish this, the overflow tank is mounted so that it is the highest point in the cooling system. This also allows our fluid fill point to be separate from the radiator which is a design requirement since the radiator is located under the aircraft.

The final component of our cooling system was the placement of the system. As discussed in our EDR, we were considering two possible locations for the cooling system. One possibility was to mount the radiator horizontally under the engine compartment. In this scenario, the wedge-shaped ducting would have been placed directly under the engine. This was our initial plan; however, after receiving our engine from Rotamax, we discovered that there was not sufficient space beneath the engine for the necessary duct work.

With this in mind, we elected to place the radiator at a second location, under the fuselage. For this design, we positioned the radiator vertically beneath the fuselage with a surrounding, trumpet shaped duct under the fuselage. This location allowed for a more efficient duct design as well as easier serviceability of the radiator and ducting. Diagrams showing our various cooling systems ideas and final design can be found in Appendix 9.10C. The complete final construction of the cooling system is shown in Appendix 9.10D.

Exhaust System

One initial challenge with the exhaust system was the selection of a muffler that could handle the high temperature exhaust released from the rotary engine. In collaboration with Rotamax, they sent us two Flowmaster, Inc. Hush Power mufflers to test for our use. These mufflers use a conical mesh design that is more heat-resistant than a typical baffle system.

The next challenge was the positioning of the muffler and exhaust pipes to reduce extra drag, vibration, and damage to other components. For our initial design we had the muffler mounted directly to the engine positioned behind it underneath the thrust mount. The muffler would be mounted directly to the engine which allows them to vibrate as one. This reduces the likelihood of cracks developing due to vibration. Also, this design removes the muffler out of the airstream cutting down on extra drag. This also requires no new vibration mounting for the muffler. Appendix 9.11A shows the initial design idea.

We received our engine from Rotamax with the oil pump attached at the back of the engine. This eventually will be removed once an electronic oil pump arrives and is installed. The problem was that the current oil pump interfered with the space for the initial muffler mounting design. Also, upon further brainstorming, we decided that there are too many other components that needed to be in the engine compartment resulting in not enough room to mount the muffler behind the engine. Therefore, we created our final design for the exhaust system with the muffler mounted underneath the fuselage and exhaust piping connecting it to the engine. To minimize drag we positioned the muffler inline with the airstream. We also incorporated a flex pipe in the exhaust pipe to minimize the vibration transferred to the fuselage and also reduce the potential for crack formation. This final design is shown in Appendix 9.11B. The final construction of the exhaust system can be seen in Appendix 9.11C.

3 IMPLEMENTATION

3.1 Construction

The first part of construction was welding a bracket that bolts to the bottom of the engine. To do this, we used a plywood jig to bolt everything down and the cut-off/chop saw and horizontal mill to cut and fish-mouth the chromoly tubes. The Project I & II students helped us in this endeavor by facing off the ends of the tubes that the engine bolts go through so we would be guaranteed a smooth and level surface.

Next we cut and welded in ½” bar steel into the corners of the engine compartment. These are where our vibration isolation mounts will be located. The 1.25” diameter holes for these were more difficult to drill that we anticipated. Fortunately, John Meyer helped us when we had dull bits and could not spin the drill press slow enough to drill the holes properly. Another major challenge with this part was manipulating the fuselage in order to access all the weld points. This required planning ahead and caution so that the fuselage did not hit other things in the welding area.

Perhaps the most challenging part of construction was the rest of the engine mounting hardware. All the pieces for the top mount, as well as the other tubes for the bottom mount, were all fitted and welded together the same day. Construction and alignment at this stage were crucial as it would have cost us significant time to redo any mistakes. Welding was also quite a challenge as the engine and fuselage created a lot of obstacles to weld around and required creative positioning. Other welding challenges included jigging issues, such as firmly holding various components in place and effects of heat on jig components. A final major factor in this day was focus as we spent quite a few hours working.

Another major area of construction involved our cooling system design. First, we made a testing duct for the radiator on our test stand. This was made out of sheet metal using the metal shear and bending brake. The lessons learned in this step were to carefully plan out the bending process so that bent parts do not interfere with the bending of later pieces. After using our duct on the test stand for design purposes, we constructed our prototype. This was built using plywood for the top and sides and aluminum sheet metal for the bottom. The contours of the plywood were made using a jigsaw and the aluminum was screwed to the plywood.

The exhaust pipe was also custom-made. For this we used scrap pieces of exhaust pipe that included elbows and straight runs. These were cut on the chop saw and TIG-welded together to form the desired shape. The flexible exhaust pipe is attached to the end of this with one end expanded to be inserted snugly into the muffler. We welded tabs to the muffler and the fuselage and hung the muffler from these.

Other components were mounted either in the engine compartment or behind the pilot's seat using plywood and pipe hangers. This method allowed us to build things quickly and also allows them to be removed or relocated easily as necessary.

3.2 Operation

As a part of our design process, we engaged in testing to help us make some key decisions. We also conducted some testing at the conclusion of our project to verify whether or not we had actually achieved our objectives.

Most of the testing we did throughout the semester focused on determining what size radiator we needed. To do this we used the pre-production Rotamax engine on our test stand. Basically, our testing with the test stand focused on determining how much waste heat the engine was generating and then experimenting with different duct designs.

To determine how much heat the engine was producing we measured the flow rate of the electric water pump on the test stand and then measured the coolant temperature rise across the engine running at full throttle. With this information we calculated that the Rotamax engine was producing about 1400 Btu/min. Below is an example of this test data taken Feb. 2, 2008:

RPM	Coolant Temp °C	Change in Temp.	Ambient Air = 3.5 °C
2510	38.5	5.5	Kiev Propeller, Pitch #9
4000	45.3	7.0	
2350	47.3	6.4	
4710	53.2	7.9	

One we determined how much heat the engine was producing we used our test stand to try and benchmark our radiator sizing calculations with real life. To assist us in our calculations we used an Excel spreadsheet written by Neil Willford. When we were satisfied that our calculations were reflecting real life, we used our test stand to try different duct designs. An example of one of our test set-ups is shown in Appendix 9.12.

At the conclusion of our project we also performed a little testing on our final prototype. Most of this testing was of a qualitative nature but we were able to verify a few of our objectives. Specifically, the engine remained secured in the engine compartment during running of the engine, the engine temperature never exceeded 150 °F and sound levels were noticeably less than the 100db recorded on the test stand.

4 SCHEDULE

Shown in Appendix 9.13 is a copy of our Gantt chart as of the end of the fall semester and a Gantt chart showing how things actually panned out. There are a few things worth noting here.

Perhaps the biggest influence on our schedule was the arrival of the Gen. II engine from Rotamax. At the beginning of the fall semester, we were scheduled to receive our engine in October. With this in mind, we originally planned to have the engine mounted by Christmas with the cooling system and exhaust system beginning to take shape in the early winter.

In reality, we did not receive our engine until mid-March. In order to try and finish our project in time, we focused on doing a lot of design work on the exhaust and cooling system despite not having a clear idea of how everything would fit into the engine compartment. When we eventually received the engine, it had a few variations that we were not planning on so we needed to make some minor design changes. To summarize our project scheduling, we spent most of the year designing on paper as best we could before receiving the engine in mid-March and building our mounting, exhaust and cooling systems in the month of April.

5 BUDGET

See Appendix 9.14 for a breakdown of all costs. This includes only the costs of the system components. Major donated components include the engine and muffler, given to us by Rotamax with an agreement that we would offer them support and feedback to aid with their development and entry into the aircraft engine market.

6 CONCLUSIONS

The project overall has been a success as we were able to accomplish most of our initial objectives. First, we designed and built an engine mounting system which can easily support our engine as well as the thrust and torque generated. Next, we selected a muffler that closely met our specifications and created a design for the placement of the muffler underneath the fuselage. Finally, we were able to select an appropriate radiator to maintain acceptable engine temperatures in operation. Along with this we designed and built the ductwork to mount the radiator underneath the fuselage. More testing will be required to verify our last objective of the required inspection time. Overall our goals have been adequately achieved.

One of the biggest lessons we learned was unpredictable reliability problems arising with shipments. Our engine was originally scheduled to arrive in October and we planned our work out accordingly. However, it did not actually arrive until after spring break. This gave us a challenge and stalled some of our efforts which relied on the engine. Scheduled plans often change, sometimes very drastically. We learned how to better predict the length of time required to create and revise designs as well as build the final product. Also, we learned that the final construction is much smoother with good thorough designs. The better you make and analyze your design the fewer problems you run into in construction.

7 RECOMMENDATIONS FOR FUTURE WORK

The most significant phase of future work is testing. Our group was able to perform limited ground testing, but there is no better way to test actual performance than by flying the aircraft once it is built. Specifically, cooling system efficiency will be what is most proven by air testing. We have made our best estimates for radiator size and duct shape, but accurate ground tests are difficult because the radiator is not moving through the air, and less airflow means less cooling capacity

In light of this, we have done our best calculations to choose our radiator and duct size. With the way we have designed our setup, optimization of the cooling system should require only duct shape changes that would increase or decrease airflow over the radiator (also increasing or decreasing drag, respectively)

Another necessity for testing is to determine the actual life span of components. Due to time constraints we will not be able to accumulate many hours on our system or see the effects of wear and tear. This will be left to be determined by future efforts.

Other fixtures that we are using for testing that should be replaced or relocated include the fuel tank, header tank, battery, and firewall. These should be upgraded to the most desirable size and durability once the aircraft is closer to flight. Final locations will also need to be determined based on accessibility and weight and balance.

We also have a few suggestions for future groups. One thing we wish we had learned sooner was to keep asking questions until you get or figure out what you need. This project requires a completely different thought process than what we have been accustomed to in the classroom. While we are used to having enough material in our possession to find our own answers, this is not the case with a project. Many times we struggled for a while trying to figure something out, only to have a quick phone call or conversation answer most of our questions. Whether it be an advisor, professor, an informed person at a company, or John Meyer, the “you never know unless you ask” philosophy is good to adopt early on. There are more resources available than most of us realize. Senior Project is much more a process of finding the right answers than it is of figuring them out for ourselves. Talking to people about your project can sometimes give you leads you never would have expected.

8 BIBLIOGRAPHY

Bingelis, Tony. Firewall Forward. Oshkosh, WI: EAA, 1992

Dzik, Stanley J. Aircraft Detail Design Manual. Appleton, WI: Aviation Publications, 1988

Lamar, Paul. How to Cool Your Wankel. Dayton Beach, FL: Daytona Press, 2007

Lamar, Paul. “The Mazda Wankel Rotary Engines For Aircraft Website” <www.rotaryeng.net>

9 APPENDIX

9.1 Cooling Design Research

9.2 Our Cooling Designs

9.3 Picture of Tangential Muffler with Fishtailed Tailpipe

9.4 Final Control Panel

9.5 Initial Engine Mount Design

9.6 Vibration Analysis

9.7 Final Two Mount Engine Design

9.8 Rubber Bushing Fuselage Mount

9.9 Final Thrust Mount Design

9.10 Radiator and Duct Work

9.11 Exhaust System

9.12 Test Stand Setup

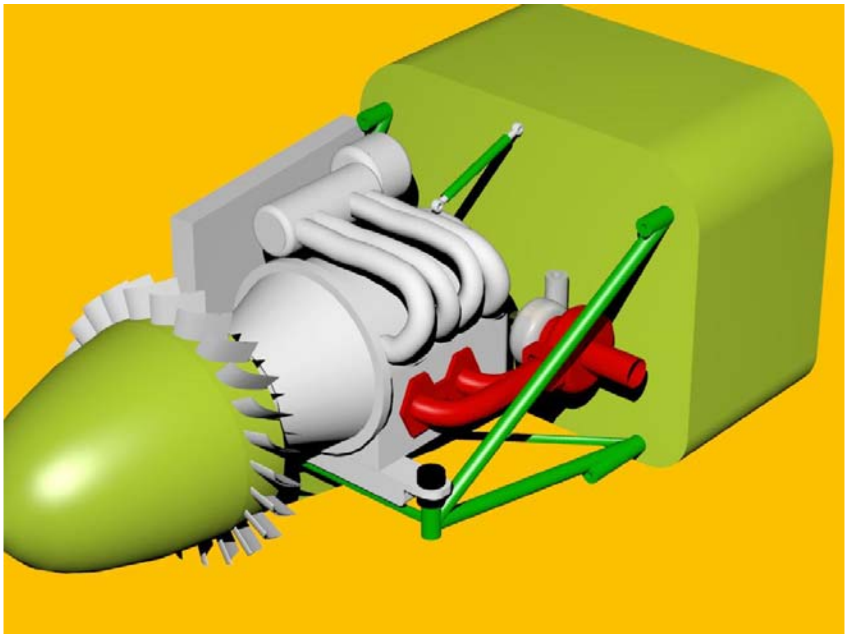
9.13 Gantt Chart

9.14 Budget

9.15 Original Specifications

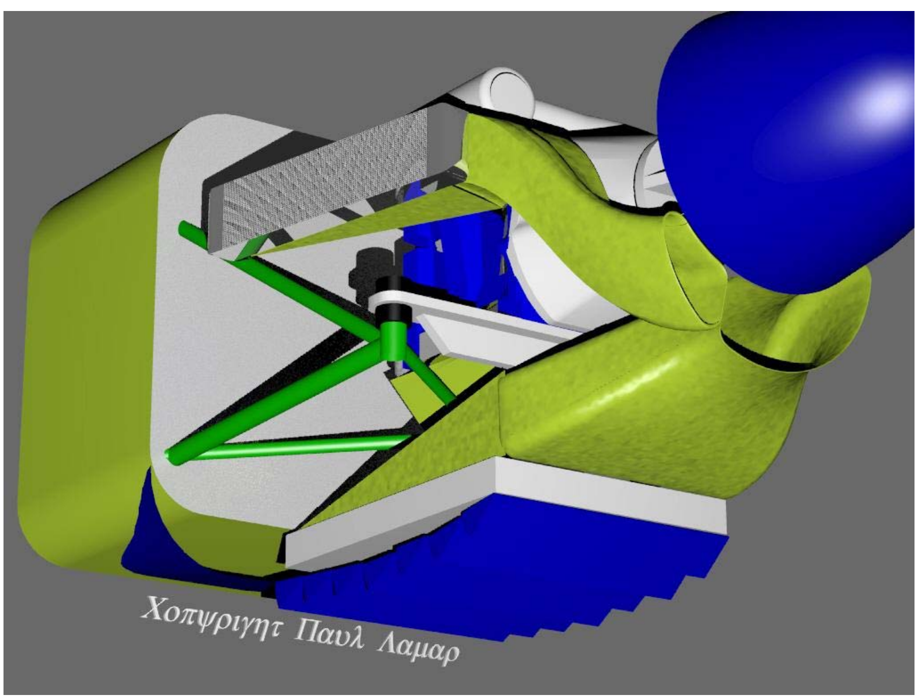
9.1 Cooling Design Research

A. Design with Two Bottom Rubber Isolators and One Rear Thrust Connection:



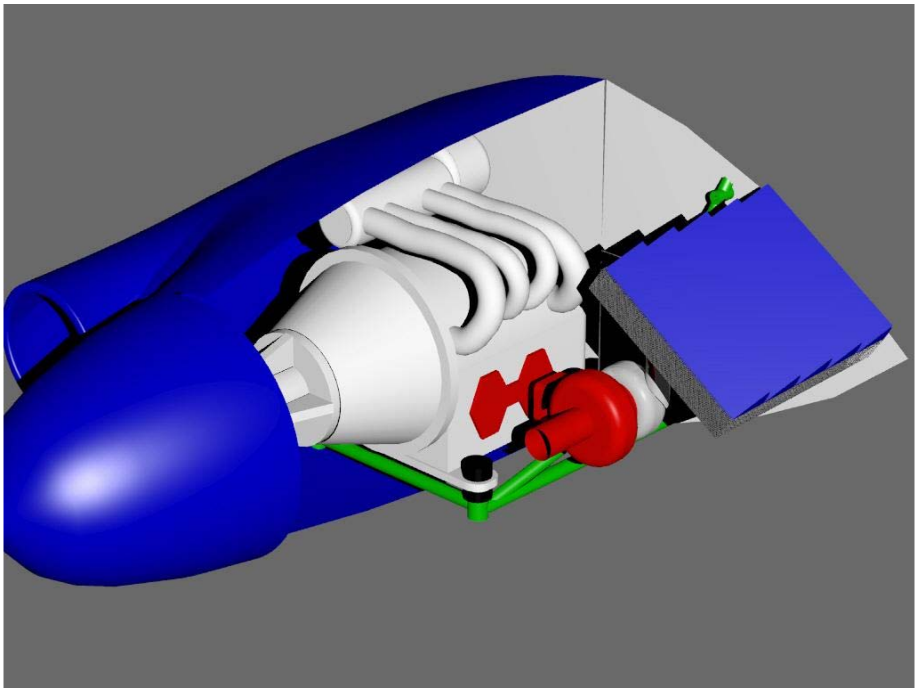
(from www.rotaryengine.net)

B. Design of Radiator Mounted Below Engine with Two Bottom Mounts and One Rear Mount



(from www.rotaryengine.net)

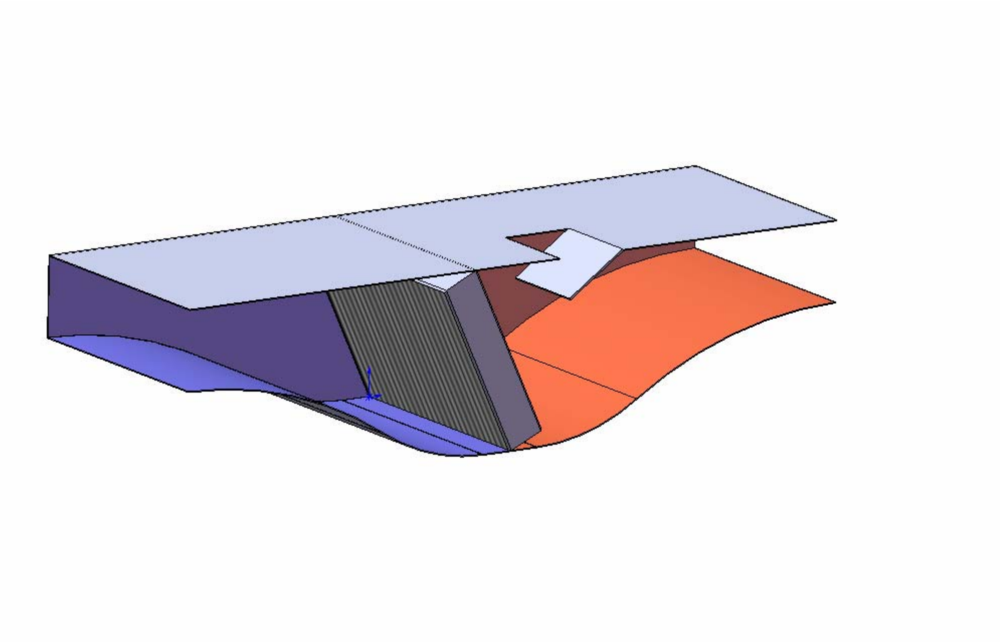
C. Alternative Radiator Location with Two Bottom Mounts and One Rear Mount



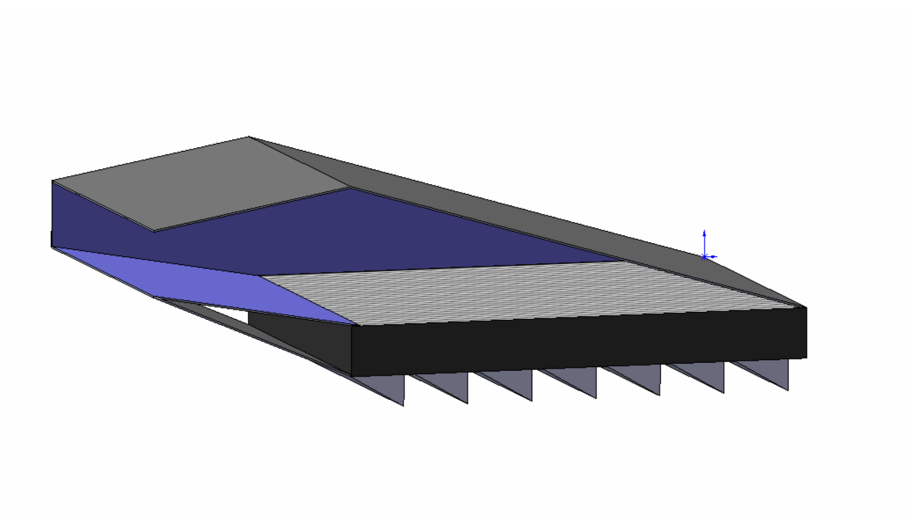
(from www.rotaryengine.net)

9.2 Our Cooling Designs

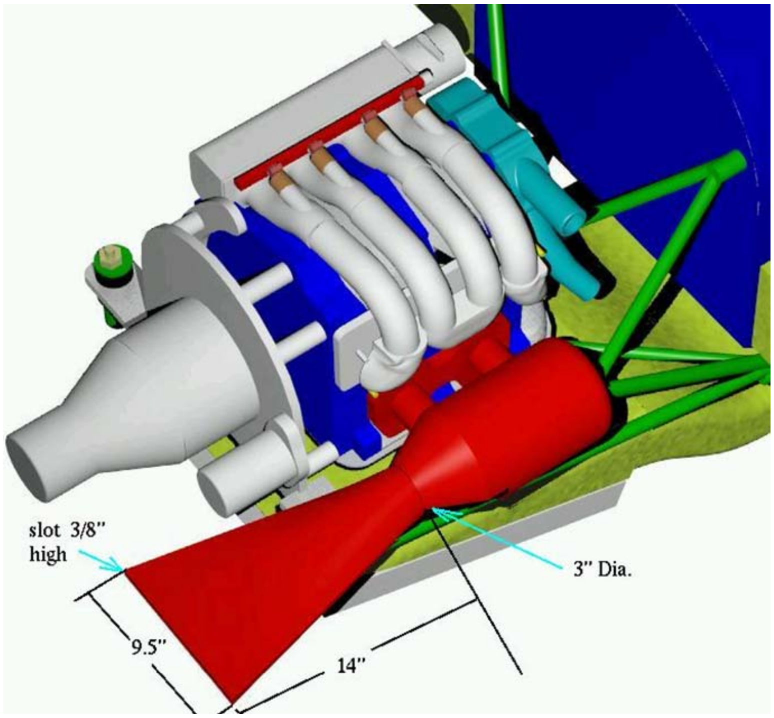
A. Under-Belly Design



B. Under-Engine Design

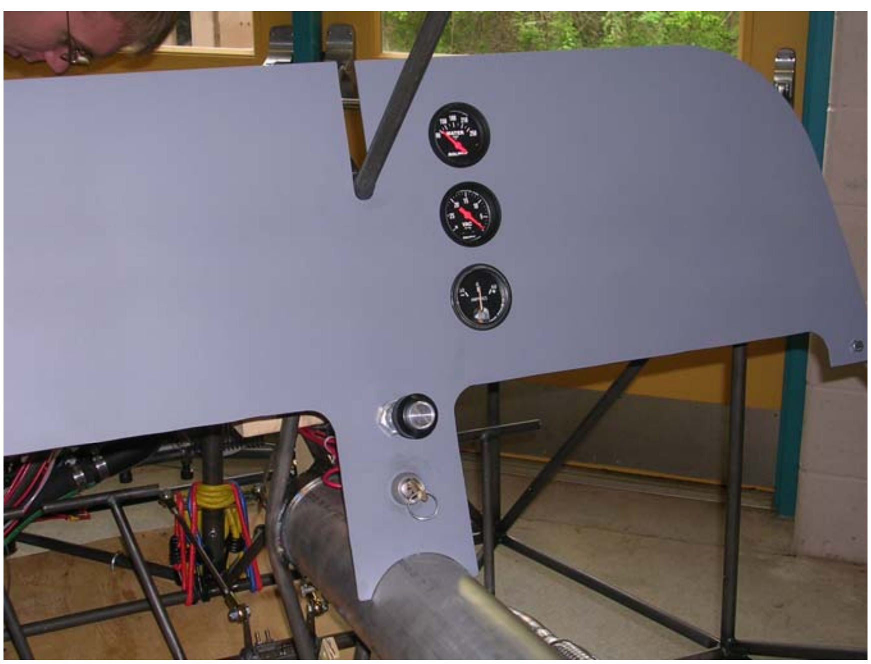


9.3 Picture of Tangential Muffler with Fishtailed Tailpipe



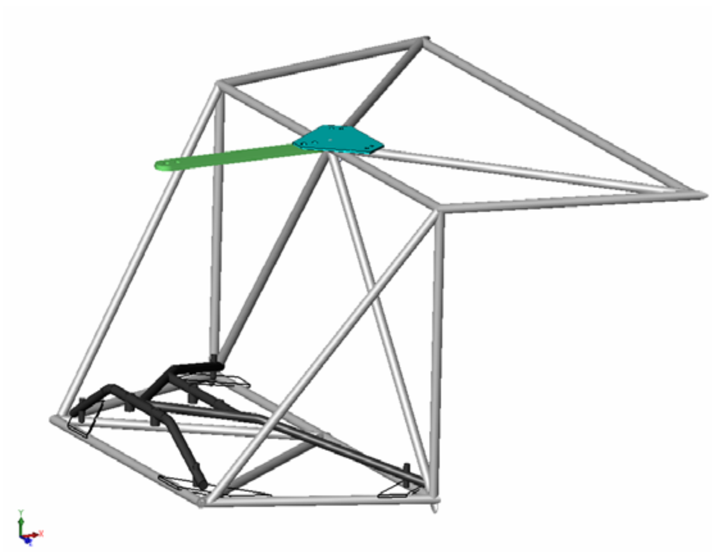
(from www.rotaryengine.net)

9.4 Final Control Panel

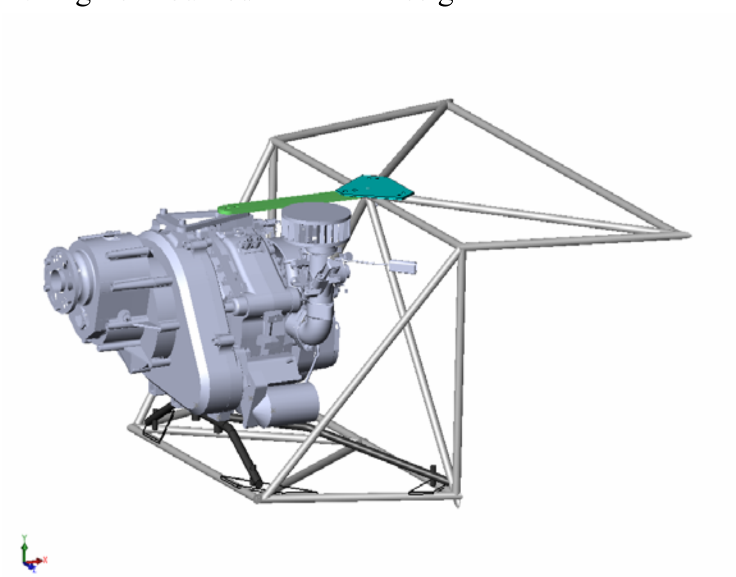


9.5 Initial Engine Mount Design

A. Four Mount Design with Thrust Mount

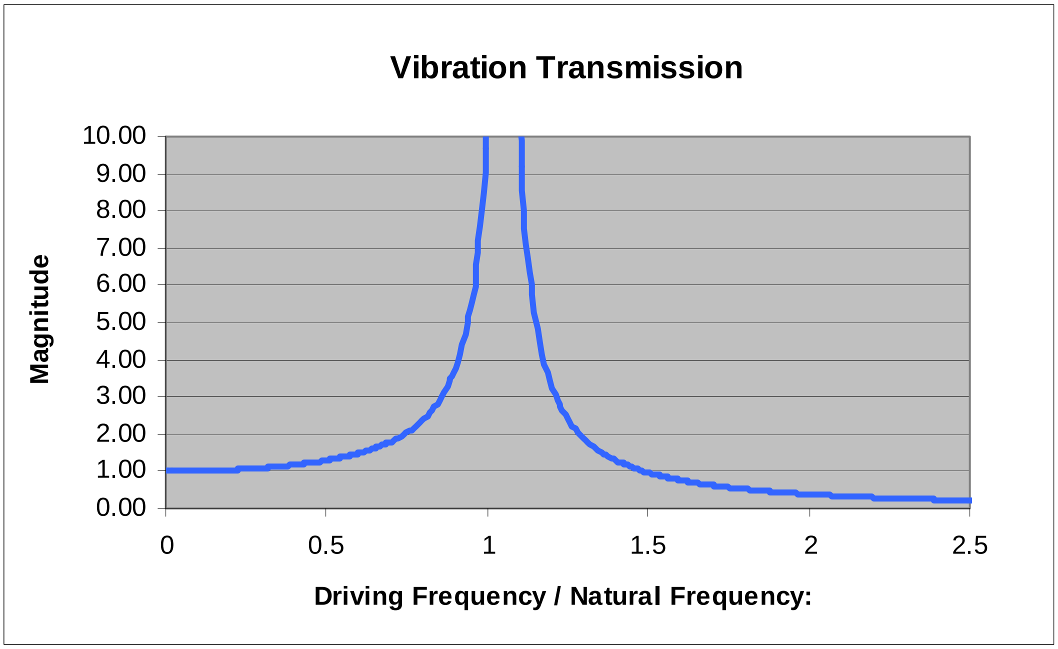


B. Engine Mounted in Initial Design

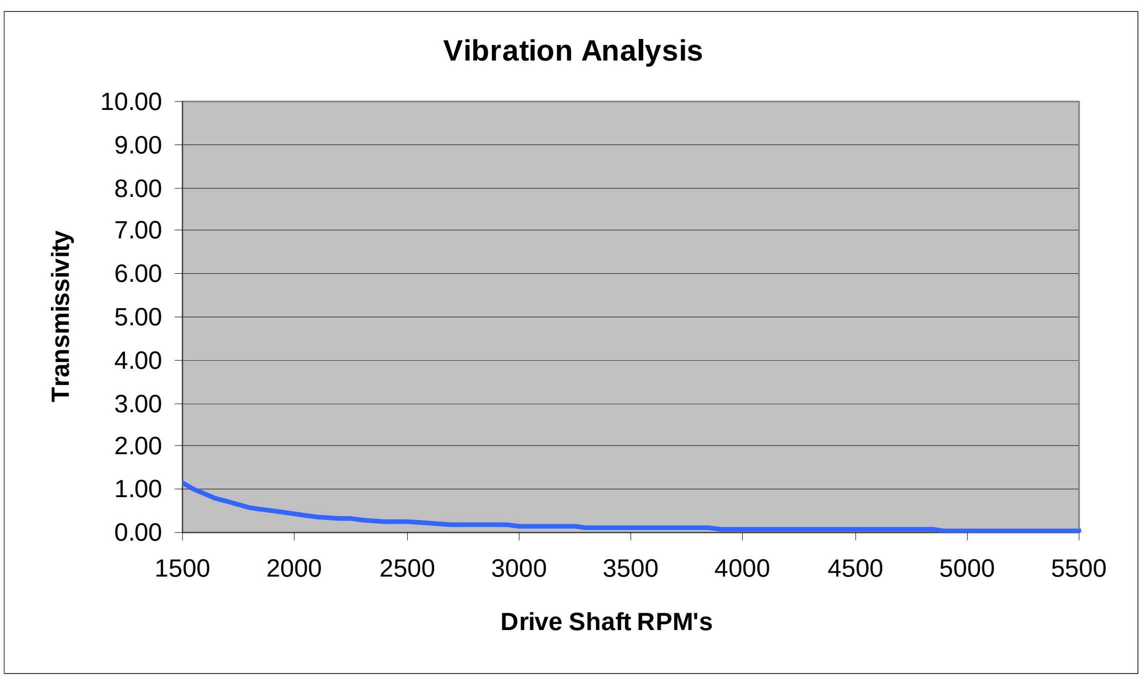


9.6 Vibration Analysis

A. Graph of Vibration Transmission as a Function of Frequency Ratio

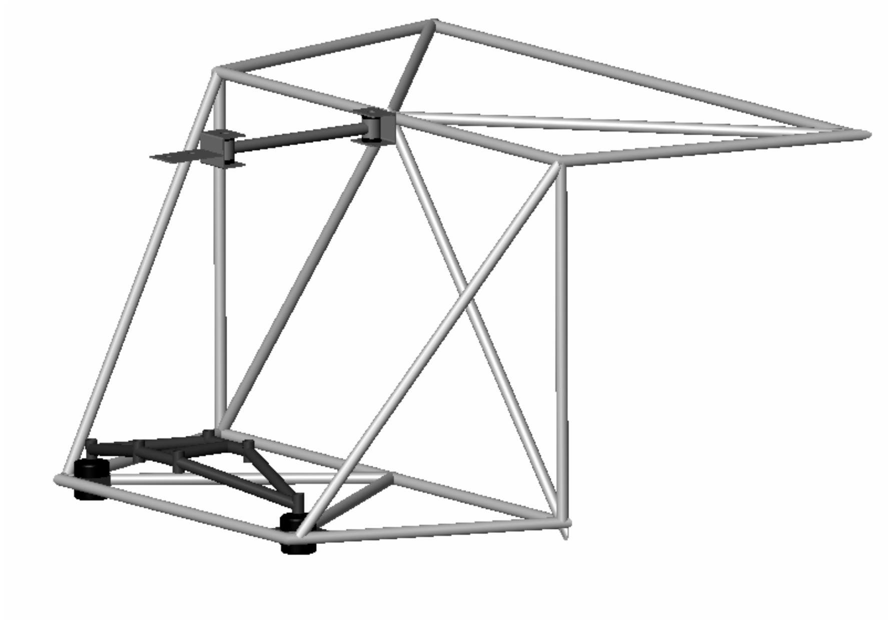


B. Graph of Moving Propeller Blade Vibration Response

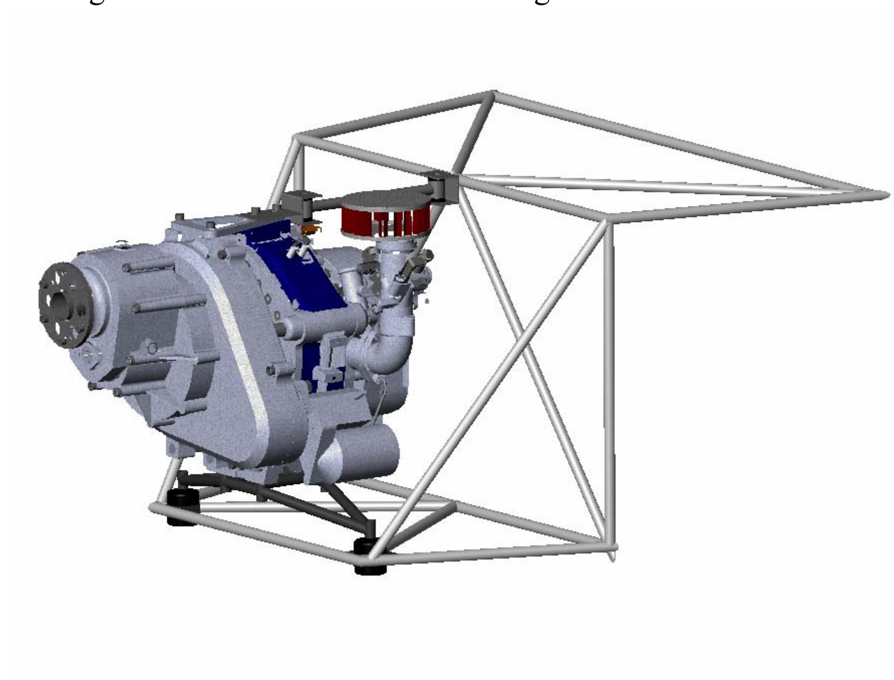


9.7 Final Two Mount Engine Design

A. Two Mount Design with Thrust Mount



B. Engine Mounted on Two Mount Design



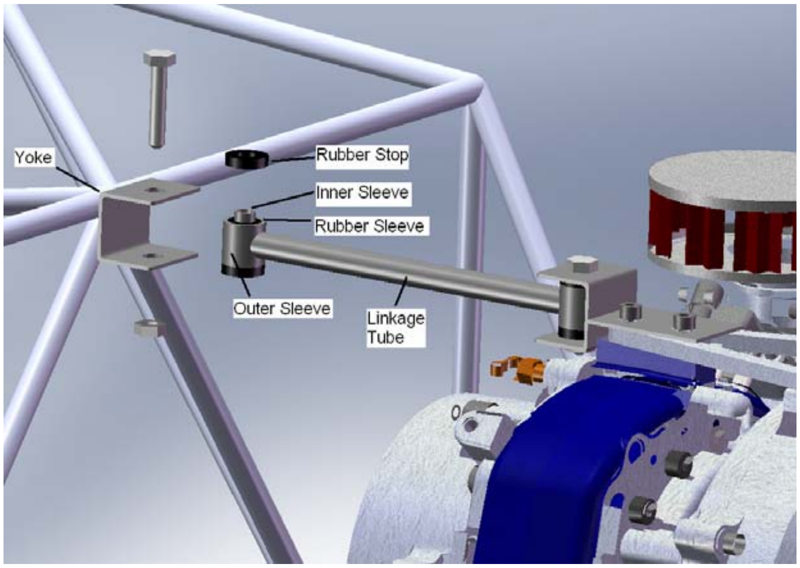
9.8 Rubber Bushing Fuselage Mount

A. Welded Bushing Plate

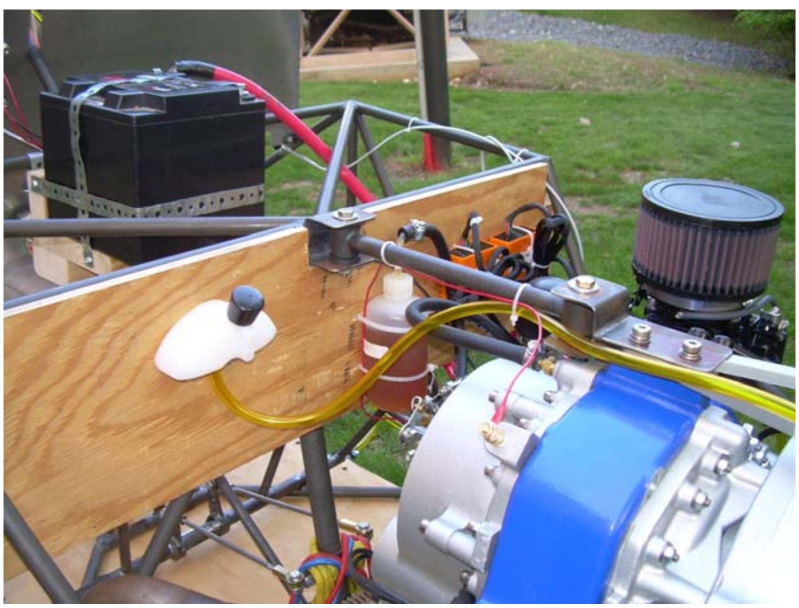
B. Completed Plate Construction

9.9 Final Thrust Mount Design

A. Thrust Mount Components

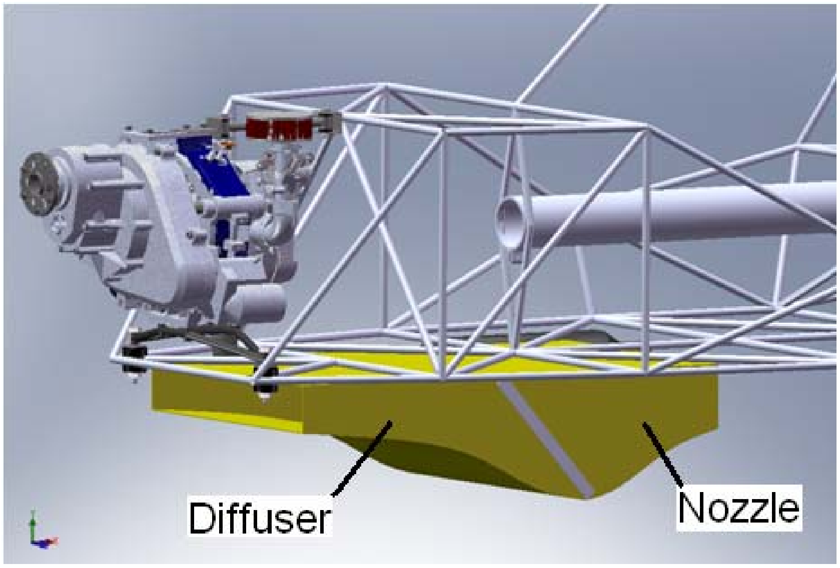


B. Completed Thrust Mount Construction



9.10 Radiator and Duct Work

A. Duct Work Components



B. Radiator Spreadsheet Example

Microsoft Excel - radiator sizing 3-29-08 - under fuse.xls

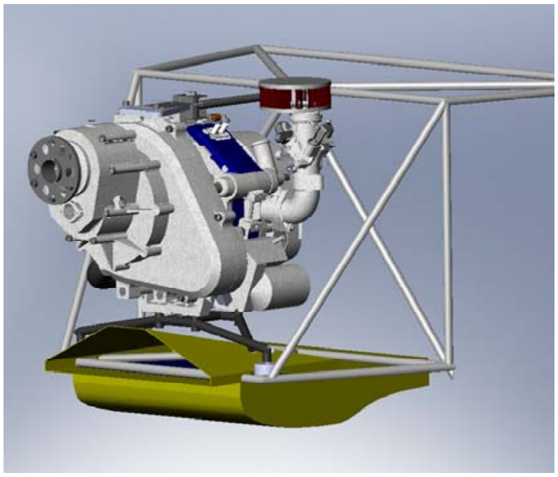
File Edit View Insert Format Tools Data Window Help Adobe PDF

D45 fx 0.43

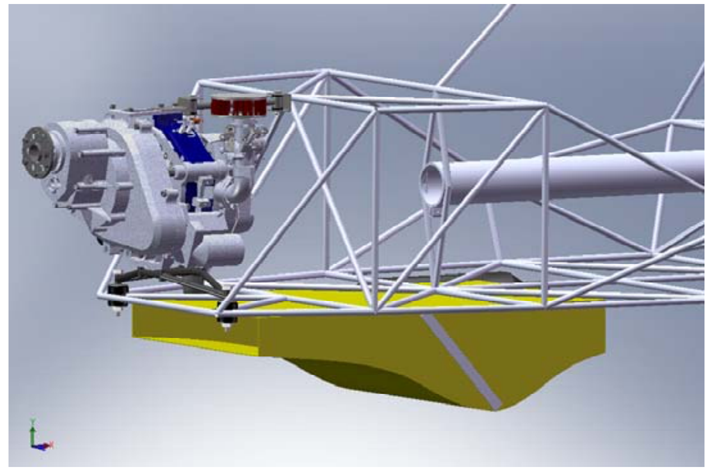
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
38																
39	**Radiator or Intercooler:**															
40	Max Coolant or Intercooler Air Temp			**160**	deg F											
41	estimated radiator requirement =			**1167**	BTU/min											
42	actual radiator requirement:			**1407**	BTU/min											
43	Velocity of cooler air/cruise airspeed:			0.4	Hoerner's book recommends for design purposes a value of 0.1 to minimize cooler drag, use larger value if result is too big of a radiator											
44	Velocity of cooler air/climb airspeed=			**0.30**												
45	cooler open area ratio:			**0.43**	ratio of area between radiator fins to 1 sq. in. of radiator size. Auto style radiator checked was .54											
46																
47	Pressure drop constant can be estimated if the cooler cell size and depth of radiator is known															
48	Cell area:		**0.046**	sq. in. (area of a single radiator cell)					Hydraulic Diameter =	0.137	in.					
49	Cell Perimeter:		**1.34**	in. (perimeter length around a single radiator cell)					Re =	6795	SL Std day for 40 ft/s					
50	Cooler thickness:		**1.47**	in.					Kp =	3.8	SL Std day for 40 ft/s					
51	cooler open area ratio:		**0.43**	ratio of area between cooling fins to 1 sq. in. of cooler area.												
52	Estimated pressure drop constant =			7.9												
53	Pressure drop constant:			**7.9**	7 was the estimated constant for auto style radiator (2" thick) that I checked											
54																
55	Estimated cooler pressure drop coefficient =				4	Estimated cooler heat transfer coefficient =				0.4						
56																
57	**Estimated minimum radiator area =**				**195**	**sq. in.**			Radiator Area used:		210	"12"17.5"	0.135m^2			
58	**Estimated radiator airflow needed =**				**4.84**	**lbs/sec**							1.56lb/sec			
59																
60	**Calculating the pressure drop constant using actual cooler data**															
61	The pressure drop constant can be calcutalte if airflow through the cooler versus pressure drop across the cooler is available															
62	This is should be used whenever possible, as the coefficent will likely be more accurate than that calculated using the cell dimensions															
63	Using the cooler data, a mass flow value and the corresponding pressure drop value															
64																
65	Mass flow:	**1.0**	lbs/sec	Pressure drop for the given mass flow:				**14.5**	in. H20 =	75	psf					
66	Cooler area:	**29.78**	sq. in.			air density rho:		**0.00238**	air density for cooler data. Usually SL std day, for which rho is .00238							
67										velocity thru cooler =		63	ft/sec			
68	**Pressure drop constant =**			**36.4**		Cooler conductivity, K =			0.25	q thru cooler =		4.7	psf			
69																
70																

C. Cooling System Designs

a. Initial Design



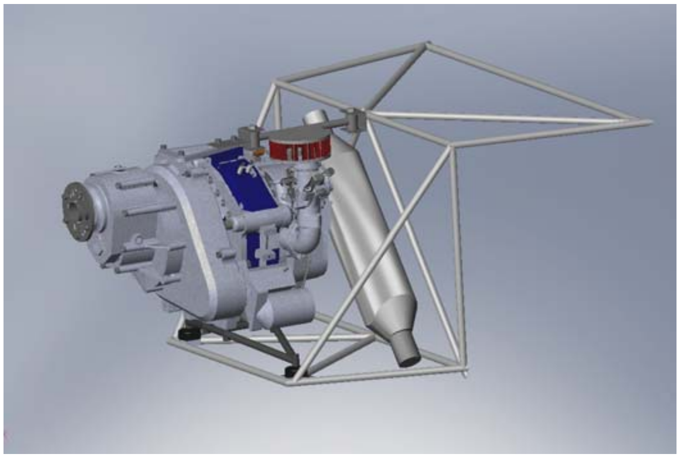
b. Final Design



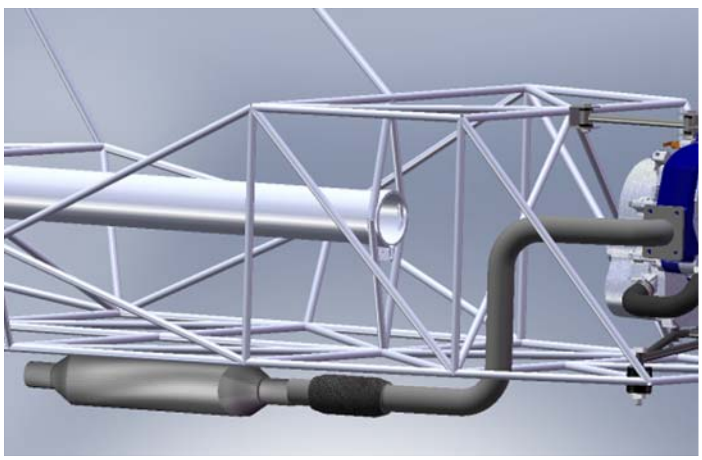
D. Completed Cooling System Construction

9.11 Exhaust System

A. Initial Muffler Mounting Design

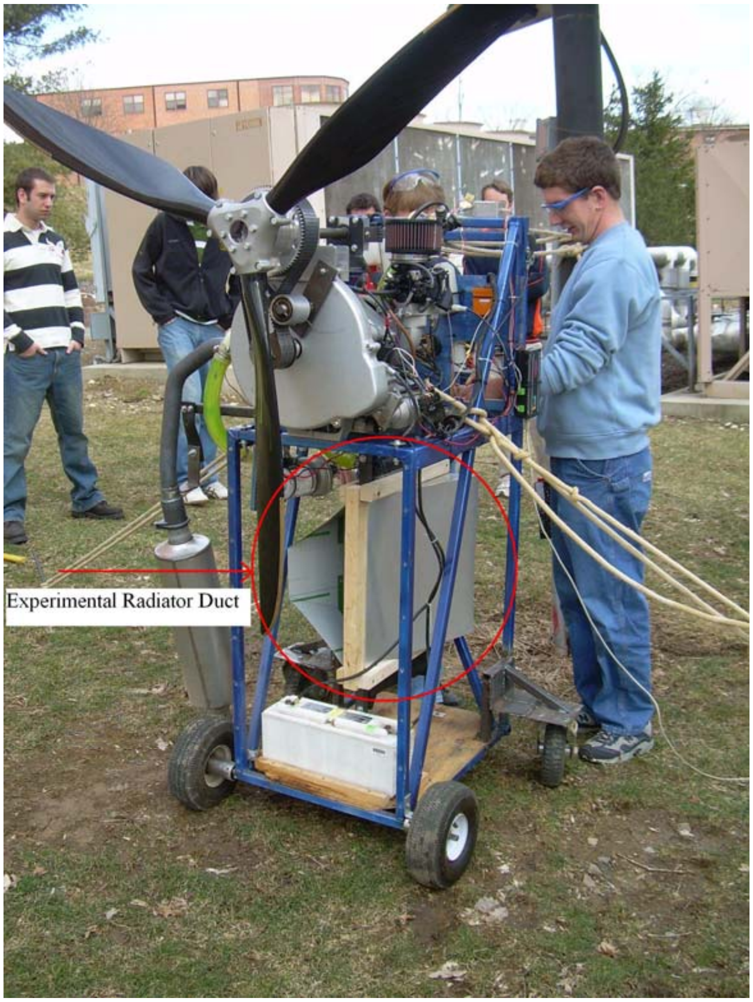


B. Final Muffler Mounting Design



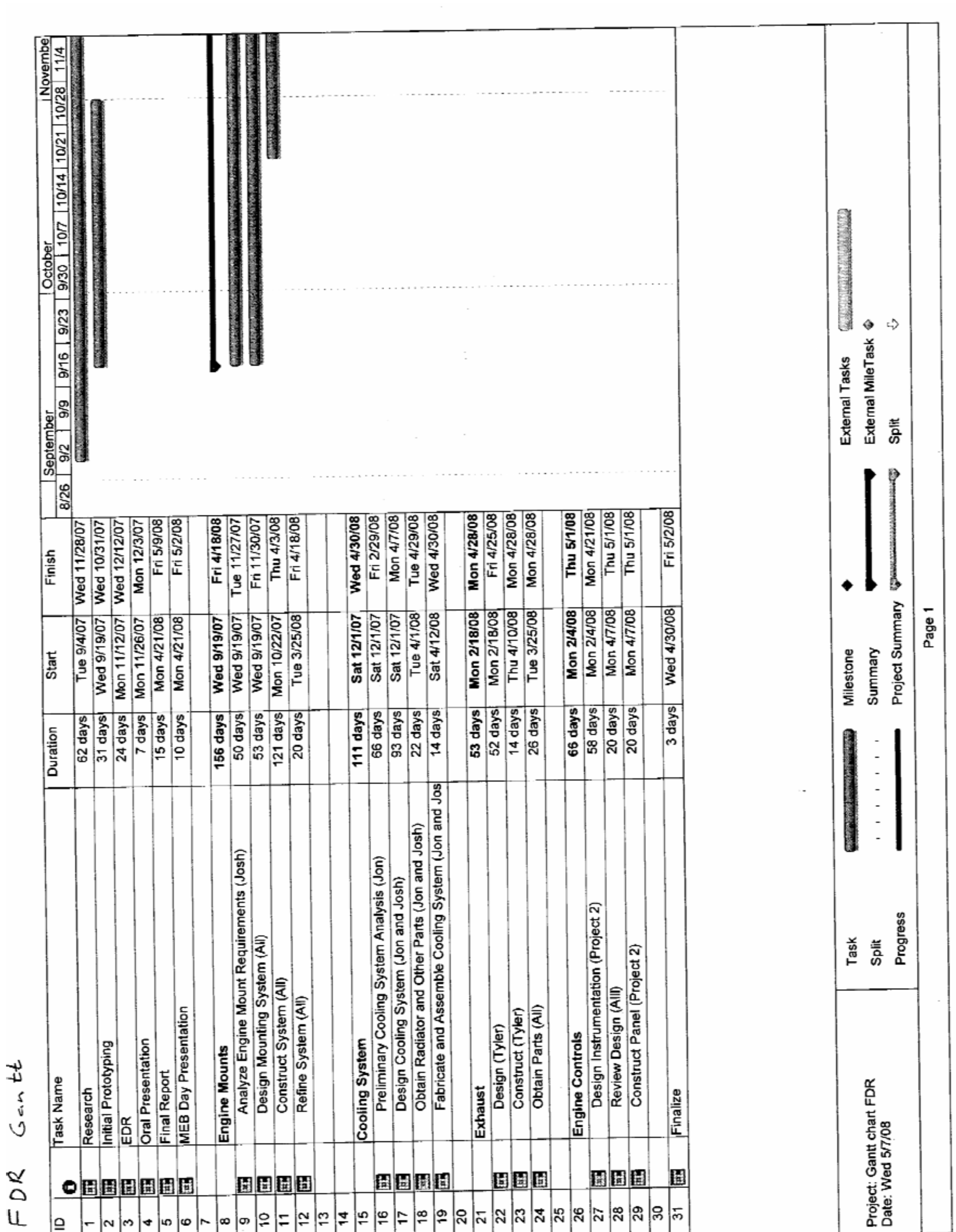
C. Completed Exhaust System Construction

9.12 Test Stand Setup



9.13 Gantt Chart

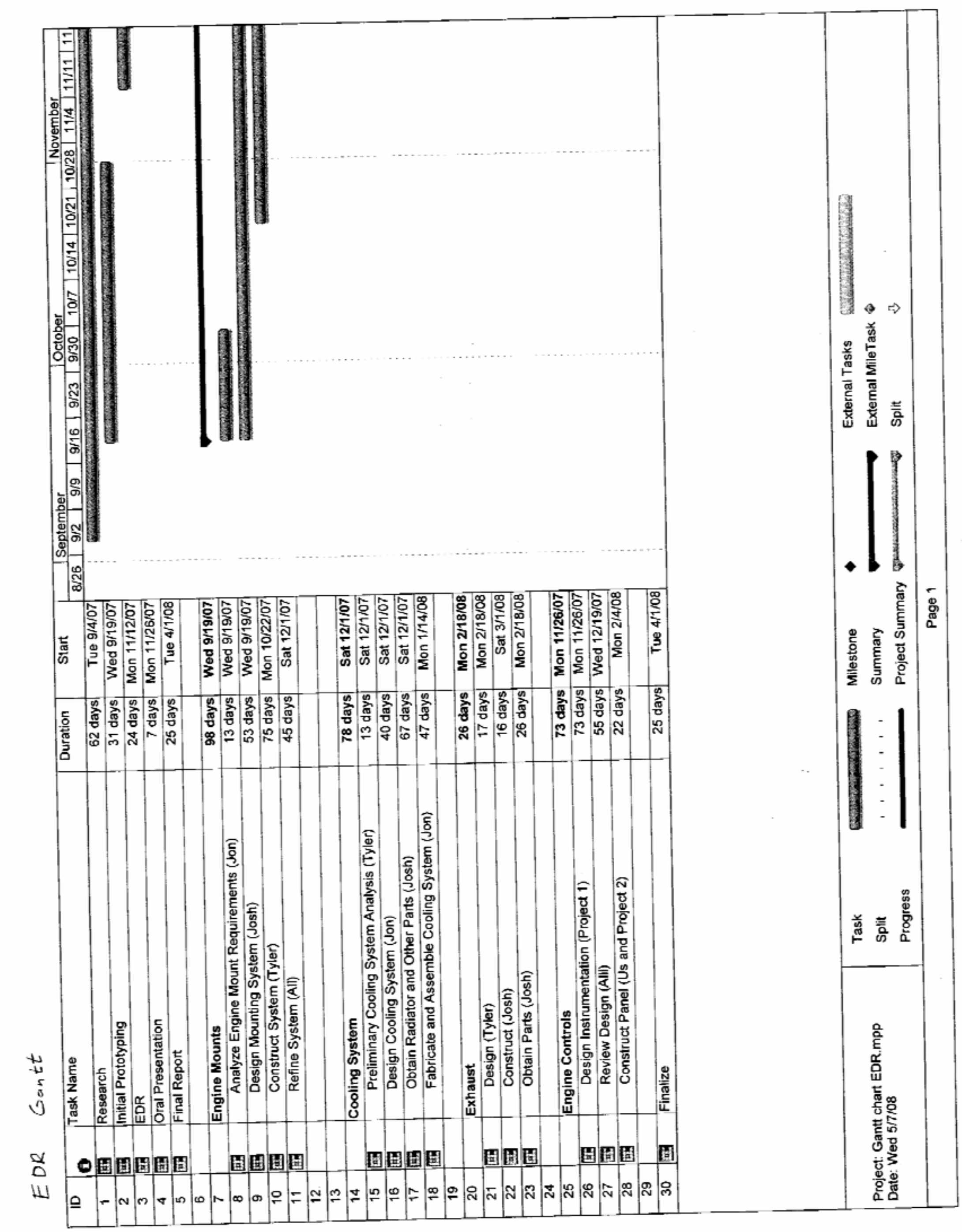
A. FDR (final) Gantt Chart



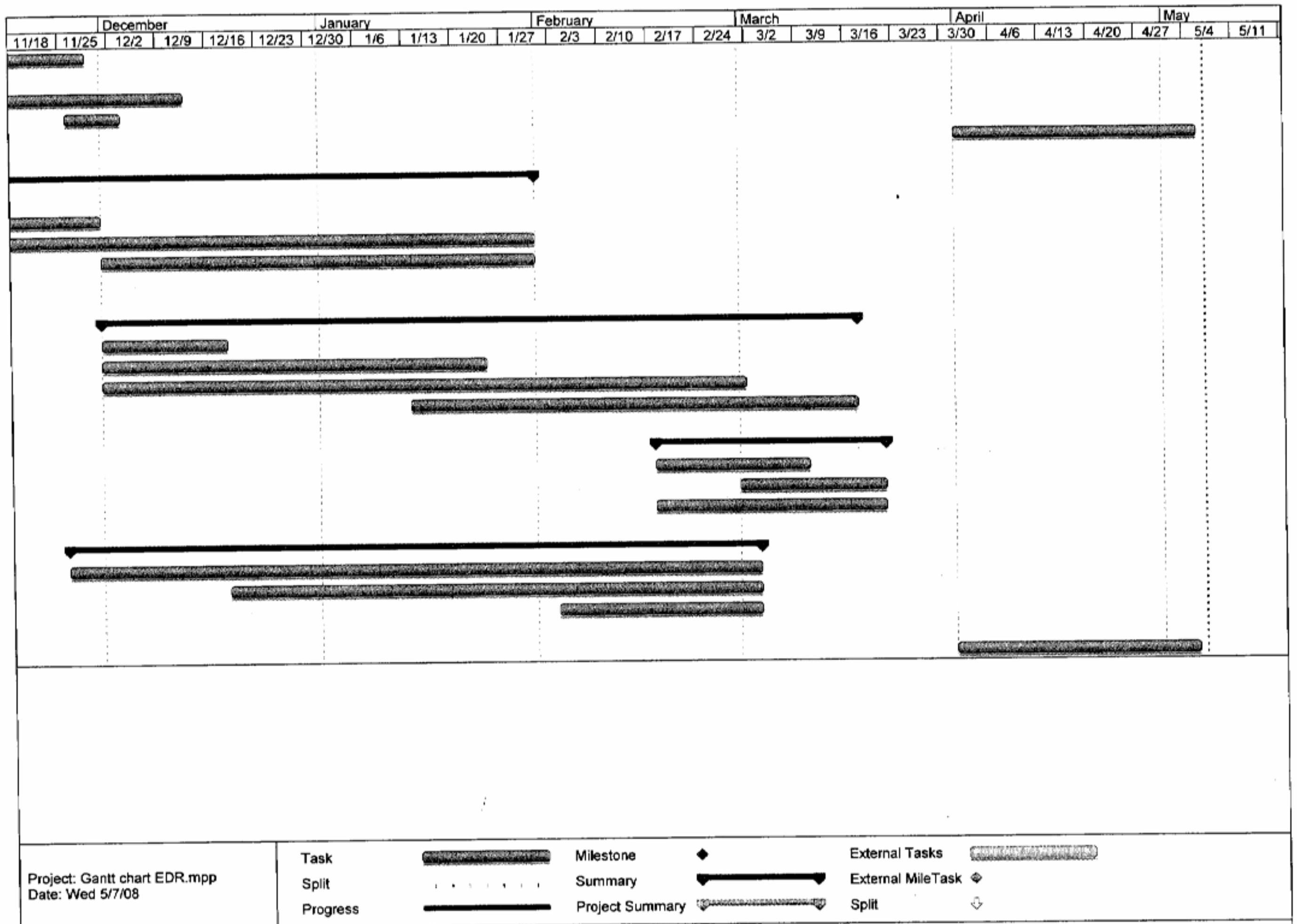
ID	Task Name	Duration	Start	Finish
1	Research	62 days	Tue 9/4/07	Wed 11/28/07
2	Initial Prototyping	31 days	Wed 9/19/07	Wed 10/31/07
3	EDR	24 days	Mon 11/12/07	Wed 12/12/07
4	Oral Presentation	7 days	Mon 11/26/07	Mon 12/3/07
5	Final Report	15 days	Mon 4/21/08	Fri 5/9/08
6	MEB Day Presentation	10 days	Mon 4/21/08	Fri 5/2/08
7				
8	**Engine Mounts**	**156 days**	**Wed 9/19/07**	**Fri 4/18/08**
9	Analyze Engine Mount Requirements (Josh)	50 days	Wed 9/19/07	Tue 11/27/07
10	Design Mounting System (All)	53 days	Wed 9/19/07	Fri 11/30/07
11	Construct System (All)	121 days	Mon 10/22/07	Thu 4/3/08
12	Refine System (All)	20 days	Tue 3/25/08	Fri 4/18/08
13				
14				
15	**Cooling System**	**111 days**	**Sat 12/1/07**	**Wed 4/30/08**
16	Preliminary Cooling System Analysis (Jon)	66 days	Sat 12/1/07	Fri 2/29/08
17	Design Cooling System (Jon and Josh)	93 days	Sat 12/1/07	Mon 4/7/08
18	Obtain Radiator and Other Parts (Jon and Josh)	22 days	Tue 4/1/08	Tue 4/29/08
19	Fabricate and Assemble Cooling System (Jon and Jos	14 days	Sat 4/12/08	Wed 4/30/08
20				
21	**Exhaust**	**53 days**	**Mon 2/18/08**	**Mon 4/28/08**
22	Design (Tyler)	52 days	Mon 2/18/08	Fri 4/25/08
23	Construct (Tyler)	14 days	Thu 4/10/08	Mon 4/28/08
24	Obtain Parts (All)	26 days	Tue 3/25/08	Mon 4/28/08
25				
26	**Engine Controls**	**66 days**	**Mon 2/4/08**	**Thu 5/1/08**
27	Design Instrumentation (Project 2)	58 days	Mon 2/4/08	Mon 4/21/08
28	Review Design (Alll)	20 days	Mon 4/7/08	Thu 5/1/08
29	Construct Panel (Project 2)	20 days	Mon 4/7/08	Thu 5/1/08
30				
31	Finalize	3 days	Wed 4/30/08	Fri 5/2/08

Project: Gantt chart FDR Date: Wed 5/7/08	Task	Milestone	External Tasks
	Split	Summary	External MileTask
	Progress	Project Summary	Split

B. EDR Gantt Chart



ID	Task Name	Duration	Start
1	Research	62 days	Tue 9/4/07
2	Initial Prototyping	31 days	Wed 9/19/07
3	EDR	24 days	Mon 11/12/07
4	Oral Presentation	7 days	Mon 11/26/07
5	Final Report	25 days	Tue 4/1/08
6			
7	**Engine Mounts**	**98 days**	**Wed 9/19/07**
8	Analyze Engine Mount Requirements (Jon)	13 days	Wed 9/19/07
9	Design Mounting System (Josh)	53 days	Wed 9/19/07
10	Construct System (Tyler)	75 days	Mon 10/22/07
11	Refine System (All)	45 days	Sat 12/1/07
12			
13			
14	**Cooling System**	**78 days**	**Sat 12/1/07**
15	Preliminary Cooling System Analysis (Tyler)	13 days	Sat 12/1/07
16	Design Cooling System (Jon)	40 days	Sat 12/1/07
17	Obtain Radiator and Other Parts (Josh)	67 days	Sat 12/1/07
18	Fabricate and Assemble Cooling System (Jon)	47 days	Mon 1/14/08
19			
20	**Exhaust**	**26 days**	**Mon 2/18/08**
21	Design (Tyler)	17 days	Mon 2/18/08
22	Construct (Josh)	16 days	Sat 3/1/08
23	Obtain Parts (Josh)	26 days	Mon 2/18/08
24			
25	**Engine Controls**	**73 days**	**Mon 11/26/07**
26	Design Instrumentation (Project 1)	73 days	Mon 11/26/07
27	Review Design (All)	55 days	Wed 12/19/07
28	Construct Panel (Us and Project 2)	22 days	Mon 2/4/08
29			
30	Finalize	25 days	Tue 4/1/08


December
January
February
March
April
May
11/18
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12/16
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1/20
1/27
2/3
2/10
2/17
2/24
3/2
3/9
3/16
3/23
3/30
4/6
4/13
4/20
4/27
5/4
5/11
Project: Gantt chart EDR.mpp
Date: Wed 5/7/08
Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External MileTask
Split

9.14 Budget

LSA Integration Budget

Item	Quantity	Total Cost	Purpose	Supplier	Notes
650cc Single Rotor Engine			Aircraft Version with 2.2:1 PSRU	Donated - Rotamax	~$5500 new
Mounts					
Big Barry Mounts	2	13.64		Brandon Products Group	
Shipping for mounts	4	10.52		Brandon Products Group	
Dillsburg Hardware (total)		22.00			
1/2"x3" bolt	2	n/a	Bottom mount	Dillsburg	
1/2" all metal locknut	2	n/a	Bottom mount	Dillsburg	
Snubbing washer	4	n/a	Bottom mount	Dillsburg	
3/8" Aircraft Grade bolts, lock nuts	2	n/a	Bolts thru C sections	Dillsburg	
0.080" x 2" x ? 4130 steel	1	n/a	C sections	Dillsburg	
1/2"OD tube insert	1	n/a	Thrust mount	Dillsburg	
Cooling					
Radiator		124.00		Advance Auto	
1/4" bypass hose (by foot)	3	3.54		Advance Auto	
1/4" hose clamps	12	9.00		Pepboys	
1/4" fuel/oil/coolant hose	25'	12.50		McMaster	
1.25" cooling hose	10'	62.00		McMaster	
1.25" hose clamps	4	6.00		Pepboys	
1 Gallon jug antifreeze	1	14.00		Advance Auto	
Recovery jug	1	7.18			
1.25" hose clamps	4	2.86		Lowes	
Pipe straps	10	1.58		Lowes	
1.25" elbow		1.00		Lowes	
1.25 preformed elbow/U		20.00	Used for bends in cooling lines	Advance Auto	
Exhaust					
Mesh flex pipe to muffler	1	22.11		Fisher's / Federated Auto	
Flex pipe expansion	1	3.00	Fit flex pipe to muffler	Shumakers	
1.75"? Exhaust pipe	1	donated			
Hushpower Muffler		donated		Rotamax	
U-bolts (2x2", 1x1 7/8")		5.79		Pepboys	
U-bolt: 2.5"		2.50		Advance Auto	
Metal hanger (5ft)		3.00		Pepboys	
1.75"-2.00" adapter		3.00		Pepboys	Cut, but not used
Lubricants					
Gear Oil - Coastal Synthetic 75/90	2	14.00	PSRU oil	Advance Auto	
Gear Oil - Mobile One Synthethic 75/90	2	16.00	PSRU oil	Advance Auto	
10w30 motor oil (1 qt)		2.50	Engine oil	Advance Auto	
30 shell Rotella (1 gallon)		11.00	Engine oil	Advance Auto	Recommended by Skip

Gauges:					
Tach		future			
Hour Meter		future			
Ammeter		n/a		Autometer	IPC/Collaboratory
Temperature		n/a		Autometer	IPC/Collaboratory
Controls					
Choke cable		9.99			
Throttle				Aircraft Spruce	IPC/Collaboratory
Twin ignition key switch					IPC/Collaboratory
Fuel System:					
2.5 gallon gas can		9.00			
Ball valve for shut off		6.27			
1/4" NPT to 1/4" hose barb	2	4.14			
Rubber grommets for tank		2.99			
Filter		4.99			
Miscellaneous:					
Control Arm Bushing	2	n/a	Idea for top mount	Advance Auto Parts	Returned- $20
Barry medium mount	1	14.00	Idea for bottom mount	Aircraft Spruce	too late to return
Barry hard mount	1	15.00	Idea for bottom mount	Aircraft Spruce	too late to return
Advance Auto tax (Rad included in price)		10.10			
Pepboys tax (4/17)		3.23			
Home Depot tax		0.81			
Lowes tax		0.52			
John Meyer Hardware		12.00			
Rubber sheet bushings	4		Thrust Mount		
Rubber hose 1" section	2		Thrust Mount		
4.25"x2"x1/2" bar steel	1		Corner brackets		
1" wood screws	50				
1/2" wood/metal screws	20				
zip ties	40				
#10 flat and lock washers	15				
#10 lock nuts	4				
1/4-20 lock nuts	31				
3/16 lock nuts	15				
Total Funds Spent:		$485.76			

9.15 Original Specifications

Mounting Design

- Support 100 lb static engine load at up to 4 G's
- Horizontal thrust link travel of less than 1/10 of an inch at full power
- Absorb 400 lbs of thrust with a safety factor of 2
- Design the rubber mounts to eliminate resonance between 2000 and 6000 rpm's
- Required inspection of mounting design every 800 hours of flight or better
- Allow one person to remove the engine from the fuselage in less than one hour with common tools

Cooling System Design

- Install a radiator with duct work capable of maintaining an engine temperature of 160^{o}F with ambient air temperatures at 110^{o}F at idle
- Incorporate a baffle system to control air flow through radiator
- Install baffle for redirecting radiator exhaust which produces noticeable temperature change within cabin in less than one minute

Exhaust System Design

- Design an exhaust system to maintain sound levels less then 85 dB at a 25m distance. (Assume pilots have ear protection)
- Incorporate exhaust system to withstand engine exhaust heat for four hours of continuous operation
- Require inspection every 100 hours

Instrumentation and Controls

- Provide controls for ignition, throttle and baffle system
- Provide operator feedback for engine temperature, fuel level, rpms and battery voltage all to within +/- 5% of nominal value.