

PENNSTATE



In response to the 2008 Annual AHS International
Student Design Competition – Undergraduate Category

SMART-COPTER: RAZOR RESCUE



*The Pennsylvania State University
Vertical Lift Research Center of Excellence
University Park, PA 16802*

REVISION HISTORY

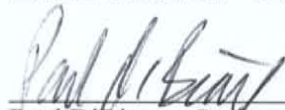
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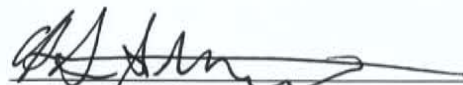
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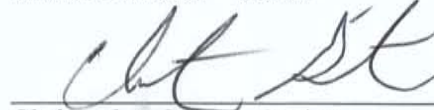
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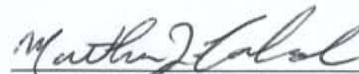
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All students received 5 hours of academic credit for participating in the 2008 AHS design competition. These credits were divided into two classes: AERSP 402A Helicopter Design - Preliminary and AERSP 402B Helicopter Design - Detailed.

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Dr. Joe Horn	Zihini Saribay	Mihir Mistry	David Maniaci
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RFP COMPLIANCE

Design Requirement	Razor Rescue Capability	Section
Military/Paramilitary/Public Missions	Three variants	12.0
Minimize Energy Consumption	Turbocompounded Diesel Engine	Throughout
Enhanced Safety	Very good autorotative capability, Fenestron, cockpit and cabin systems	7.7, 11.1.6
Reduced Noise	Low Tip Speed, Fenestron	14.0
Low maintenance	Overbuilt drive system, easy access to components, integrated HUMS system	Throughout
Takeoff within 10 minutes of being positioned on the heli-surface	Detailed startup procedure	5.5.1
Semi-automatic takeoff and landing system	Integrated avionics	9.0
Use by non-professional pilots	Integrated avionics	11.0
1 pilot, 4 passengers with luggage or 550 kg freight	Single pilot up front, 4 passengers in cabin	10.0, 17.0
Minimum internal volume 1.1m x 1.4 m x 1.0 m	Large passenger cabin	Foldout 2
HOGE 15min with MTOW @ 1500m ISA +20	Efficient rotor and engine, large fuel tanks	17.0
Minimum Cruise speed 100 kts	122 kt cruise speed	17.0
Range 300 nm	405 nm range	17.0
Comfort of Passengers should be equal to equivalent helicopter	Large cabin, noise and vibration reduction	11.1

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1.0 Introduction

"I always believed that the helicopter would be an outstanding vehicle for the greatest variety of life saving mission and now, near the close of my life, I have the satisfaction of knowing that this proved to be true."

The last letter written by Igor Sikorsky, October 25 1972 (1)

This proposal, in response to the Eurocopter sponsored 25th AHS Annual Student Design Competition, describes a small disaster relief rotorcraft that will save lives. Razor Rescue is designed to operate in congested or devastated areas where VTOL aircraft are the only feasible method of transporting people and/or material. Achieving an initial operational capability (IOC) in 2020, the helicopter has three main variants to prosecute all conceivable military, paramilitary and civil transport missions requiring short range and moderate speed. Primary emphasis was on the minimization of total energy consumption and pollution, from cradle to grave. Many aspects of the final design were tailored to increase flight efficiency or reduce manufacturing energy.

The design team worked to meet and exceed all specifications in the RFP, without sacrificing overall helicopter performance. The Razor Rescue uses state of the art technology to meet these demands with minimal energy consumption and pollution while maximizing aircraft utility. If produced, Razor Rescue would save countless lives by the timely transportation of injured people to medical facilities and supplies to areas devastated by tsunamis and earthquakes. Recent events in Myanmar and China emphasize the need for a vehicle of this type.

2.0 RFP Requirements

2.1 Size

The rotorcraft is only required to carry a pilot and four passengers (plus luggage), so the aircraft will fit into what is generally called the "light helicopter" category. Existing vehicles in this class include the Robinson R-44, the Eurocopter EC-120B Colibri and the MD-500 series. Gross weights are generally between 2000 and 4000 lbs.

2.2 Energy Consumption

The primary design objective is to minimize energy consumption throughout the lifespan of the aircraft. This includes manufacturing, operation and eventual helicopter disposal and recycling. In addition, total aircraft impact on the environment through pollution must be minimized.

2.3 Urban Environments

The aircraft will be used in urban environments, which requires the aircraft to employ various technologies to reduce its impact on residents. Reduced noise and enhanced safety, both in the air and in the event of a crash, are the most important design drivers. Other aspects, such as overall aircraft size and collision avoidance are also important to consider while operating in congested areas.

2.4 Missions

Missions detailed in RFP require the aircraft to assist in disaster relief or otherwise operate in areas with little aviation infrastructure. The aircraft will primarily be flying short range, medium speed (~ 120 kts) missions, but long range dash missions are important to ferry the aircraft to the disaster area.

2.5 Usability

Since the aircraft will be performing disaster relief missions, utility is of utmost importance. The helicopter might be required to transport supplies into the devastated region and then carry injured persons out of the area to a medical facility. A rotorcraft able to perform both of these missions (and more) without reconfiguration is more valuable to a customer.

Additionally, the RFP requires that the aircraft be used for Military, Para-military and Public transport missions. Therefore the basic airframe must be able to complete a wide variety of required missions. The primary difference between the three variants will be the avionics. Other, related systems, such as generators will also be tailored to fit each operator's requirements.

2.6 Non-Professional Pilot

The RFP states that the aircraft must be able to be flown by a non professional pilot. The design team interpreted this as the typical SMART-COPTER pilot would have flight training in rotorcraft. However, the pilot would not have the amount of experience as a professional pilot, such as one who flies medivac missions. This requirement entails a significant amount of automation and docile flight characteristics.

2.7 IOC 2020

The SMART-COPTER is designed for an initial operational capability (IOC) of 2020. This allows for the use of advanced technology. However, it takes a significant amount of time to certify a new aircraft. The team decided that a prototype first flight must be made by 2018, which requires the technology development of major components be completed by 2016. Therefore, only technologies judged to have a current TRL of 3 or higher were considered. As specified by NASA, this entails a working proof of concept of the technology (2).

3.0 Configuration Downselect

3.1 Configuration Evaluation

Many rotorcraft configurations could perform the missions required by the RFP. In order to begin the downselect process, a configuration selection matrix was created by rating concepts against primary and secondary RFP drivers. A weighting factor, from 0 – 1, was assigned to each driver based on its importance to the final design. Scores in each category were generated based upon available literature, design experience and team discussions. The primary configurations that were explored are included in Table 1.

Table 1: Configuration Selection Matrix

Driver	Weighting Factor	Conventional	Conventional - Fenestron	Conventional - NOTAR	Coaxial	Synchropter	Tip Powered	Tandem	Compound	Tilt Rotor
Cruise Efficiency (120 kts)	1	6	6	6	8	6	6	7	9	10
Hovering Efficiency	0.8	8	8	8	10	10	7	9	7	4
Ground Safety	0.9	6	8	9	8	5	8	8	6	5
Autorotation	0.7	8	8	8	7	7	8	6	6	2
Complexity	0.8	9	9	7	5	5	7	5	4	3
Utility	1	8	8	8	8	8	8	9	8	7
Propulsion Integration	1	8	8	7	7	7	10	6	6	6
Empty Weight Fraction	0.5	9	9	8	8	8	9	8	6	5
Cost	0.3	9	8	6	5	5	7	4	4	2
Compact Configuration	0.7	8	8	8	10	9	8	6	7	5
Loiter Endurance	0.6	8	8	8	8	8	8	8	8	4
Max Speed	0.3	4	5	5	3	4	4	6	7	10
Noise	0.8	6	8	9	5	5	1	6	6	6
Crosswind Performance	0.6	6	6	2	5	6	6	7	6	6
Score	100	73.8	77.2	72.8	72.3	67.8	70.6	69.6	65.8	54.9

Overall, the conventional (single main rotor and fenestron anti-torque device) scored the highest. Since other configurations scored almost as well, they were carried into the next design phase for further evaluation.

3.2 Initial Technology Evaluation

Significant technology advances will occur between the present date and the SMART-COPTER's IOC in 2020, so an evaluation of technology advances is required for the configuration downselect. This process was concerned with major technologies that will drive the rest of the design, such as unconventional propulsion systems.

3.3 Potential Configurations

The five top scoring configurations were integrated with the top scoring primary technologies for further evaluation. These configurations will be briefly discussed in the following sections.

3.3.1 Airfoil Tailboom

In order to provide increased flight efficiency through lower weight and drag, this configuration features a modified form of the NOTAR anti-torque system. NOTAR utilizes ejector slots and the Coanda Effect to turn the

main rotor downwash in order to create an anti-torque sideforce on the tailboom. This

system requires a compressor that has significant weight and diameter. In order to reduce the weight of the aircraft, this proposed configuration uses a tailboom with a highly cambered airfoil cross section to generate the required sideforce. Yaw control would be provided by engine bleed air vented at the end of the tailboom. In high speed flight, yaw control would be provided by movable tail surfaces powered by engine bleed air.

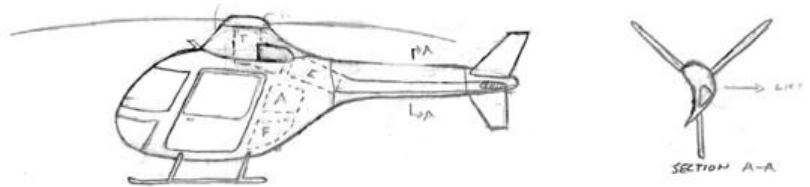


Figure 1: Airfoil Tailboom Design

Although this concept reduces the requirement for a large internal compressor, the design has some serious drawbacks. First, the tailboom would require careful design to efficiently convert the rotorwake into a sideforce. Since the wake is highly unsteady and varies significantly depending on flight condition, a variable camber or variable angle of attack would be necessary to successfully control the aircraft. Cross winds would also pose a problem for an inexperienced pilot. Actuators plus ducting in the tail would add significant weight back to the aircraft, resulting only in drag savings. At the low speeds that the SMART-COPTER is operating, this would not generate a large increase in fuel efficiency.

3.3.2 Coaxial

This configuration features contra rotating coaxial rotors that are common to most Kamov designs. Coaxial rotors increase low speed efficiency, important to the SMART-COPTER due to its disaster relief missions. In addition, the aircraft is compact and does not require an anti-torque device, important for safe operation from remote sites. The proposed configuration differs from previous aircraft by replacing the

complex swashplate system with servos that provide individual blade control built into each rotorhead. Two servos would be installed per blade, with each one optimized for a different activation frequency. A (relatively) low frequency servo would provide the equivalent cyclic and collective control while its counterpart, biased to a much higher frequency, would provide vibration control. These servos would increase the drag due to the hub by adding increasing the size of the hub, but would allow the blades to be mounted closer together because the individual blade control reduces the possibility of blade impact. The results in an overall drag reduction from a standard coaxial design.

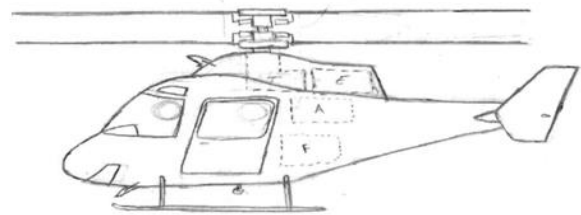


Figure 2: Coaxial Design

Although the coaxial design has benefits, it also has some flaws. Compared to a conventional helicopter, the aircraft is more complex, resulting in higher operational costs due to higher maintenance requirements. In addition, the contra

rotating rotors produce much more noise than a conventional helicopter, mainly because of blade vortex interaction. Finally, large vertical tails are required to control yaw during autorotation. This increases the tail weight, minimizing the benefits of not requiring a tail rotor.

3.3.3 Tip Powered

The tip powered configuration is the most unconventional, but it offers potential energy efficiency advantages. The aircraft will be lighter because there is no need for a heavy fuselage mounted engine and drive system. Additionally, there is no need for a tail rotor, which means additional weight savings. Yaw control would be provided by a control surface in the rotor wake. The biggest benefit is the fact that the aircraft would be insensitive to fuel selection because the rotor is driven by tip burners. Although they generally have high SFC's, exotic, but low polluting fuels, could easily be used.

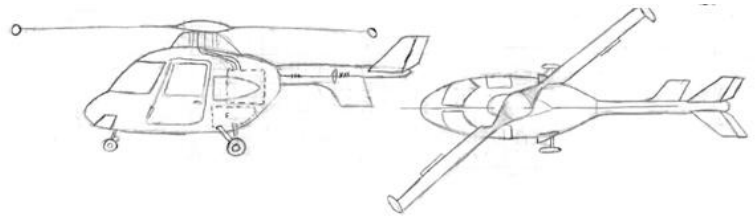


Figure 3: Tip Powered Design

The tip burners are also the source of the design's largest drawback, however. They generate unacceptably high noise signatures that has led to the cancellation of many aircraft contracts. Although significant work on mufflers is possible, this drawback alone was enough to prevent further consideration.

3.3.4 Rear Loading

The rear loading concept is primarily designed for utility and is essentially a scaled down MD-900. The large rear cargo doors allow for fast loading and unloading, important in a disaster relief mission. The presence of this door is the primary reason for the incorporation of a NOTAR system. This increases ground safety because there are no whirling tail rotor blades, which are nearly invisible, in the vicinity of ground crews.

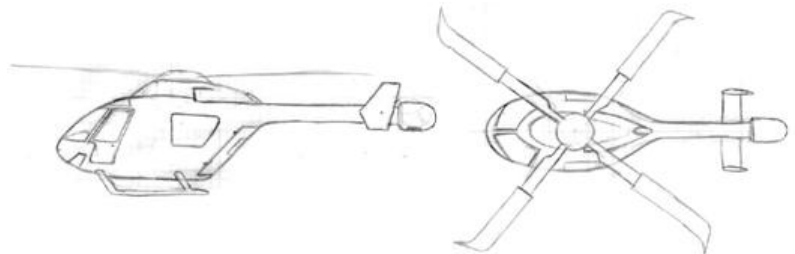


Figure 4: Rear Loading Design

Additionally, the aircraft features a variable diameter rotor, which significantly enhances flight efficiency. Combined with a variable speed transmission, the rotor would be able to operate at maximum efficiency throughout the flight envelope.

The rear loading door reduces aerodynamic efficiency, however. The large rear fuselage upsweep angle causes significant flow separation at high forward speeds, increasing parasite drag. In addition, the integration of the compressor for the NOTAR system would be difficult due to the placement of the door.

3.3.5 Fish

The final primary design iteration considered is a scaled up A160 Hummingbird. The design features a rather long fuselage to minimize drag by preventing flow separation. This large fuselage allows the installation of a diesel engine, which offers significantly lower SFC's than a comparable turbine engine. The diesel also has a wide RPM range, permitting the rotor to have a variable RPM rotor without requiring a variable speed transmission. In addition, the aircraft incorporates individual blade control in the form of trailing edge flaps. This reduces overall vehicle weight, vibration, and noise while increasing maneuverability.

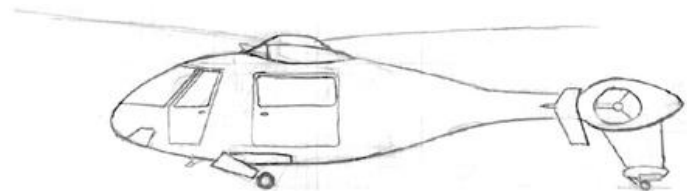


Figure 5: Fish Design

The primary drawback is the higher empty weight of the aircraft compared to similar aircraft. The large fuselage and diesel engine, which has a lower power density than a turbine, are the primary reasons for the higher weight. This requires the engine size to be increased, which in turn further increases the weight.

4.0 Primary Design Features

After comparing the various combinations of configurations and technology, the Fish concept was selected as the starting point for the final design, which agrees with the original concept downselect. However, various combinations of technologies were further traded off during detail design at the system level. A summary of final design features is provided below.

Engine: A 376 HP Opposing Piston Opposing Cylinder (OPOC) Turbo-Compounded Diesel Engine provides power for the Razor Rescue. This engine produces lower SFC's than a comparable turbine engine and will run on B20 biodiesel. The system is equipped with a Selective Reduction Catalyst unit for very low pollutions. A general overview was made for a possibility of being fuel by on hydrogen with an IOC of 2040.

Rotor: The Razor Rescue features an advanced variable speed rotor system controlled by trailing edge flaps with variable blade indexing. This allows for an overall reduction in power requirements and increases aircraft performance. Furthermore, rotor noise will be significantly lower than current aircraft.

Fuselage: The fuselage design of the helicopter was inspired by Boeing's A160 Hummingbird UAV. The long and thin fuselage has low drag through reduced flow separation. The fuselage is somewhat larger than other light helicopters to fit the large engine and because the design team strived to make the aircraft as utilitarian as possible. This utilitarian point of view dictated placing all four passengers in the cabin with only the pilot in the nose, to maximize the cabin space.

Anti Torque: Razor Rescue uses a fenestron anti-torque device because it is safer and less noisy than a conventional tail rotor. Additionally, this device also offers higher control power than a NOTAR based system, important for non-professional pilots.

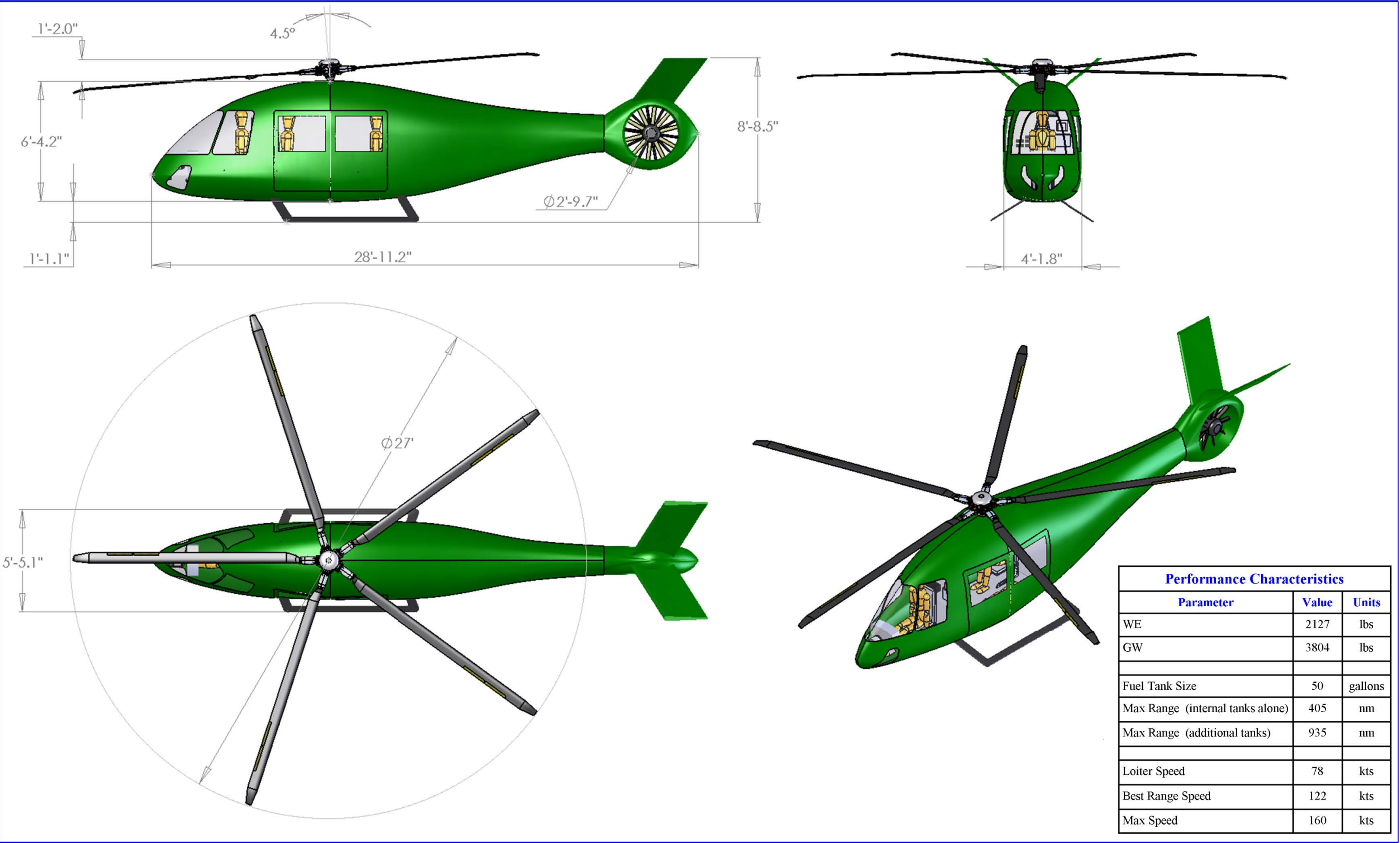
5.0 Propulsion

All Razor Rescue versions are installed with an opposed piston opposed cylinder turbocompound diesel engine that operates on B20 fuel with 20% biodiesel with 80% ultra low sulfur diesel (ULSD). The engine is capable of delivering 376.6 hp uninstalled at ISA SSL and 348.1 hp at ISA +20°C at an altitude of 1500m. The OPOC turbocompound diesel engine was chosen due to its low fuel consumption in operation while retaining the ability to vary rotor rpm. This engine is a result from intense research in advanced diesel engines and coming across FEV Engine Technology, Inc and Scania engine technologies. The design is FEV's OPOC diesel engine as the core with addition to Scania's turbocompound technology. Key features include a lightweight structure at 240 pounds while having have a .33 SFC. Other notables are no ignition system required, a FADEC fuel control system, and Selective Catalyst Reduction system.

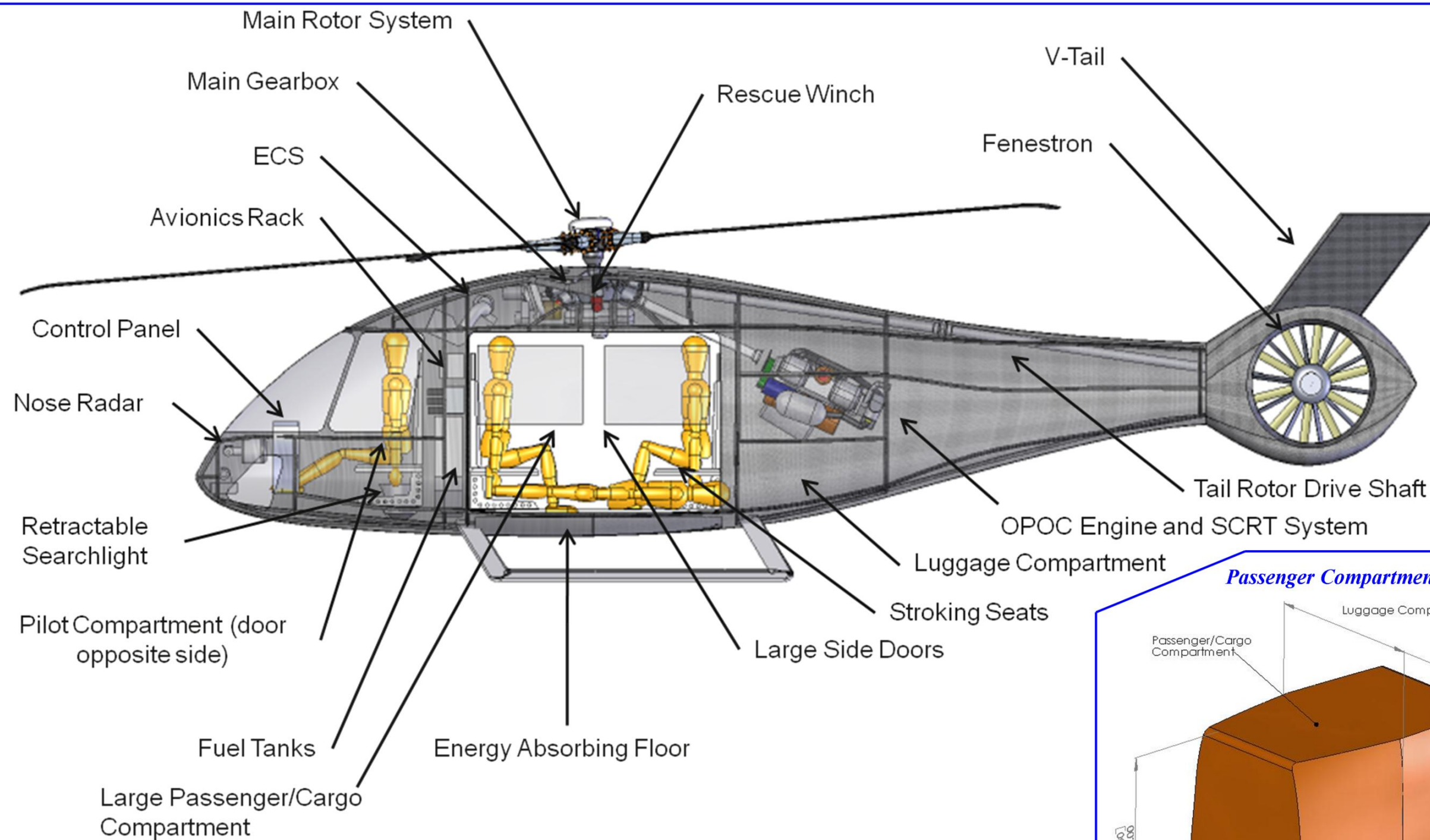
5.1 Engine Concept Selection

Reaching a decision on the OPOC turbocompound diesel for the engine design required research in all power sources. The RFP wanted a green design that was safe to environment in production, operation, and recycling. One important technical design taken into account was source of fuel whether it was kerosene, petroleum, electricity, or hydrogen. The RFP also asked to make comparison to EC120, R22, and R44, which were all powered by turboshaft engines. However, this engine does not need to be operable until 2020, so there is some room for future research and development.

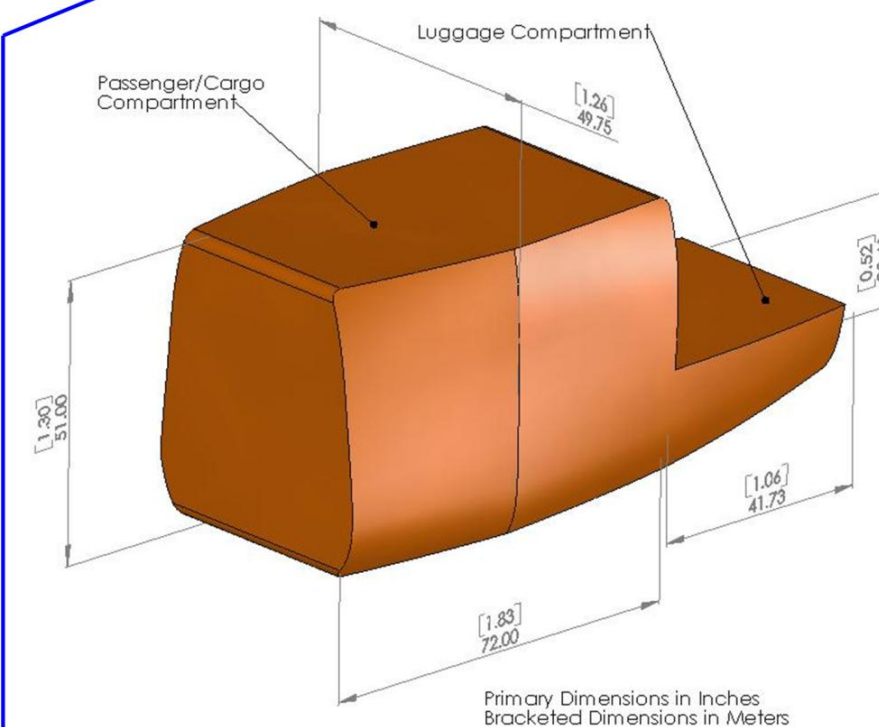
Foldout 1: Razor Rescue 4-View



Foldout 2: Razor Rescue Inboard Profile



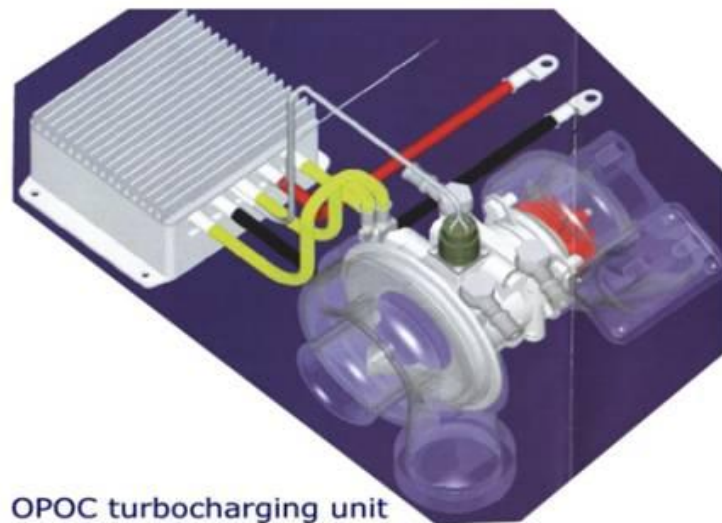
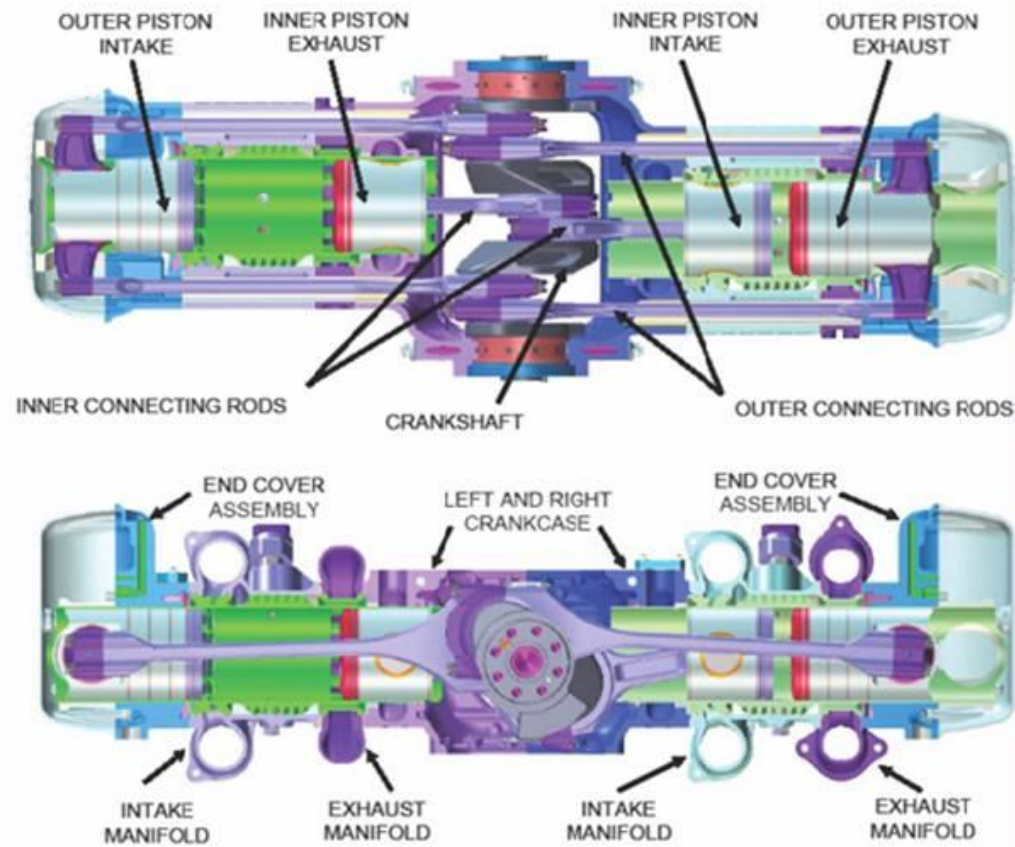
Passenger Compartment Dimensions



Foldout 3: Razor Rescue Propulsion

OPOC Diesel

Opposed Piston Layout



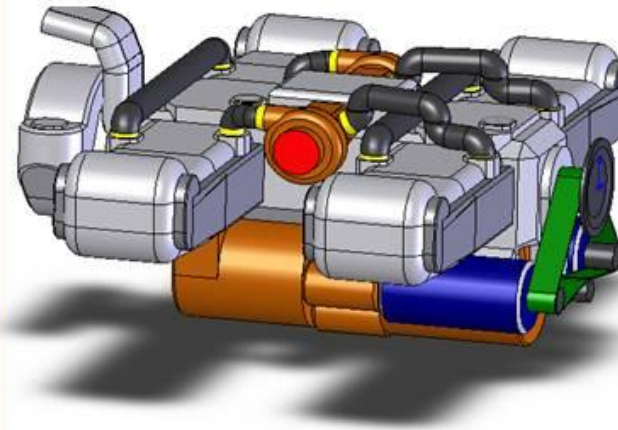
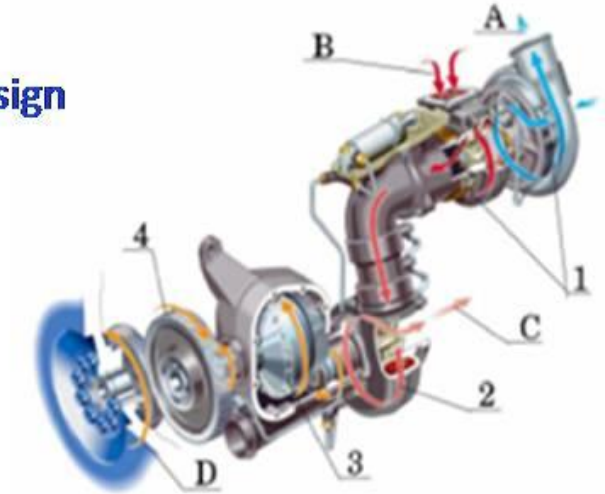
Turbocompounding

Turbocompound Design

1. Turbo-compressor
2. Power turbine
3. Hydrokinetic clutch
4. Toothed gear

Functioning of this system:

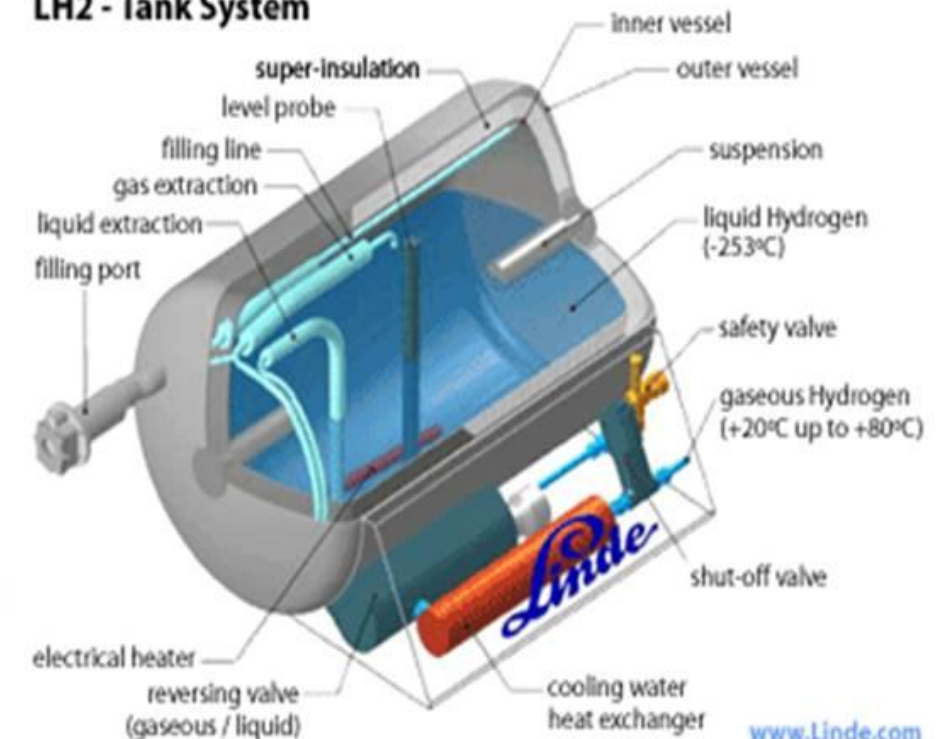
- A. Air is pressed by the compressor into the supercharged air cooler.
- B. Exhaust gases blown on to the turbine blades undergo cooling and expansion giving away a part of its energy.
- C. Exhaust gases, having passed the traditional turbo-compressor flow on to the power turbine where they still lose a part of energy.
- D. Energy recovered from exhaust gases is transmitted by the gear system on to the crankshaft of the engine.



OPOC Diesel with Turbocompounding

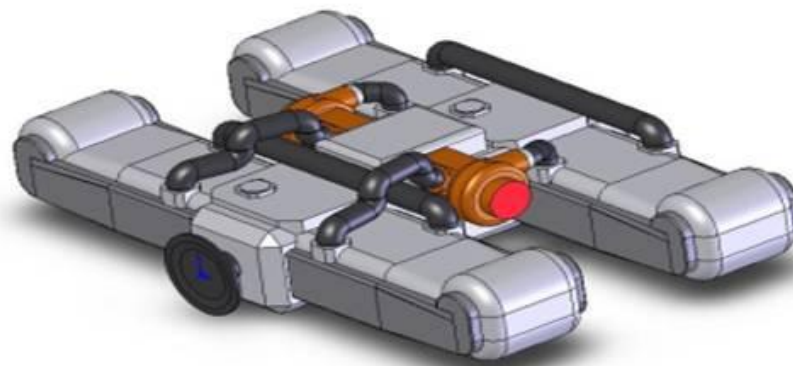
Hydrogen Tank

LH2 - Tank System



www.Linde.com

Diesel Core 3-D view



5.1.1 Gas Turbine

Gas turbines are the most popular of propulsion system for helicopters of our size. However, it has relatively high specific fuel consumption (SFC). A higher SFC will need more fuel to complete a mission resulting in more pollution. Jet A fuel sources will be rapidly diminishing by 2020. Figure 6 display a comparison of fuel consumption and mission fuel weight with diesel and turboshaft engines.

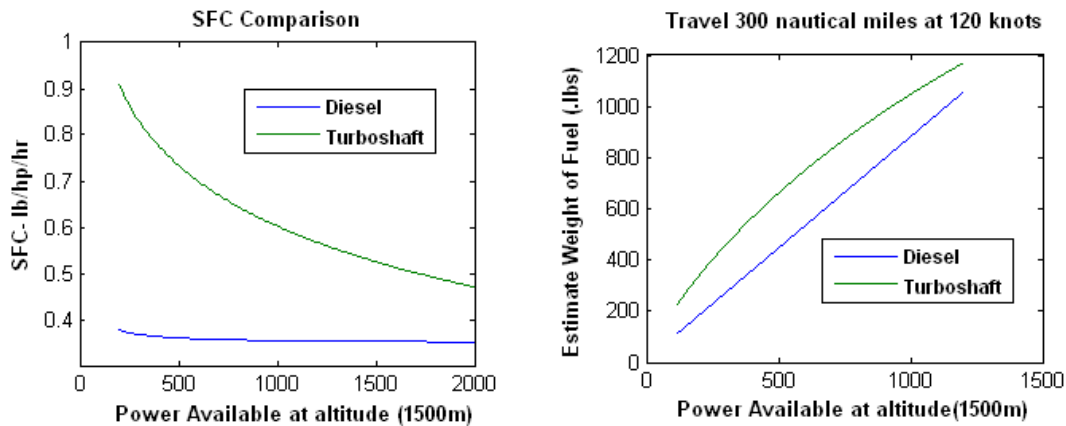


Figure 6: Diesel & Turboshaft Comparison

5.1.2 Electric

An electric propulsion system is tempting with its zero pollution that also has high power ranges. Unfortunately, electric systems are dependent upon batteries, which are a high source of pollution in production. Batteries also require long charging times and have short operating ranges limiting a helicopter's range. Lithium polymer batteries are currently the most powerful and energy dense batteries on the market and by 2020 would still require over a thousand pounds of battery to complete a normal mission as shown in Figure 7. However, more batteries would be required to fulfill the mission requirement after taking into account the loss distance from the original battery weight.

5.1.3 Diesel

Diesel has a promising outlook for future rotorcraft propulsion systems. Manufacturing has recently increased with diesel due to their low SFC. Research is growing to increase power to weight ratios of diesel engines(3). Diesels also have the advantage over gas turbines by being able to run on biodiesel with minimal performance effects. A diesel engine with a few changes is a top choice for 2020 operational capability.

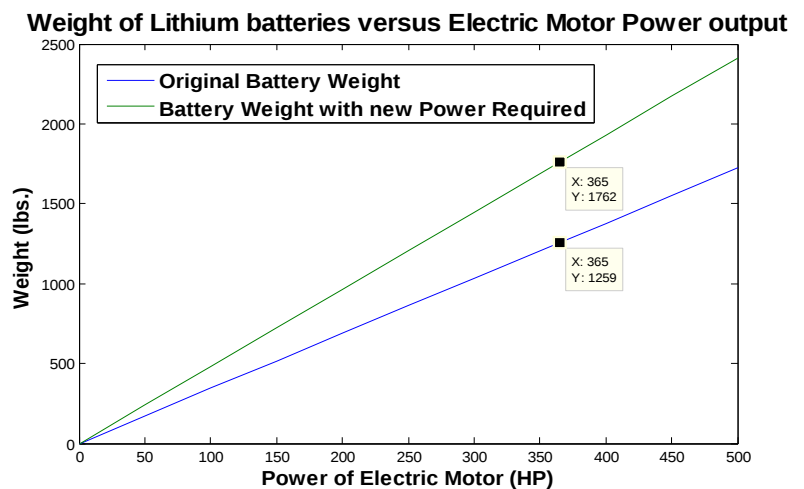


Figure 7: Battery Weight Estimation for Mission

5.1.4 Hybrid

A hybrid has the advantage of using a smaller propulsion system such as diesel or turboshaft combined with electric power. Research is currently high for advanced hybrid automobiles. Hybrid propulsion has advantages because they use electric power for the bulk of a mission. Then, they use auxiliary power for power boosts. Bulk of our helicopter mission requires a estimated minimum of 250 hp at cruise speed, which correlates to 800 pounds of battery weight.

For this reason, a hybrid propulsion system for a helicopter is not feasible for 2020 until specific power of batteries drastically improve.

5.1.5 Fuel Cell

Fuel Cells have a strong possibility in the future. They emit relatively no emissions when in operation. They run on hydrogen and can produce high power ranges. However, fuel cells technology is still in development stage and is not feasible by the year 2020. Currently, they have short life spans and almost no fueling infrastructure.

5.2 Propulsion Design

The propulsion system is focused on an opposed piston diesel turbocompound engine shown in Foldout 3. Its primary ability is to produce high power with low specific fuel consumption. It was modeled off the turbomachinery system implemented by Scania turbocompound technology.

5.2.1 Opposed Piston Opposed Cylinder (OPOC) Diesel

The most important problem of diesel engines is their poor power density (hp/lb). FEV Engine Technology, Inc was able to counter this problem with multiple solutions. Their developing OPOC engine technology has emphasis on precise combustion control, proper cylinder scavenging, high-efficiency, high-EGR dilution, low vibration, low weight, small packaging volume, and manufacturing cost reduction (4). All of these solutions help reduce emissions, weight, manufacturing costs, but increase performance at the same time.

The OPOC engine is a two-stroke engine, having opposed cylinders. All pistons are connected to a single crankshaft, located between the two opposed cylinders, by unconventional connecting rods as seen in Foldout 3. The volume formed between the two opposed pistons is the combustion chamber, and on top of them is a strategically placed fuel injector. Intake and exhaust ports are located at the ends of the combustion chamber. These positions, in conjunction with an electrically assisted turbocharger, provide the means for cylinder scavenging (there are no valves or camshafts).

Optimal scavenging helps the engine achieve almost perfect combustion. This is achieved by utilizing uniflow scavenging, controlled boost pressure, pulse turbocharging, and asymmetric intake and exhaust timing. The innovative controlled boost pressure technology, exhaust gas recirculation rates are expected to be high. The uniflow scavenging minimizes the mixing of exhaust gas and intake air and creates maximum combustion. It is achieved through the opposed piston, which allows for the highest level of volume efficiency. Asymmetric timing is achieved by splitting the crankshaft throws for each cylinder. It also helps with accomplishing supercharge scavenging process described previously.

The electrically assisted turbocharger is an integral subcomponent of the OPOC engine. It optimizes scavenging and increases EGR rates, which help reduce NOx emissions. It will also be capable of monitoring and maintaining a constant air fuel ratio. Before starting the engine, the turbocharger compresses and recycles air in order to heat it to 100°C in less than one second to ensure easy start in cold weather. Compression ratios are in range of 15-16:1, resulting in reduced fuel consumption and NOx emissions.

The OPOC diesel engine has the advantage of requiring 25% fewer parts than a conventional diesel engine. This reduces overall engine weight, maintenance, and friction. Fewer parts would also reduce manufacturing costs. Another advantage is the OPOC achieves a total balance with only two cylinders. A larger engine required by the Razor Rescue would only need two small engines placed side-by-side and coupling their crankshafts, allowing pairs of cylinders to be uncoupled when not needed at low loads(4).

5.2.2 Turbocompound

Turbocompounding, relatively new to practical applications such as diesel trucks, is a very feasible possibility of 2020. All it means is the introduction of a power turbine downstream of the turbocharger. Turbocompounding works by recovering energy of wasted exhausts. Instead of the exhaust gas from the diesel combustion being expelled, more

heat is extracted from the exhaust gases by a second exhaust turbine downstream from the turbocharger. The second turbo spins at 55,000 RPM. This motion is passed through turbine gears and a hydraulic coupling, then through the timing gears to the crankshaft. Stepping down the revs produces an extra boost in torque without having to increase fuel consumption. This allows the engine to reach a wide range of speeds and helping to even out the fluctuating pressures induced by combustion. In other words, the engine runs more smoothly. In addition, the extra power allows the diesel core to be sized down further reducing overall engine weight (5).

5.2.3 Fuel System

The fuel tanks will be placed between cockpit and the cabin. It will be above the crash structure for extra safety and protection from accidents. Each fuel tank holds a maximum of 25 gallons of B20 fuel. Although, it appears to be one fuel tank, there is a divider within with a two-way valve. The two-way valve is for balancing of the fuel weight and so the location for fuel pumping will be placed on one side of the helicopter. The fuel tank is made out of Toray M35J carbon composite with Kevlar coating and special flame retardant outer coating resistant to numerous chemicals(6).

There is one electric boost pump inside each tank, which pumps continuously as long as there is fuel in the tank. The fuel is pumped into two common supply hoses that run up and over the cabin. There is fuel filter within each supply line to rid of contaminants in the fuel. If the filter were to become clog, the fuel would travel through a bypass valve and proceed unfiltered to the engine. There is also a fuel shut-off to stop fuel flow in case of emergencies. Because the fuel flow will be monitored and controlled by FADEC system, there is a possibility of excess fuel, which will flow back to the fuel tank via a purge line. After passing through these points, the fuel will proceed to the fuel injectors and travel into the cylinders of the OPOC turbocompound diesel engine.

5.3 Diesel Engine Fuel Selection

The purpose of fuel selection was to choose a fuel that would be minimal in pollution. All fuels differ in the energy content and densities. Figure 8 displays the energy content per US gallon of possible fuels to be implemented in the helicopter.

5.3.1 Petroleum (Regular Diesel)

Currently, most diesel engines run on petroleum gas. It has the highest specific energy content of the choice of fuels and it is already mass refined. Hence, energy to produce petroleum is relatively low compared to alternative fuels. However, petroleum has the highest particulate matter. In addition, the recent price fluctuations and vulnerability of petroleum sources for transportation are pushing the need for synthetic fuels.

5.3.2 Ultra Low Sulfur Diesel

Due to tough diesel emissions standards set by the U.S. Environmental Protection Agency, petroleum refiners are producing Ultra-Low Sulfur Diesel (ULSD). ULSD is a cleaner diesel fuel that has a 95% sulfur reduction. In addition, this low sulfur diesel protects the function of catalytic converters, oxidation catalysts, and/or units like Selective Catalyst Reduction (SCR). However, reducing sulfur decreases the lubricity of the fuel but can be fixed with proper blend with another alternative fuel.

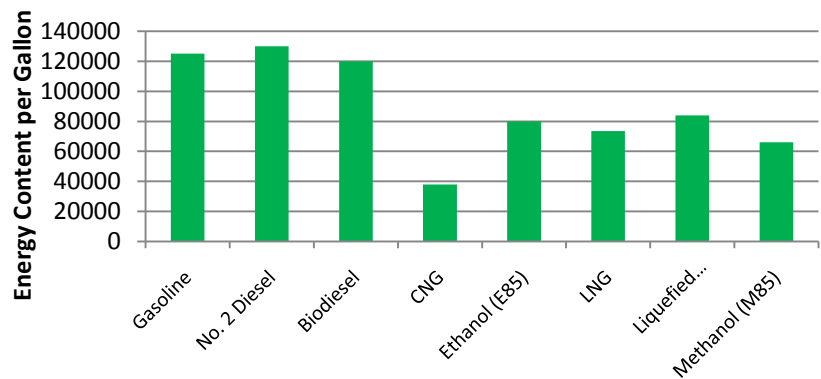


Figure 8: Energy Content of Various Fuels

5.3.3 Synthetic Fuel (Coal-Derived)

Synthetic jet fuels are manufactured, using a Fischer-Tropsch process, from coal, natural gas or other hydrocarbon feedstocks. The advantages of these fuels are that they are cleaner burning fuels with no sulfur and higher thermal stability. Fischer-Tropsch fuels have excellent low-temperature properties, maintaining a low viscosity at lower

ambient temperatures. This would improve high-altitude and possibly low-temperature operability of our helicopter. Because this process could make fuel sources such as coal, it would lessen our dependence on oil reserves in the Middle East. Unfortunately, large quantities of energy are used up to produce synthetic fuels. Approximately, 1.8 times more CO₂ is released into the atmosphere over its lifetime compared to regular petroleum (7). Another disadvantage for synthetic fuels are their energy content. As seen in Figure 8, synthetic fuels or LNG have 40% less energy content than regular diesel. This would require 40% more fuel to carry. Synthetic fuel is also less dense than gasoline or diesel so the 40% more fuel would also take up more volume.

5.3.4 Biodiesel

Biodiesel or bio-mass are made from natural products such as corn, nuts, rapeseeds, soybeans. It makes the fuel a renewable energy source because the source can be reproduced unlike oil. Pure biodiesel has disadvantages of high freezing points and poor high thermal stability characteristics. This can be fixed by having appropriate blends of biodiesel. B20, or 20% biodiesel mixed with 80% ULSD, will have almost equal specific energy content as regular diesel. Biodiesel also has a promising feedstock known as algae, which U.S. Department of Energy projects this feedstock to produce 150-300 times more oil than a crop of soybeans. This would stop the problems of having to give up food supplies for an energy source. Looking at Figure 8, biodiesel has about 99% the energy content of regular diesel and would only take 1% more fuel to accomplish the same mission.

5.3.5 Hydrogen

Hydrogen as a power source is very promising for helicopters. It has minimal pollution with very high-energy content. Once obstacles of storage and volume of hydrogen tanks are solved, no other propulsion system compares. 2020 feasibility is very unlikely with manufacturing problems though. A 2040 IOC will broadly be examined for a hydrogen-powered version of our helicopter.

5.4 OPOC Turbocompound Performance

The performance of the engine was modeled using a mixture of trending sizes and engine equations. Fuel, torque, and power curves were computer simulated for overall mission analysis. A lot of research has gone into compound engines and contributed to optimally model the Razor Rescue's engine.

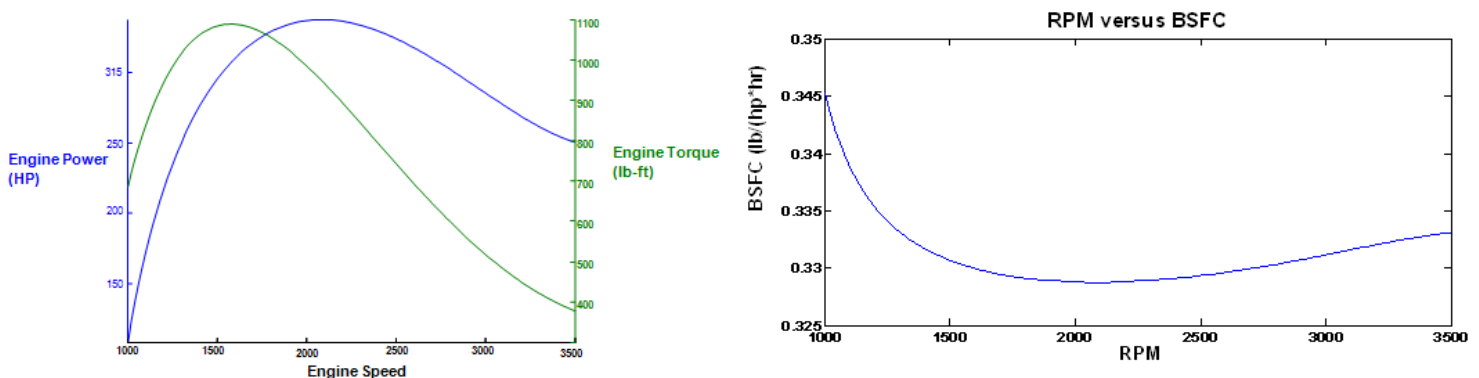


Figure 9: Engine Power, Torque, & SFC

Once inputting a permanent cylinder displacement of 225.7 in³, the total torque & horsepower versus engine speed curve was calculated and shown in Figure 9: Engine Power, Torque, & SFC. Horsepower, torque, and engine speed were modeled from these equations:

$$\text{Torque} = \frac{\text{BMEP} * \text{Cubic Displacement}}{75.4} \quad \text{for 2 Stroke Diesel}$$

Equation 1

$$\text{Horsepower} = \frac{\text{RPM} * \text{Torque}}{5252}$$

Equation 2

This helps analyze the drive system to know how to gear to the rotor hub. This matches closely to trend curves of other compound engines. The max torque of 1080 lb-ft occurs at 1500 RPM compared to max Power of 376.6 hp occurring at 2080 RPM.

Figure 9 displays a graph of specific fuel consumption versus engine's speed at 1500m ISA + 20°C. It ranges approximately from .329 to $.345 \frac{\text{lb}}{\text{hp-hr}}$. The fuel consumption is lowest at engine speed where the designed maximum power is 376.6 hp. There is very small change of the SFC because of turbo compounding and the added power without the cost of extra fuel. This will give the Razor Rescue a high-speed range for the rotor with very good performance (9).

The OPOC diesel turbo compound engine was sized using a set of equations that used trend data to size the components that went into this engine. The equation is slightly modified from Reference (10) for Razor Rescue's engine because of the fact it is opposed piston and uses 25% less parts resulting in a quarter less weight. The overall weight of the engine was calculated to be about 240 pounds. This was a 10% improvement of weight from the original diesel core sizing before the adding of the turbocompounding.

Table 2: Razor Rescue Engine Characteristics

Maximum Power	376.6	HP
Torque @ Max. Power	950.3	lb*ft
Engine Output Speed	2080	RPM
Airflow Intake	1.422	lb/s
Fuel Flow	0.03442	lb/s
SFC	0.329	lbs/(hp*hr)
Exhaust flow	1.022	lb/s
Intake Temperature	267	Celsius
Exhaust Temperature	500	Celsius
Bore	4	inches
Stroke	4.5	inches

Table 2 shows the engines basic characteristics and best possible performance. Some of the data like intake and exhaust temperatures were found through the help of general thermodynamic assumptions, engine trend data, and basic relationship equations from above.

5.5 Operation

The OPOC turbocompound diesel engine is designed to operate at full engine power. This permits the engine to run at maximum efficiency top speed. There is a FADEC system controlling and monitoring the engine. Items that will be monitored by FADEC are air/fuel ratio, exhaust gas recirculation, electric turbocharger, power turbine, temperature and the exhaust gas system. It will optimally change these items based on the cyclic and collective inputs made from the pilot or systems control. However, the FADEC will also limit the operation to prevent any overheating or over engine speeding, and a warning to the pilot will be display on the control panel.

5.5.1 Starting

Diesel engines often have trouble starting in cold weather. There are also concerns of B20 possibly gelling at low temperatures. The system implemented for overcoming these possible startup problems will consist of using the electric turbocharger, powered by an auxiliary power unit, with the combustor as generator to provide hot pressurized gas to the power turbine. It requires the insertion of valves to have air inflow bypass the diesel core to the turbocharger. A tiny combustor will also be installed on to the turbocharger to provide energy for cranking. The turbocharger will be able to crank the shaft to a minimum starting point where the combustor is ignited and hot gases

flow to the power turbine. Then, the power turbine will be able to transfer a large amount of torque to output shaft of the diesel core. This will reduce any startup problems(10).

Table 3: Takeoff Timeline

	Task Time (min)	Total Elapsed Time at Completion (min)
Exterior Inspection	2.0	2.0
Cockpit Inspection	2.0	4.0
Start Engine	0.5	4.5
HUMS Analysis	1.0	5.5
Radio and Navigation Settings	1.0	6.5
Oil and Fuel Pressure Buildup/Warmup	1.0	7.5
Appropriate Engine RPM reached	1.5	8.5
Take-off		8.75 min

5.5.2 Emergency

If the turbomachinery of the turbocompound were to fail, there will still be power produced from the diesel core. However, without a turbocharger, power output will be low. This power will not be enough to fulfill most mission requirements but should be able to provide enough time to find a safe landing spot(10). Also, if one of the diesel core engines were to fail, there will still be power output from the engine. There would even be enough to fulfill some small mission requirements. It would be recommended to return to the home base. Any malfunctions and/or ballistic damage to the fuel system, the FADEC will see observe uncontrollable change in flow and will warn the cockpit of danger. However, there are two tanks and fuel lines and one would be enough to supply fuel to the engine.

5.6 Hydrogen 2040 Option

It is understandable that petroleum will not be the source of energy in the long term. The current problem is a weak infrastructure of hydrogen production, transportation, and storage. On top of that, considerations must be placed for locations to store hydrogen in aircraft. It is estimated that by 2040, there will be strong hydrogen system in place. Also, a miniature liquid hydrogen plant could be at the airports holding the Razor Rescue just by taking the hydrogen from the air and compressing it into liquid.

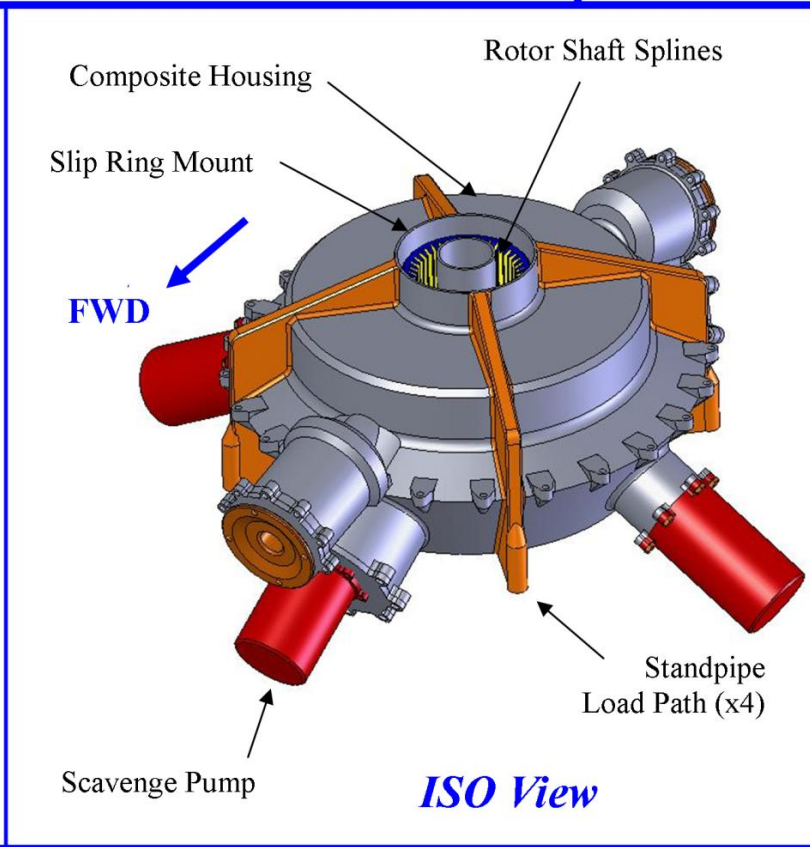
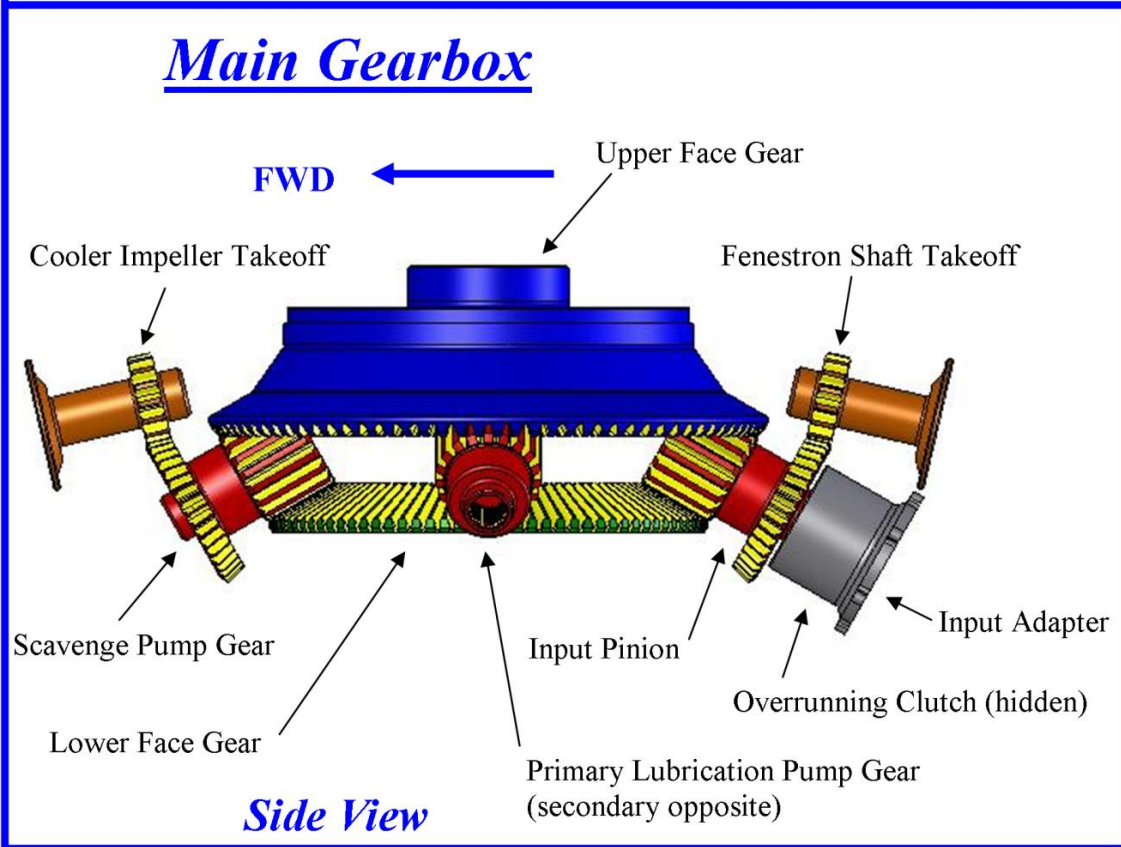
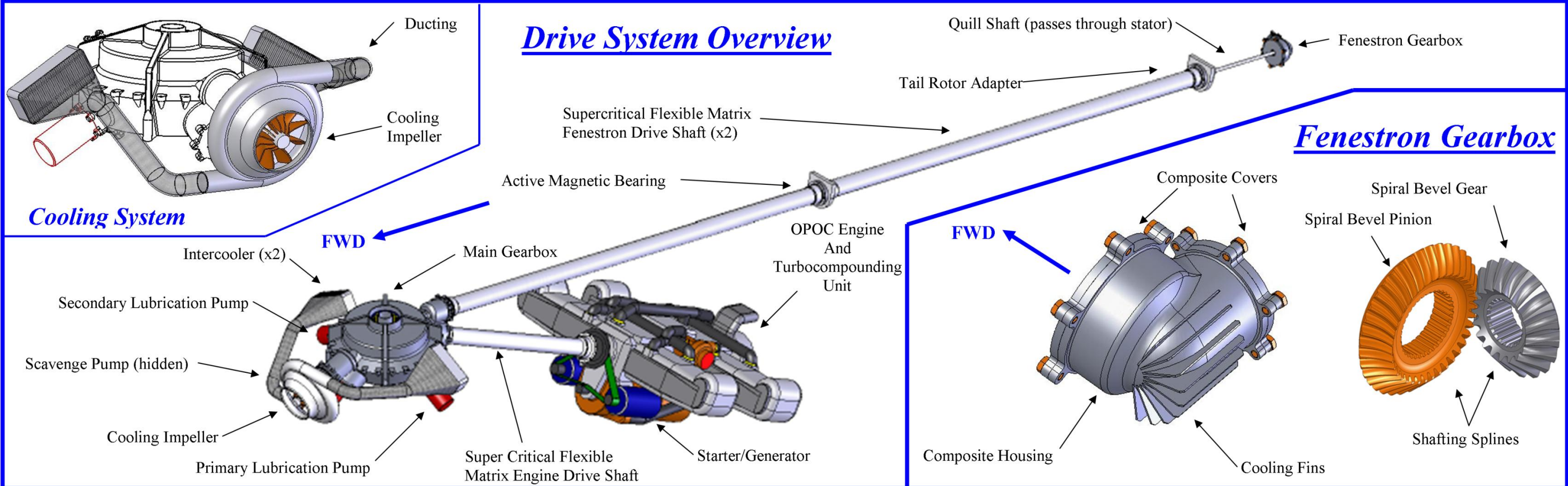
Fortunately, the OPOC diesel turbocompound engine will be able to run on hydrogen with a minimal change to the engine. Research has shown possible improvements in performance characteristics with hydrogen fuel while operating at near zero emissions(11). The only emission will be water.

The 2040 option will use liquid hydrogen for storage to save volume space and forgo any possible changes in the fuselage structure. The design of the fuel system is modeled off of a tank from Linde, shown in Foldout 3

The volume of the liquid hydrogen needed is approximately 24.15 ft³ and that weighs 106 lbs. Using carbon composite material and factor of safety of 2.25, the mass of the tank is 14.7537 lbs.(12). This puts the total hydrogen fuel tank weight at 120 lbs, which is 150 lbs less weight than the biodiesel fuel. Hydrogen fuel would also not require any SCRT system or urea tank, which would decrease weight by another 100 lbs. One problem with liquid hydrogen storage is that there is a 1% boil off per day that would increase with multiple tanks, so the Razor Rescue would have one larger tank for efficiency (11). The storage tank would be surrounded by 6 inches of Mylar insulation foam to increase storage efficiency.

Overall, the total mass is approximately 250 pounds less weight than the biodiesel fuel system. The overall weight of the helicopter would decrease, so the overall performance would ultimately increase with the benefits of near zero pollution(11).

Foldout 4: Razor Rescue Drive System



Gear	Pitch Dia (inches)	Teeth	Face Width (inches)	RPM (in hover)	Reduction Ratio
Input Pinion	3.0	19	2.4	2080	4.91
Upper Face Gear	14.14	93	2.4	424	
Lower Face Gear	14.14	93	2.4	424	
Lubrication Pump 1	3.0	19	2.4	2080	
Lubrication Pump 2	3.0	19	2.4	2080	
Scavenge Pump	3.0	19	2.4	2080	
Cooler Pinion	4.7	39	0.75	2080	0.59 (increase)
Cooler Gear	2.76	22	0.75	3536	
Fenestron Shaft Pinion	4.7	39	0.75	2080	0.59 (increase)
Fenestron Shaft Gear	2.76	22	0.75	3536	
Fenestron Hub Pinion	4.0	27	0.85	3536	0.78 (increase)
Fenestron Hub Gear	3.2	39	0.85	4500	

6.0 Drive System Design

6.1 Requirements

The drive system transfers power from the engine to the main rotor, fenestron and auxiliaries. The primary design driver was overall system efficiency, but consideration was given to system simplicity, form factor, weight and maintenance. There is the additional design requirement of interfacing with a diesel engine, which has a different rpm and torque profile than turbine engines. The diesel engine has a wide HP/rpm range, so a variable speed rotor can be implemented without the incorporation of a variable speed transmission.

6.2 Initial Configuration: Balancing Pinions

One transmission type currently utilized is a split torque configuration, which transfers power to the output shaft through multiple load paths to a single large bull gear. This concept was selected for the Razor Rescue because it provides high ratio of speed reduction at the final stage, fewer reduction stages, lower energy losses and fewer gears and bearings(13). The difficulty lies in achieving an even torque split among the load paths. This problem is potentially solved by incorporating a balancing mechanism to the input pinions (14). This ensures that each pinion is transferring half of the engine torque to the bull gear. This configuration was attractive for the Razor Rescue because of its thin form factor, allowing it to easily fit above the passenger cabin. The balancing pinions would reduce vibrations by continually adjusting to the varying torque loads. This has the additional benefit of increasing fatigue life of the transmission and rest of the aircraft. This configuration, however, has some flaws when applied to the Razor Rescue. The optimal arrangement of the pinions reduces the spacing between the connection shaft and the rotor shaft (14), placing a significant part of the drive system into the passenger cabin. Adding an angled connection shaft would improve mounting flexibility, but would add more stages to an already complex system.

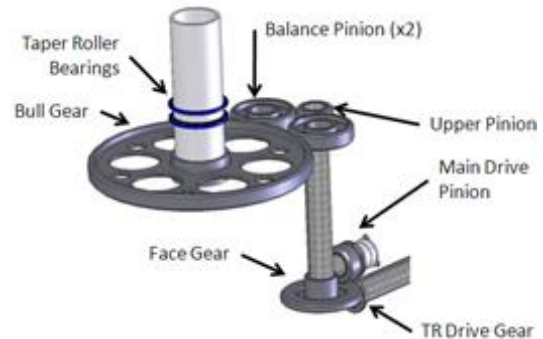


Figure 10: Initial Transmission Config.

6.3 Final Configuration: Split Torque Face Gear (STFG)

Due to the mounting difficulties, a new transmission concept was needed. A face gear arrangement was ultimately selected because it retained the positive aspects of the Bull Gear configuration, but has more mounting flexibility. Torque is split between two concentric face gears, which can be arranged to accept input from a variety of angles without the need for a balancing mechanism.

This use of face gearing in a helicopter transmission was first proposed by the McDonnell Douglas Helicopter Company in an Advanced Rotorcraft Transmission Report in 1993 (15). During Boeing testing of a proof of concept gearbox, torque was shared almost equally between the face gears, with the upper carrying 48% of the load (16). Furthermore, other tests performed by NASA Glenn and Boeing have demonstrated the feasibility of face gears (17) (18). Overall, the advantages face gears offer in torque splitting arrangements, high ratio capability, and strength will provide the motivation to bring this technology to its full fruition (19).

The STFG has only one stage, reducing weight and complexity by eliminating many parts. Foldout 4 shows the main components of the face gear transmission. Power is supplied by the engine to the input adapter via an extension shaft. It contains two redundant sprag overrunning clutches that disconnect the engine from the drive system in case of an engine failure. These clutches connect the input adapter to input pinion, which has two gearing meshes. The primary is the face gear mesh, where it interfaces with the upper and lower face gears. This drives the main rotor shaft, which is connected to the upper face gear via splines. Tapered roller bearings react the thrust loads. The input pinion's second mesh drives the tail rotor, which requires an rpm increase. The first stage occurs at the input pinion/tail rotor output mesh and the second occurs in the fenestron hub.

Finally, three gears are mounted at 90° intervals around the azimuth of the upper and lower face gears. They spread the torque load onto the face gears and provide outputs for the auxiliary components. The two gears perpendicular to the input pinion drive the primary and secondary lubrication pumps, while the remaining gear drives both the scavenge pump and oil cooling/ECS impeller.

6.4 Fenestron Gearbox

The fenestron gearbox consists of a simple 90° direction change and rpm increase. Spiral bevel gears are used to increase contact ratios while reducing gear fatigue and noise.

6.5 Stress Analysis

Foldout 4 details basic gear properties. The main drive gears are manufactured from AISI 9310 high-alloy steel, a Grade 2 material. Auxiliary gears are manufactured from a Grade 1 material, carburized AISI 9310 steel. These materials have been proven to be relatively easy to manufacture and give high performance over their useful life. Tooth numbers of each pinion and gear in a mesh were carefully selected to be a hunting ratio. This ensures that each pinion tooth meshes with each other gear tooth before meshing with any tooth twice and promotes even wear over time. Hunting ratios dictated a two stage increase in rpm from the engine to the fenestron.

The gears were designed according to AGMA standards, primarily following the guidelines of Dudley (20). All components were designed for a minimum life of 6500 hours with a 25% margin of safety using guidelines for tooth contact and bending stresses established by AGMA 411.02 (21). All gears have a 20° pressure angle and are sized in the hover condition, where the engine is producing the most power and torque. In general, the gears are substantially oversized, especially in regards to face width. This is designed to reduce the number of overhauls and gear wear. Although this incurs a weight penalty, the lack of infrastructure in Razor Rescue's operational environment may preclude major maintenance facilities. Over sizing the drive system also allows propulsion growth in later versions of the aircraft. Table 4 gives these values.

Table 4: Stress Limits

Stress Cycles	Bending Stress (psi)		Contact Stress (psi)	
	Grade 1	Grade 2	Grade 1	Grade 2
10^8	60,000	51,000	197,000	175,000
10^9	55,000	47,000	173,000	155,000

There are no substantiated stress formulas available for sizing face gear sets in the same manner as traditional bevel or spur gear sets (19). Modification to current spur gear analysis and finite element methods used to calculate contact and bending stresses have shown that the pinion is the weaker of the two gears in the set (19). Furthermore, the spur pinion in a face gear set has approximately a third less tooth bending stress than if it was installed in a standard spur set under the same loading conditions (19). Therefore, only the input pinion was completely analyzed in the primary mesh.

The tail rotor drive train spiral bevel gears were sized and analyzed using a procedure detailed by Saribay (22). Since the cooler drive mesh utilizes the same gear geometry as the tail rotor drive, but transmits much lower horsepower, the mesh is assumed to have a longer life and is not analyzed.

Table 5: Gear Stress Results

Stage	HP	$S_t (x 10^4)$ Bending Stress	$S_c (x 10^5)$ Contact Stress
Input Pinion	175	4.0836	1.3896
Upper Face Gear	175	5.7455	0.6526
Lower Face Gear	175	5.7455	0.6526
Lube Pump 1	4	0.1909	0.4650
Lube Pump 2	4	0.1909	0.4650
Scavenge Pump	10	0.4773	0.7414
TR Drive Pinion	40	11265	1.0347
TR Drive Gear	40	11419	1.3612
TR Fenestron Pinion	40	13456	1.4652
TR Fenestron Gear	40	13824	1.7686

All gears are isotropically superfinished to further improve their wear characteristics. This finishing technique removes all microscopic peaks and valleys on gear tooth surfaces, allowing the tooth to better bend under load. In tests, superfinished gears demonstrated the ability to improve surface fatigue by at least 300% and 10% improvements in bending fatigue compared to baseline ground samples (23). This translates into improved system durability, lighter transmissions, and 12-15% reduction in man maintenance hours per flight hour (MMH/FR) (24). Tests on CH-47 Chinook transmissions with ISF technology have recently been completed at Boeing. This technology will further improve Razor Rescue's transmission reliability and reduce time between overhauls (TBO).

6.6 Shafting

Razor Rescue requires three drive shafts to transfer power between the engine and gearboxes. Traditionally, rotorcraft drive shafts have been extruded aluminum tubes with either machined or riveted adapters at both ends. They are linked by flexible couplings and hanger bearings, which allow for slight shaft misalignment due to fuselage flexing in flight. Many individual shafts are often used to make the system subcritical, with its natural frequency higher than all resonant frequencies, reducing dynamic loads on components (25). The couplings account for a significant percentage of the weight in the shafting and the bearings are prone to failure.

Recent advances in composites permit significant weight reduction. This is due to the fact that ply orientations in the composite can be tailored to make the shaft stiffer in torsion than in bending, eliminating heavy joints. Furthermore, the shafts can be made supercritical, with the shafts spinning near resonance frequencies, which is a requirement for a variable speed rotor. Tests have shown that an 89% reduction in deflection can be achieved with the flexible matrix shafts (25). Further gains can be made by utilizing captured composite end fittings. These reduce the size, weight, complexity and cost of drive shafts by reducing parts and manufacturing complexity (26).

Since Razor Rescue requires a tail rotor drive shaft approximately 16 feet long, a joint is required to maintain acceptable shaft strength. This joint contains an active magnetic bearing. These devices have already been proven to reduce vibration (27). Recent advances in the bearing technology will allow the active bearing to be used as an actuator to enhance system stability, reducing manufacturing tolerances (25).

6.7 Housings

The main transmission housing has to react all load and moments created by the main rotor blades. Razor Rescue's main transmission housing features a stand pipe design, in which the rotor loads are passed directly to the airframe through four load paths. This allows the rest of the housing to be built lighter. Foldout 4 shows the location of the standpipe mounts.

In addition, the main transmission housing is designed to be made from composites, which differs from lightweight magnesium alloys currently utilized. Research at Boeing for the RDS-21 program has demonstrated that composite materials reduce gearbox housing weight by 30% (28). The housing design maximizes the benefits of this new material because most loads are concentrated in the standpipe mounts. In addition, an internal dry standpipe allows for the passage of wires to the slip ring.

The fenestron hub gearbox housing is also constructed from composites, but is simpler than the main gearbox. Most loads in the hub are passed through the fenestron stator vanes. Two removable cartridge assemblies, each containing the gear bearings, provide access to the gears.

6.8 Lubrication and Cooling System

The transmission requires an oil cooling system to prevent gear hot scoring and keep the gearbox heat below the oil flash temperature. Two primary lubrication pump, one secondary pump and one scavenge pump keep oil flowing through the gearbox. During normal operation, oil flows from the sump to the primary pump, oil filter, jet protection screen and the cooler before being discharged through jets onto the primary gear meshes. Bypass flow valves keep oil flowing if one of the screens gets clogged and a warning is issued to the pilot to alert him/her of the situation. There are two separate oil flow paths, each with a lubrication pump to provide system redundancy. The scavenge pump keeps oil from collecting at the low points in the transmission.

Assuming 98% efficiency for the main gearbox, the estimated heat generation is 319 btu/min. Oil is allowed to enter the gearbox at 250°F and leave at 400°F. Standard properties for MIL-PRF-7808 oil as prescribed by Dudley (20) require that the main gearbox pumps have a total of 0.5 gallons per minute capability. In order to provide redundancy, each pump will be capable of moving 0.5 gallons per minute. Total oil usable capacity prescribed by 14CFR29.1011 is 1.25 gallons, but the Razor Rescue main gearbox will contain at least 2 gallons.

Two separate coolers are mounted on the opposite sides of the transmission as shown in Foldout 4. Air is forced over the intercoolers by an impeller powered by the main transmission. The impeller is fed air from an inlet on the upper fuselage. The intercoolers are sized to cool both the main gearbox and engine oil. Within the intercoolers, oil from different components is kept separate. The front half dedicated to the engine, which has higher cooling requirements, while the main transmission oil is cooled in the rear of the intercoolers. The lubrication system for the main transmission is estimated to weigh 15.1 lbs. The fenestron gearbox is splash cooled by oil contained in the gearbox. The oil is in turn convectively by air flowing over cooling fins. No pumps are required, but oil level indications are provided to the pilot.

Chip detectors are installed on both the main and fenestron gearboxes to monitor debris in the gearbox oil. They capture metal shavings with magnets and alert the pilot to gearbox internal damage. The detectors are equipped with an electrical circuit that burns off small particles associated with normal transmission operation. This reduces nuisance warnings to the pilot.

6.9 Auxiliaries

Due to the turbo compounded diesel engine, the drive system requires a clutching system to mechanically disconnect the engine from the rotor during startup. In addition to the clutching system, the drive system features an optional rotorbrake. The brake prevents the rotor from wind milling while the aircraft is parked on the ramp. Estimated to weigh 5 lbs, it is mounted between the engine output adapter and the engine drive shaft.

7.0 Rotor Design

7.1 Design Constraints

Razor Rescue's main rotor was designed for efficient hovering and good high speed cruise performance. These flight regimes require tradeoffs between conflicting requirements. Since the aircraft will become operational in 2020, many years of technological advances can be incorporated into the design.

7.2 Primary Rotor Technology

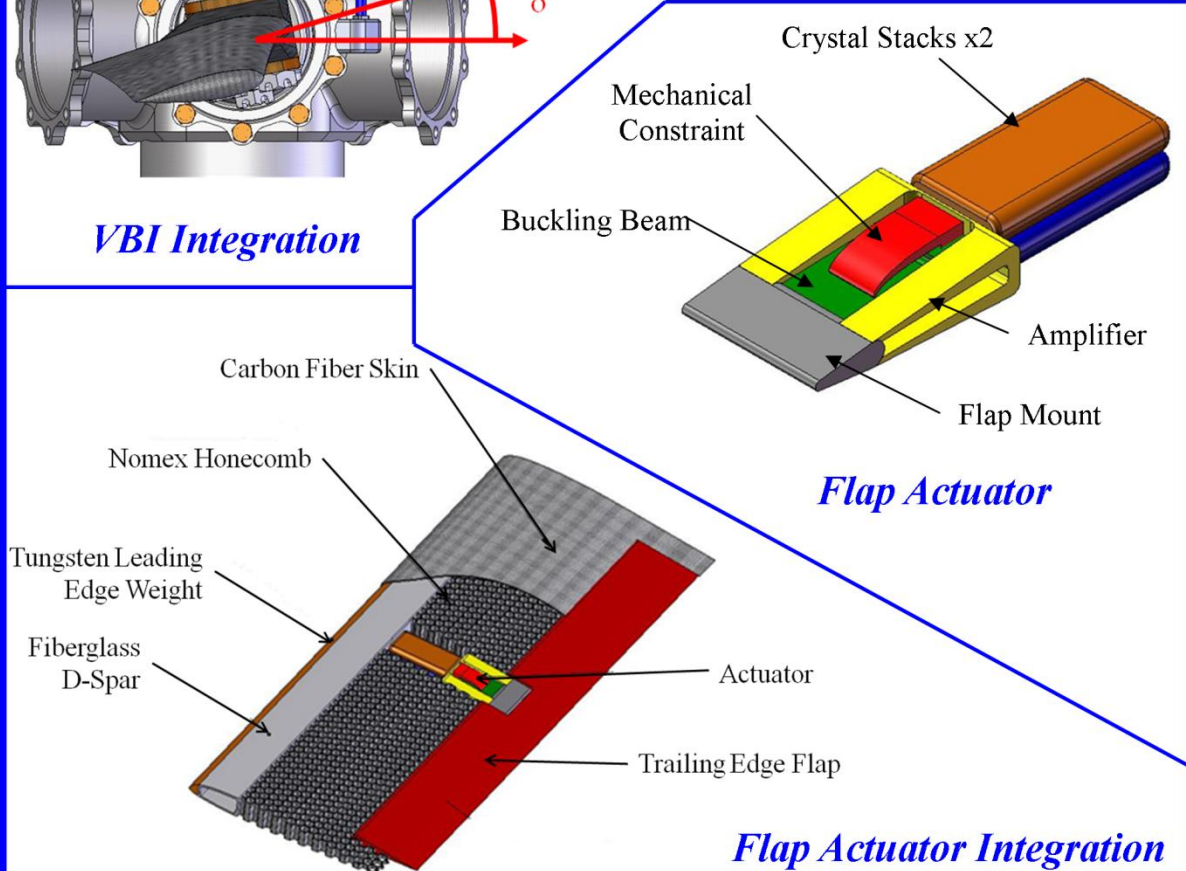
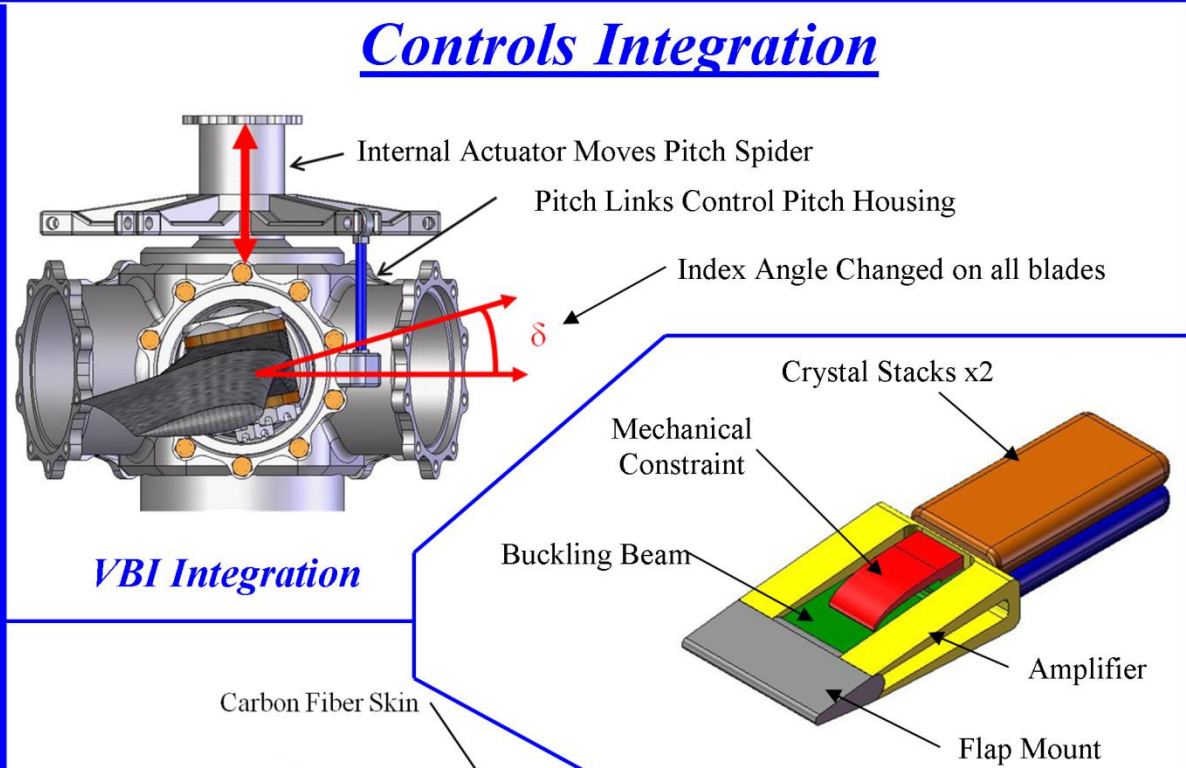
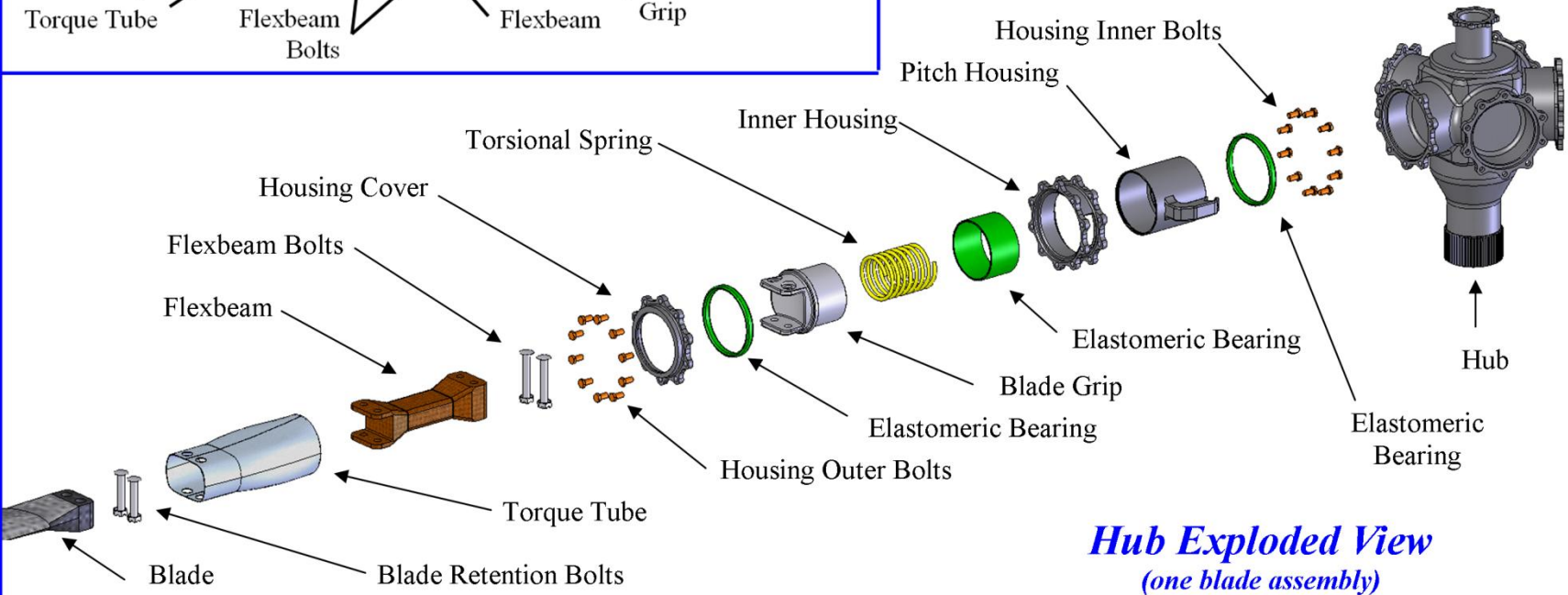
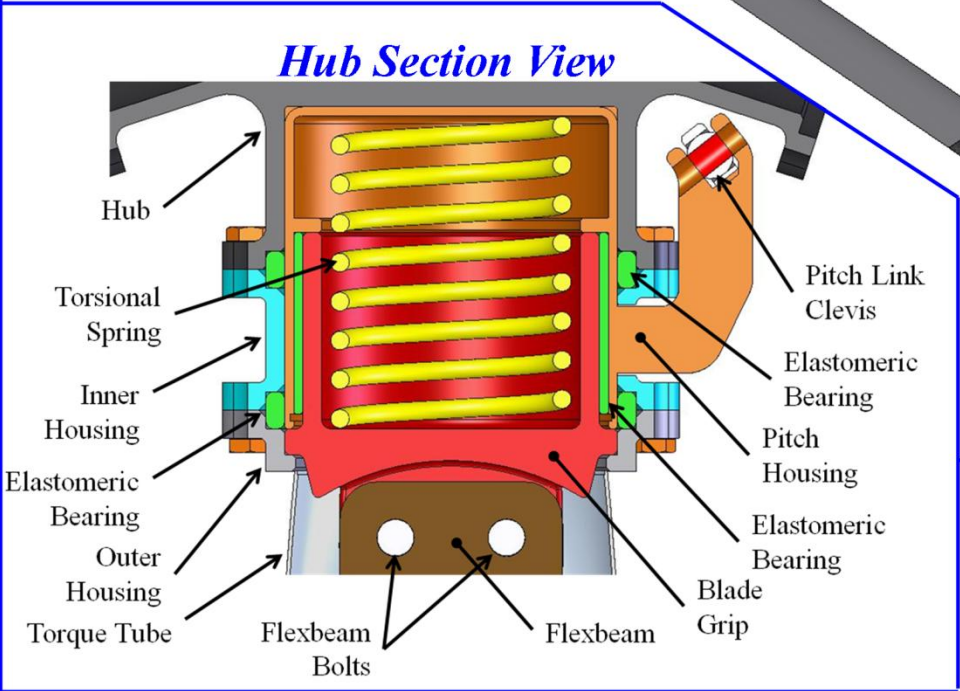
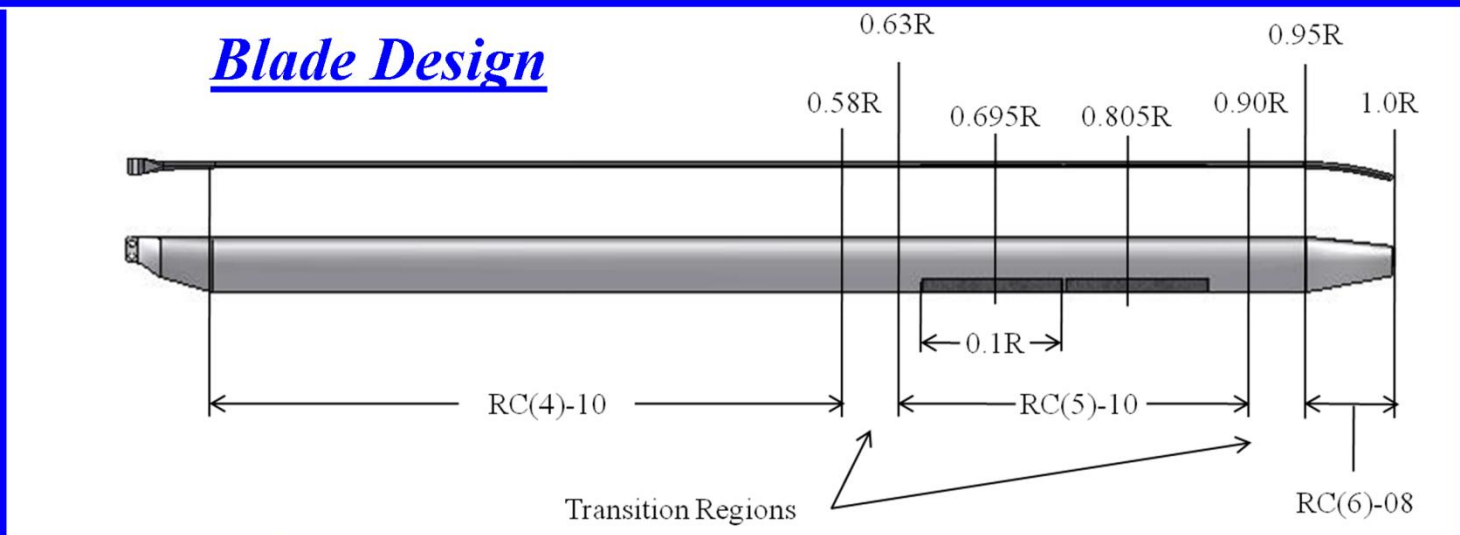
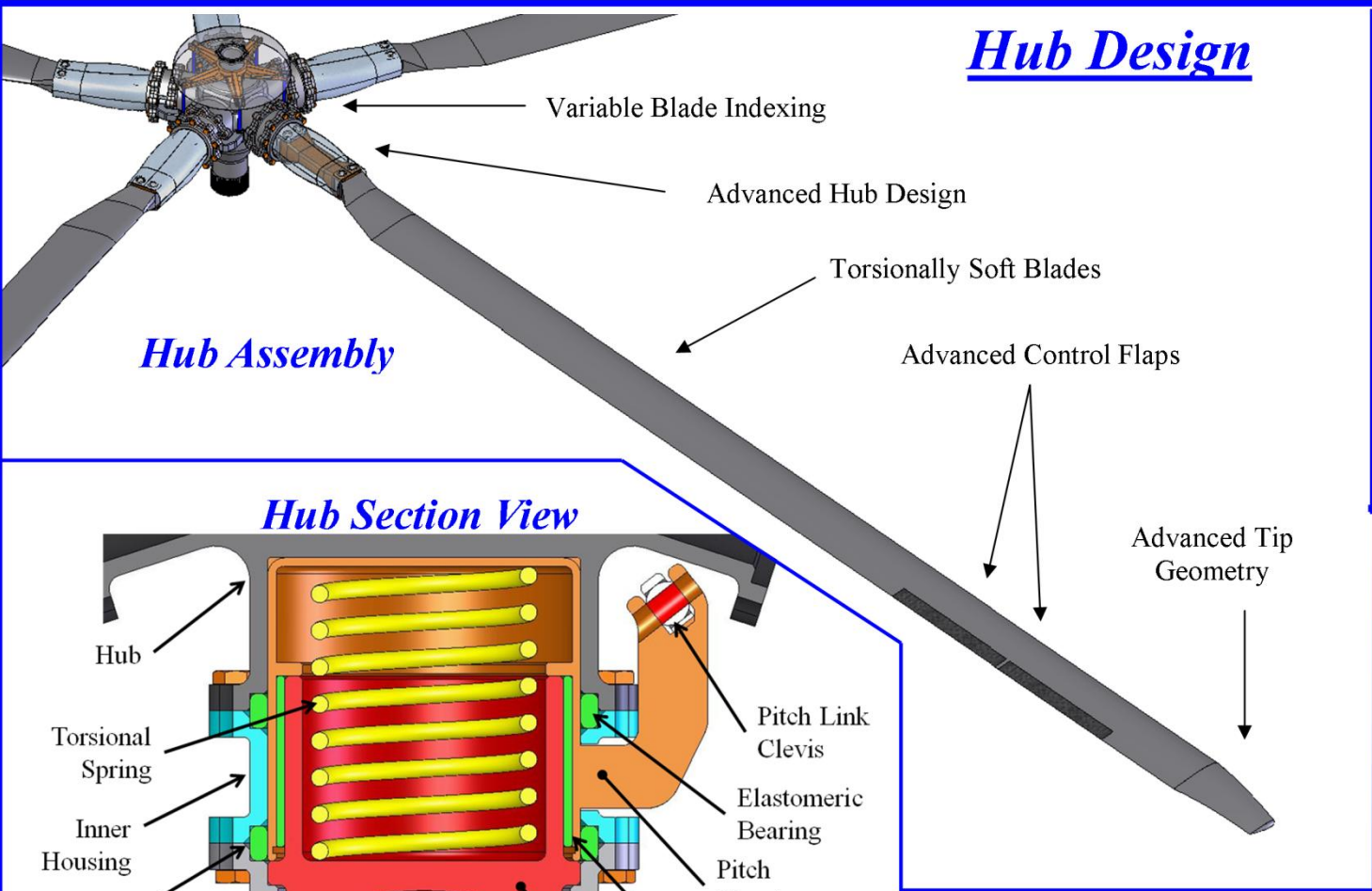
Variable Diameter Rotors: Variable diameter rotors have the potential to offer significant performance and efficiency benefits over the standard fixed diameter rotor (29). Momentum theory shows that low disk loadings due to a large rotor increase hovering performance, while smaller rotors are more efficient at higher forward speeds.

The primary drawback of these rotors is the fact that they require a locking system, which incurs additional maintenance. Extra weight is added to the blades, and the sliding outer portions will preclude significant blade twist. Moreover, if one blade fails to extend or retract, the resulting load imbalance will quickly cause the aircraft to crash. Increasing system reliability to avoid this catastrophic failure will significantly delay certification. It is estimated that variable diameter rotors have a TRL of 2.

Variable Speed Rotors: Variable speed technology can offer significant benefits to the aircraft. The A160T Hummingbird currently utilizes a two-speed transmission, which expands its flight envelope to allow for long duration flights. The EC-120, utilizes a variable speed rotor to reduce rotor noise during low speed flight. Since noise is a primary consideration, this is attractive to the Razor Rescue.

Variable Twist Rotors: Another potential technology for the Razor Rescue are variable twist rotors. Blade twist is employed to modify the lift distribution of the blades by offloading the tips to more evenly loading the entire blade. A

Foldout 5: Razor Rescue Rotor System



Flap Actuator Integration

large negative twist is especially beneficial in hover because it reduces the induced power, and therefore figure of merit (30). However, high twist is detrimental to forward flight performance because it creates negative lift at the tip of the advancing blade. Using a smaller amount twist improves the Lift/Drag ratio and maximum aircraft speed (31). Various methods exist to modify the twist along rotor blades. One way is using a series of piezoelectric actuators mounted spanwise along the blade and applying a voltage to each one to twist the rotor. Another method is using Shape Metal Alloys (SMAs) and a torque tube, as tested by Boeing on the reconfigurable rotor blade (RRB) (32). Use of SMAs has so far been limited to a few degrees of twist.

Finally, a third way to vary the twist of the blades is through trailing edge flaps. These devices, similar to ailerons on aircraft wings, are control surfaces mounted in the trailing edge of the rotor. They modify the lift distribution and pitching moment in the blade, resulting in blade twist. Eurocopter is currently flight testing full scale rotors with trailing edge flaps (33), while Boeing is investigating their effects on dynamic loads and vibration (34).

7.3 Design Methodology

7.3.1 Trend Studies

The rotor design process was divided into four different primary analysis phases to better understand the influence of each design variable on the system as a whole. The first phase consisted of researching existing aircraft designed for similar missions and trending their rotor parameters. Twenty eight aircraft were studied, with gross weights ranging from 1370 lbs to 7055 lbs to provide enough data to fit trend lines. Preliminary sizing methodologies detailed by Leishman, Prouty and McCormick were also employed to establish boundaries of the design space (30) (31) (35).

7.3.2 Basic Geometry

7.3.2.1 Method

The next step was to perform sensitivity analyses within the design space. This second phase of the rotor design process focused on rotor diameter, solidity and tip speed. Two Blade Element Momentum Theory (BEMT) Matlab programs were written, one for hover and one to trim the rotor in forward flight. The trim procedure was adapted from Prouty (31) and McCormick's work (36). These programs swept all three variables to uncover sensitivities. Separate optimum solutions for hover and forward flight were then found. Since the aircraft will be primarily judged on its efficiency in forward flight, the design was biased significantly towards this condition.

7.3.2.2 Rotor Diameter

After a few data runs and consideration of the urban operational environment, a diameter of 27 feet was selected. This is a compromise between the large diameter favored for efficient hovering flight and smaller diameter required for efficient cruise performance. The rotor is somewhat smaller than current aircraft, such as the EC-120 (32.8 ft) and R-44 (33 ft), but allows the aircraft to perform better at higher forward speeds. More importantly, the smaller rotor increases Razor Rescue's ability to land in small areas, important for a disaster relief aircraft.

7.3.2.3 Solidity

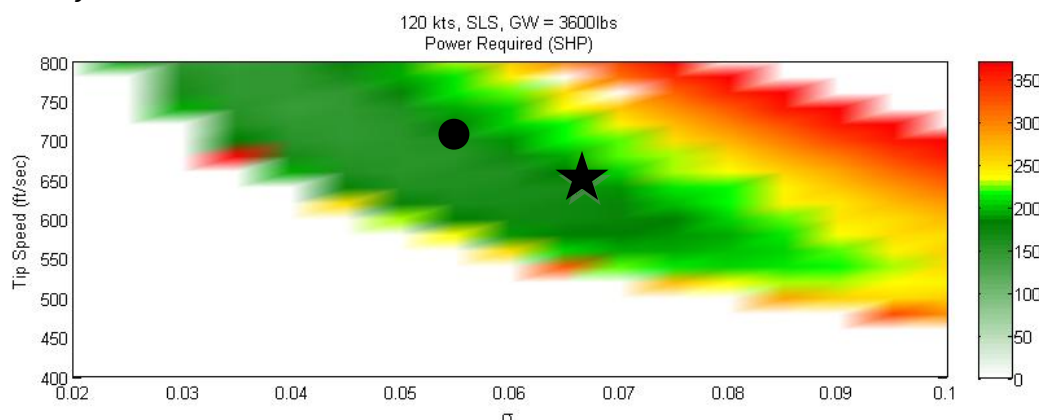


Figure 11: Forward Flight Power Required

Figure 11 shows a sample output from the forward flight program. A band of low power requirements is evident. Razor Rescue was originally designed to operate on the back side of the peak, where blade loading is lower (shown by the circle). The solidity was later increased to reduce blade loading and tip speed was reduced to avoid compressibility affects. This resulted in the final operation point, shown by the star. A higher solidity reduces blade loading, important for maneuvering performance, especially at higher speeds.

7.3.2.4 Number of Blades

Five blades were chosen to provide relatively high solidity and moderate blade loadings. This incurs a higher cost due to higher hub, blade and control system manufacturing and maintenance costs, but since total aircraft cost is not a primary factor, this was judged to be a good tradeoff.

7.3.3 Rotor Speed and Twist

7.3.3.1 Tip Speed

Tip speed is a compromise between many conflicting requirements. In order to operate at higher levels of efficiency than current rotorcraft, the Razor Rescue will utilize a variable speed rotor. Compared to current aircraft, the rpm varies widely over the flight envelope. This is primarily made possible by the wide HP/RPM curve of the turbo-compounded diesel engine.

While hovering, the primary driver of rotor tip speed is rotor noise. Slower rotor speeds significantly reduce aircraft noise due to lower tip vortex interaction. (30) For the Razor Rescue, this value is much lower than current helicopters, but the design team believes that the rotor control will be maintained by the novel rotor control system. As the aircraft speeds up, the rotor tip speed also increases to avoid retreating blade stall. Figure 12 shows the final tip speed distribution. The rotor slowly speeds up to avoid any spikes in power curves due to sudden increases in torque.

7.3.3.2 Twist

Most helicopters utilize a fixed moderate value of twist, but the Razor Rescue will feature variable twist blades. This is made possible by a novel combination of controls. For this design, all twist is assumed to be linear. Future advances in composite tailoring will allow for a non linear distribution, even with the dynamic blade twist.

Blade twist is employed to modify the lift distribution of the blades by offloading the tips to more evenly loading the entire blade. A large negative twist is especially beneficial in hover because it reduces the induced power, and therefore figure of merit (30). A sensitivity study was performed and Figure 13 shows the hover performance benefits of high twist in hover. A twist of -20° was selected for this flight condition

High twist is detrimental to high speed forward flight performance, however, because it creates negative lift at the tip of the advancing blade. Some negative twist is still needed to improve blade span lift distribution (37). Figure 14 shows how the twist varies with velocity. The control system will tailor the twist generally to this value, but it will also consider variations in aircraft weight and atmospheric conditions, so the final values might be offset slightly.

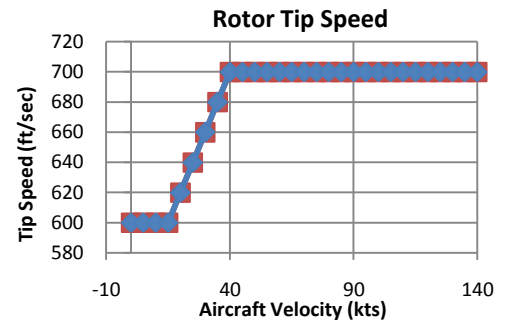


Figure 12: Rotor Tip Speed Distribution

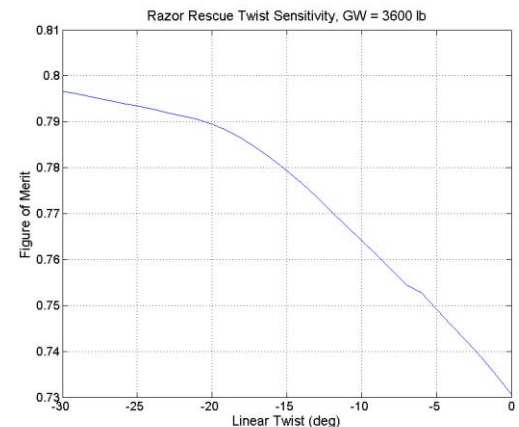


Figure 13: Hover FM vs. Linear Blade Twist

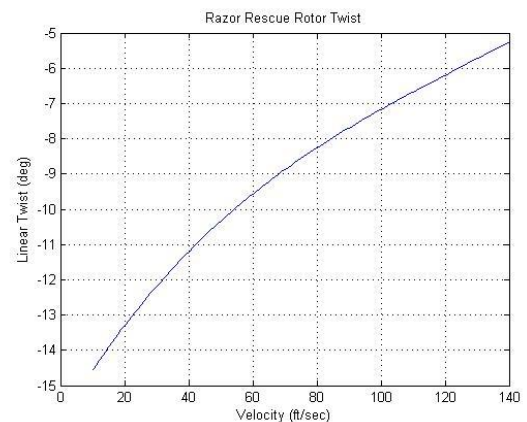


Figure 14: Rotor Twist vs. Velocity

7.3.4 Airfoil Selection and Tip Design

7.3.4.1 Airfoils

Rotor airfoils are crucial to the performance of the aircraft. The Razor Rescue is required to operate as efficiently as possible, so airfoil drag minimization is an important issue. Low tip speeds in hover require high blade lift coefficients and airfoils with high drag divergence Mach numbers are required near the blade tips. Finally, all airfoils need to have low pitching moments to reduce control system requirements.

In order to meet these conflicting requirements, a blade with multiple airfoils was designed. After comparing a variety of modern airfoils, examples from the NASA RC series were chosen. These airfoils have readily available aerodynamic characteristics (38), (39). As shown in Foldout 5, the relatively thick (~12%) RC(4)-10 airfoil is used for most of inboard section of the blade. After a transition region, the thinner RC(5)-10 is employed. This provides high across the majority of the blade. Finally, at the tips where reduced drag is more important than high lift, the RC(6)-08 is used. A second transition region separates the RC(5)-10 from the RC(6)-08.

7.3.4.2 Tip Design

Many aircraft use swept tips to minimize compressibility losses in forward flight, while others employ tapered tips to reduce tip loading and to improve hovering performance (29). After considering a variety of tip geometries, a combination of taper and sweep was selected. Figure 15 shows that only a mild amount of taper improves hovering FM significantly. A 2.5:1 taper, starting from 0.95R was selected as a compromise between performance and rotor polar moment of inertia. High taper ratios reduce the amount of tip mass available to maintain rotor rpm during autorotation. In addition, 20° of parabolic anhedral is used to increase miss distance between tip vortices of adjacent blades. This reduces BVI, especially in hover, and therefore decreases rotor noise. Slats and slotted tips were also considered for Razor Rescue, but were ultimately rejected for high manufacturing costs.

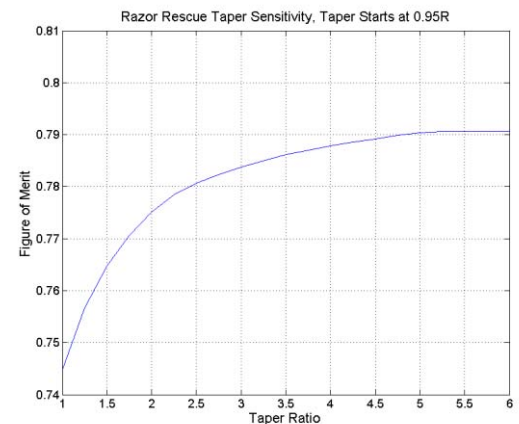


Figure 15: Taper Sweep

7.4 Controls Integration

7.4.1 Individual Blade Control (IBC)

7.4.1.1 Swashplateless Control System Overview

Traditionally, rotorcraft have been controlled through a swashplate assembly that tilts the rotor thrust vector by changing blade pitch as a function of azimuth. This system requires significant actuation force to move a swashplate assembly to influence blade pitch. This system is heavy, causes significant parasite drag due to exposed linkages and bearings and requires significant maintenance. Furthermore, blade pitch can only be affected once per revolution.

In order to improve performance, Razor Rescue will utilize trailing edge flaps for primary control. The flaps are designed to induce a pitching moment on the blade, which twists the blades to modify rotor thrust. The advantage of moment flaps over lift flaps is the fact that they are smaller and require lower control deflections (40). This translates into lower profile power requirements.

The concept of rotor control with flaps is not new. Kaman has been using similar control surfaces, servo flaps, for primary control for over 50 years, but they are mounted aft of the main rotor blade (41). This causes an increase in blade profile power due to the extra drag from the flaps support structure. Integrating these flaps into the rotor blade itself lowers control moments, but offers better aerodynamic performance due to reduced drag. Analysis has demonstrated that flaps can be used successfully for primary control (42) (43). Recent testing by Eurocopter on an EC-145 have further proved the merits of the control system (33).

Overall, a swashplateless design can allow for a 40% reduction in control system weight, 8% reduction in vehicle gross weight and 26% reduction in parasite drag (44). Finally, it has been demonstrated that the flaps can be used for blade tracking as well as vibration and noise reduction (45),(46),(47). Preliminary results from whirl tower testing of a MD-900 rotor with active flaps include an 80% vibration reduction and 10 dB decrease in hovering noise (34).

7.4.1.2 Swashplateless Control System Design

The primary design parameters are blade torsional frequency, pitch indexing angle, flap size, location and aerodynamic overhang (33). Two flaps are located on each blade to provide a level of redundancy. Based upon the work of Shen (42), the control flaps have the properties as shown in Table 6.

Table 6: Trailing Edge Flap Properties

Parameter	Value
Flap Length (each)	0.100R
Control Flap Width	0.30c
Overhang	0.15c
Inner Flap Midpoint	0.695R
Outer Flap Midpoint	0.805R

The flaps are placed relatively close to the tips to maximize dynamic pressure and control effectiveness. This has the additional benefit of placing actuator weight far from the hub, increasing the rotor polar moment of inertia. The flaps cannot be placed too near the tips, because three dimensional aerodynamic effects begin to degrade performance. Flap overhang reduces actuation power by aerodynamically balancing the flap (42).

7.4.1.3 Actuator Downselect

For a five bladed rotor rotating at 495 rpm (at high forward speed), the trailing edge flap actuators need a minimum output frequency for primary rotor control is 8.25 Hz. Much higher bandwidths are required to influence rotor noise and vibratory characteristics. The actuators are required to move the flaps $\pm 5^\circ$ (42). Typical hinge moments require that the actuators be able to supply a maximum of 25 lbs of force to the flaps. A trade study was conducted to determine the best actuator for based upon these requirements.

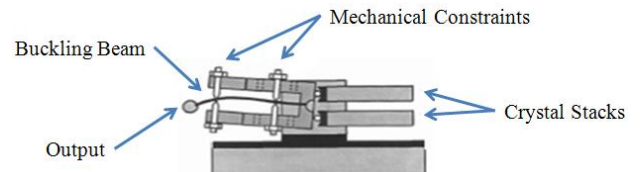


Figure 16: Actuator Concept

Based upon the trade study, the piezoelectric actuators were selected to control the flaps. They only provide a limited stroke and some type of amplification is required. A novel type of actuator has been developed that uses a twin crystal stacks and a buckling beam to amplify the stroke of the actuator (48). The single crystal piezoelectric actuators have twice the strain energy density than ceramic-based types, while providing five times the displacement as electrostatic ceramic actuators (49). The crystals bias the direction of buckling of the attached beam, which amplifies the output motion. Additional constraints placed on the beam change its mode shape, allowing for a shorter actuator. Figure 16, adapted from Reference (49), clarifies this concept.

7.4.1.4 Integration and Power Consumption

An 18 inch blade section is shown in Foldout 5, with various materials labeled. The blade is estimated to weigh 1.97 lbs/ft. One actuator is installed per flap, and is mounted to the fiberglass D-spar. Access panels are provided in the rotor skin to facilitate maintenance. Power consumption is lower than conventional hydraulically boosted control systems. Total power to trim (primary flight control only) a five bladed MD-900 rotor at an advance ratio of 0.3 is approximately 0.33 HP (50). Vibration and dynamic load control are additional power requirements, but since Razor Rescue is smaller than the MD-900, total power is estimated to be approximately the same.

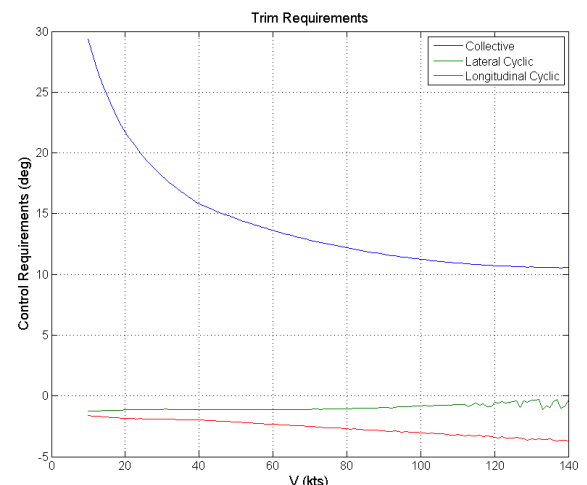


Figure 17: Razor Rescue Control Requirements

7.4.1.5 Safety

An important aspect to consider when designing a new rotor control system is flight safety in the event of a failure of a flap. To mitigate this risk, two flaps are installed per rotor. If one flap fails to actuate, the other will have enough control authority to safely maneuver and land the aircraft. The worst case scenario is when a flap is jammed at the

maximum deflection angle. It has been analytically demonstrated that a four bladed rotorcraft can be successfully controlled with only three fourths of the actuators are properly functioning (51).

7.4.2 Variable Blade Indexing (VBI)

7.4.2.1 *Benefits*

One primary design parameter for trailing edge flaps is the blade index angle, which is the angle of the most inboard section of the blade relative to the rotor plane. The proper selection of the index angle limits the flap deflection required to trim the rotor (52). This value is selected to be higher than what is required to trim the rotor and the flaps create a nose down pitching moment to twist the blade to the desired pitch position (42).

Generally, this is selected to be a fixed value but efficiencies are gained by varying the blade index angle. Analysis shows that VBI increases hover performance 4.5% for every 15° of actuation and increased stall margin of 13 kts for every 15° of actuation (53). Combining VBI with IBC via trailing edge flaps results in the ability to tailor blade twist to the optimize rotor control for every flight condition. This primarily results in increased hover performance, important to Razor Rescue because of the low tip speed.

7.4.2.2 *Control Integration*

In order to achieve VBI, an actuator is hub mounted actuator is required. Razor Rescue will use a SMA actuator located in the center of the hub, rotating with the rotor. Rotating the actuator with the hub eliminates the requirement for a small swashplate by taking advantage of the slip ring. The system changes the pitch of the blades in a similar fashion to the spider mechanism on the tail rotor of the UH-60 Blackhawk.

7.5 Hub Design

The rotor hub is relatively complex due to the two part control system. The primary design drivers were low drag in forward flight, low weight and control power. After trade studies, a soft in plane hub design was selected to provide better handling through high control power. The resultant design is best classified as hingeless due to the bearings required for the variable blade indexing system. The hub is relatively complex, but maintenance will be low due to part robustness. In addition, elastomeric bearings are less maintenance intensive than traditional ball or thrust bearings and the torsional spring will have a high fatigue life, requiring few changes over the lifespan.

Trailing edge flaps require a pitch spring to maintain a low blade torsion frequency. In previous designs, a linear spring has used in place of pitch links (40). This method requires a simple (non articulating) swashplate to mount the spring, but causes almost as much parasite drag as a standard articulating rotor. The Razor Rescue eliminates all swashplates by using a torsional spring buried within the hub. The blade is attached to a blade grip, which pivots on two elastomeric bearings to allow full blade motion. All flapping and lead lag blade motion is handled by a composite flexbeam, which is mounted inside an aerodynamic torque tube.

The complication comes when adding the VBI system to the hub. Modifying blade pitch is relatively simple, however, without special design consideration, it modifies the force on the torsional spring and therefore the blade torsional frequency. Activating the VBI system must influence blade pitch independent without influencing the torsional spring through a concentric housing assembly. An actuator influences a pitch housing, which modifies blade pitch via a torsional spring. This system is best explained by Foldout 5.

7.6 Associated Technology

7.6.1 Ice Protection

Disaster relief missions are sometimes characterized by poor weather conditions. One significant weather related hazard to rotorcraft is icing and few helicopters are certified to fly into known icing conditions. Typical thermal deicing systems can only be used periodically to avoid high power consumption and excessive heating of the leading edge structure (54). Razor Rescue will remove accreted ice with low power non-thermal ultrasonic actuators. These devices have been tested at NASA Glenn's icing wind tunnel, successfully delaminating ice with a power not

exceeding 1.2 W/in² (54). This technology is predicted to improve to the point where one actuator, mounted in the root of the blade, will have the ability to propagate a standing wave along the blade leading edge, deicing the entire blade.

7.6.2 Slip Ring

An inductance slip ring allows the transfer of power and data between the stationary fuselage to the rotating rotor. The design of the slip ring allows for higher signal reliability and lower maintenance because there is no physical contact between the stationary and rotating parts. Each blade requires at least 18 channels (6 for the servo flaps, 6 for ice protection system, the rest for HUMS sensors) and the central VBI actuator will require six channels. Therefore, the total channel count is 96.

7.7 Autorotation Safety

Helicopters must be able to land safely in the event that the engine stops providing power to the main rotor. One measure of autorotation is the time equivalent to hover. This is the time that kinetic energy can maintain rotor rpm in hover before stalling (31). The Razor Rescue has a time equivalent to hover of 1.23 seconds, placing it in the “Good” range according to pilots’ opinion (31).

For improved autorotational performance, small weights can be added to the blade tips to increase the polar moment of inertia. Adding a distributed weight of 2.1 lbs outboard of the control flaps will increase the equivalent time for hover to 1.4 seconds. This small increase in weight would allow for a “Very Good” according to pilots opinions’. More equivalent hover time is gained with the fast reacting control system. If it detects an engine failure, it will automatically adjust the VBI system and set the trailing edge flaps to the best L/D for autorotation. This will act faster than any human pilot could detect engine failure and successfully enter into autorotative flight.

7.8 Final Blade Parameters and Power Curves

Table 7: Razor Rescue Blade Parameters

Parameter	Units	EC-120	Razor Rescue
R	ft	16.45	13.5
σ	-	0.0465	0.068
chord	ft	0.98	0.70
taper	-	--	2.5:1 at 0.95R
Anhedral	-	--	20° parabolic starting at 0.95R
Twist	deg	-12	Variable
Vtip Hover	ft/sec	670.4	600
Hover FM	-	0.72	0.79
$(C_T/\sigma)_{\text{hover}}$	-	0.109	0.092
Hover Pwr Req'd	SHP	308.7	278.1
Vtip 120 kts	ft/sec	713.4	700
$(C_T/\sigma)_{\text{120 kts}}$	-	0.0747	0.083
Pwr Req'd 120 kts	SHP	317.62	287.2

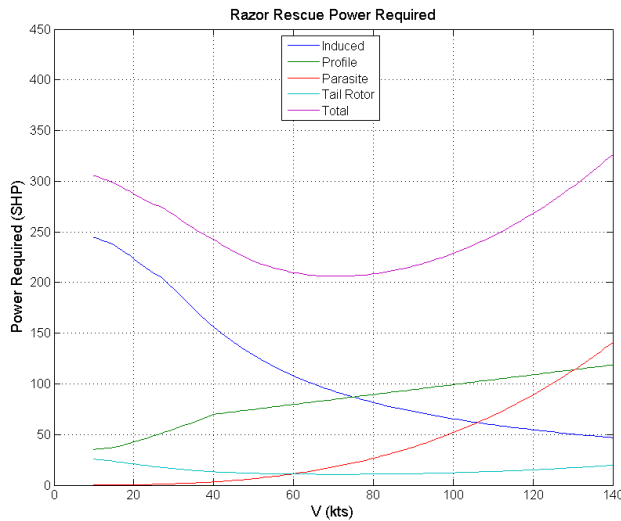


Figure 18: Razor Rescue Power Required

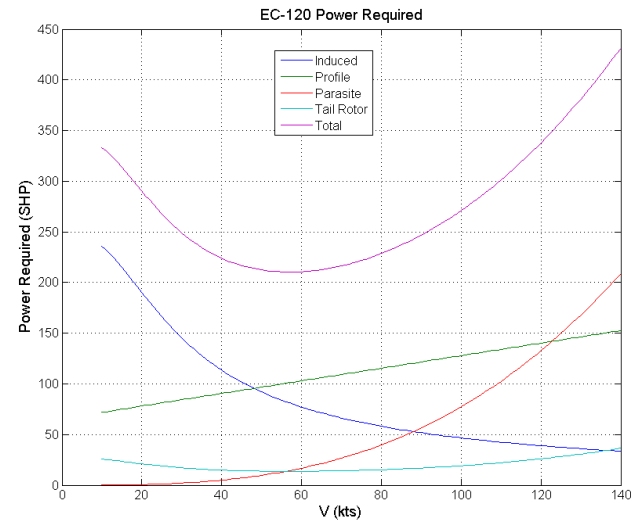


Figure 19: EC-120 Power Required Comparison

8.0 Anti-Torque System and Empennage Design

Anti-torque systems are vital to the control and stability of any rotorcraft and have an important role in the design process. Anti-torque systems counter the torque created by the main rotor and to define the shape and drive train of a helicopter. Early in the design, it became evident that this rotorcraft would have a conventional configuration, consisting of one main rotor and a tail boom. The three most common of conventional anti-torque systems were considered: NOTAR, fenestron, and conventional tail rotor.

8.1 System Selection

The main objective in the RFP is to energy conservation. Safety, noise, maintenance and maneuverability were also important factors. The three most common anti-torque systems were investigated for this rescue mission and compared with each other to select the most optimal design.

8.1.1 Energy Consumption

The main objective of this rotorcraft is to conserve energy consumption. Reduction in power required and weight are the main drivers to assure low energy consumption. The fenestron was the most efficient in terms of power required. It avoids the interference of the vertical fin for the conventional tail rotor and instead uses the duct to produce almost half of its thrust. A NOTAR system requires even more power especially in high crosswinds and maneuvers. The fenestron consumes the least amount of energy of all the anti-torque systems that were investigated.

8.1.2 Safety and Maneuverability

Enhanced safety is a major concern for the crew and passengers of the Razor Rescue. The fenestron duct provides a shield for the rotor from trees, power lines, and other obstacles, which can cause a catastrophic failure. The NOTAR system eliminates the threat of an open spinning rotor while the conventional tail rotor is much more dangerous. A semi-professional pilot might not be used to the extreme conditions on the ground caused some type of disaster, so safety is important to both the crew and the passengers. Maneuverability is also important, especially for a semi-professional pilot. The fenestron is less susceptible to vortex ring state in high crosswinds because it has a higher induced velocity than a conventional tail rotor (55).

8.1.3 Noise

Reduced noise is closely related to general safety. Crew and passengers, as well as bystanders on the ground, feel the effects of high acoustic signatures. Fenestrons spin at higher tip speeds but the duct and asymmetric blade spacing

allow for low acoustic signatures, especially from far distances by spreading the noise across a variety of frequencies. Fenestron ducts also protect from main rotor wake interactions.

8.1.4 System Selection Matrix

After examining all of the anti-torque criteria for optimal design, a design matrix, Table 8, was created to ensure the correct system was chosen. Energy consumption was the main parameter and therefore was given the most value. The fenestron system was easily the best selection of the three designs considered with a total weighted score of 275.

Table 8: Anti-Torque Selection Matrix

Design Driver	Weight Factor	Fenestron	NOTAR	Conventional Tail Rotor
Energy Consumption	10	9	5	7
Safety	7	8	10	4
Noise	5	8	10	5
Maintenance	5	7	5	8
Maneuverability	6	9	5	8
Total		275	225	211

8.2 Fenestron Detailed Design

The fenestron, or fan-in-fin system, is a ducted fan that creates thrust to provide torque and maneuverability in the yaw direction. The fan and the duct create equal amounts of thrust, so the design of both components is important to optimize the fenestron system.

8.2.1 Fan Design

Using blade element analysis in hover, a sweep of rotor diameter and solidity was performed to find the optimal value of these parameters. The maximum anti-torque required was 3700 ft lbs, which includes main rotor torque, crosswinds, and maneuver forces. The optimal moment arm from the main rotor to the fenestron was 17 ft, considering weight, center of gravity, and power requirements. This required the fenestron needed to produce 218 lbs of thrust to allow for crosswinds and maneuvers.

A fan rotor diameter of 2.8 ft and a solidity of 0.43 were selected as the best values for the Razor Rescue's applications. The most common value between fenestrans, especially in this size of helicopter, is the tip speed of 590 ft/s. This gives a fenestron rotational speed of 4024 RPM for hover. As the Razor Rescue engages in forward flight, the engine increases the fenestron rotational speed to 5240 RPM, giving a tip speed of 768 ft/s. This will increase noise in forward flight but interface with passengers, crew, and bystanders will occur at low RPM while the rotorcraft is at hover. Other fan parameters are shown in Table 9, and are comparable to the EC-120.

The fenestron blade airfoil is also important to the fan design. Fenestrans have highly cambered airfoils because they have high torsional stiffness and are small in size (56). The NACA 63A312 is shown to have a high performance for low and high tip speeds, which is important for the Razor Rescue's fenestron. Asymmetrical blade spacing is also highly considered for fenestrans because it greatly reduces noise created by the fenestron fan (30).

Table 9: Fan Parameters and Comparison

Parameter	Razor Rescue	EC-120	Fenestron Range
D_{MR}/D_{TR}	9.6	13.3	8.7 ~ 15.1
σ_{TR}	0.43	0.39	0.39 ~ 0.62
$V_{tip\ TR}$ (ft/s)	590	591	564 ~ 725
c (ft)	0.186	0.197	0.131 ~ 0.394
N_b	10	8	8 ~ 13

8.2.2 Duct Design

The duct of a fenestron anti-torque system produces about half of the thrust, therefore it is critical to have an optimal design. The inlet lip radius is important because it helps to avoid flow separation at the inlet (30). Experimental results show that 5 to 7 % of the fenestron diameter are optimal for the inlet radius(57). The Razor Rescue uses 7% of the fenestron diameter, yielding an inlet radius of 0.168 ft.

Another important aspect of the duct design is the diffuser angle, which helps to avoid wake contraction away from the rotor and prevent flow separation. High diffuser angles could cause problems due to adverse interaction with the main rotor wake in forward flight (56). The optimal diffuser angle is 10° before the instabilities in forward flight become an issue. The fenestron hub is also vital to the anti-torque design. The hub is held in place by stator vanes which help to reduce the swirl induced by the rotating fan and increase thrust (56). There are 10 stator vanes used to hold the hub on the Razor Rescue. The fenestron hub houses the collective pitch mechanisms for the fenestron fan. All of the duct parameters are shown above in Figure 20, which is adapted from Reference (55).

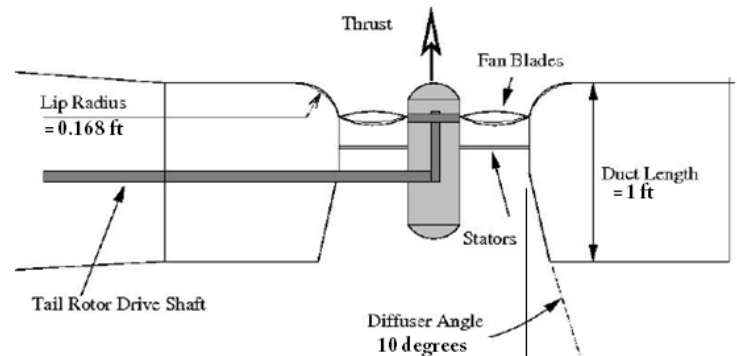


Figure 20: Section View of Fenestron Duct

8.3 Empennage Design

The empennage typically consists of a vertical and horizontal stabilizer used to provide aerodynamic forces to enhance stability about each respective axis. There are various types of empennages, but after much research, the best shape for the Razor Rescue was found to be a v-tail configuration, which acts as both a vertical and horizontal stabilizer and is very aesthetic. Most vertical stabilizers are similar in design, however the horizontal stabilizer mounting location varies across all helicopters. The three most common areas to mount the horizontal stabilizer are aft, forward, and on top of the vertical stabilizer.

The low aft stabilizer has good structural efficiency, with most loads being supported by the tail boom. This location, however, leads to unsteady transitions when moving from hover to low speed flight when the wake from the main rotor moves across the surface (30). The Razor Rescue will be performing this transition many times when searching for victims of disasters, and any means to avoid unsteady aerodynamic issues is optimal for a semi-professional pilot. The forward mounted stabilizer avoids the unsteady transition that the low aft stabilizer experiences because it remains within the main rotor wake throughout most flight conditions. The forward stabilizer has performance penalties in hover because it is directly beneath the main rotor wake, and it has a smaller moment arm, making it bigger and therefore heavier(30).

The third consideration for the empennage was a t-tail, locating the horizontal stabilizer on top of the vertical stabilizer. The benefit from this design is that the horizontal stabilizer is not affected by the rotor wake for most flight conditions. This design, however, requires the vertical fin to carry all of the loads, making it more structurally inefficient (30). Avoiding the transition between hover and forward flight, the t-tail design was more heavily considered. After continued research, a v-tail design was more applicable. This design avoids the transition from hover to forward flight while also applying the structural loads directly to the tail boom. According to a study conducted in NASA wind tunnels, a v-tail design had better overall stability than even a forward mounted stabilizer (58). The v-tail also weighs less than any of the previous empennage options because it only has two control surfaces instead of three. Reduction of weight helps to conserve energy, the main objective for the Razor Rescue. The main reason that this design is not more common is because of the "If it's not broke, don't fix it!" mentality and higher costs (59). Figure 21, from Reference (59), displays how there is a reduction in dynamic loading at high forward flight when using a v-tail design as compared to a t-tail empennage for tests performed for the Comanche.

The empennage dimensions were selected using control moment considerations. The empennage is most beneficial during forward flight. The vertical aspect off loads the anti-torque device by creating the moment needed to stabilize the rotorcraft. This also allows for the less strain on the fenestron system, which increases the life of the vehicle and reduces maintenance. The v-tail shares the vertical component with the horizontal aspect of the stabilizer used to counter the pitching moment on the rotorcraft during forward flight (30). This creates enough lift to keep the Razor Rescue stable allowing the semi-professional pilot to focus more on the mission at hand, rather than controlling an unsteady aircraft.

Planform area has the most effect on the empennage design because it contributes most to lift. A large planform area of for the entire v-tail was selected, which covers both vertical and horizontal components of stability. A larger area than normal area was chosen because the structure and skin materials weighed less than typical and stability for the semi-professional pilot was a must for safety considerations.

Comparison Of Dynamic Loading Of T Tail And V Tail At 100 Knots - $\beta = 0^\circ$, Rotor Off

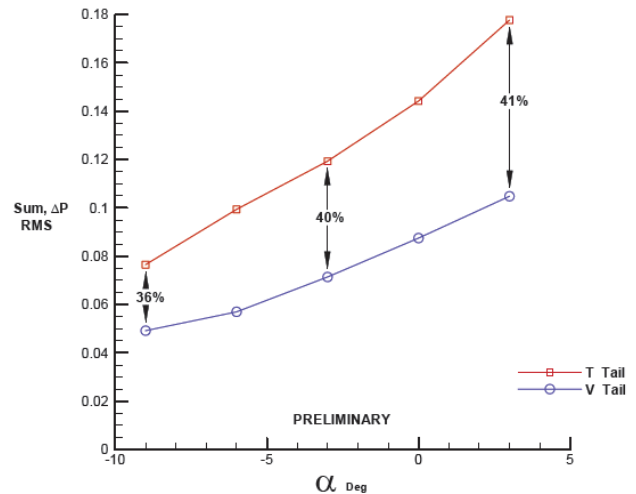


Figure 21: Comanche Tail Load Comparisons

9.0 Flight Control System

The Razor Rescue is primarily controlled by trailing edge flaps on the blades of the main rotor. Since this rotorcraft is designed for a semi-professional pilot, the flight control system must be quite reactive and autonomous to some degree. The Razor Rescue uses a fly-by-wire technology to deliver and receive vital control inputs and outputs with high speed and efficiency.

The flight control system will be controlled by redundant flight control computers, which work with each other to make proper flight decisions. The pilot will input flight commands which will be checked by the autopilot. The autopilot sends the control signals to the two computers, which also accept information concerning the current state of the rotorcraft as well as the health of critical flight components. Each computer processes the information separately and makes its own control decision. Then, using fuzzy logic, the best control decision is made and sent digitally via to actuators.

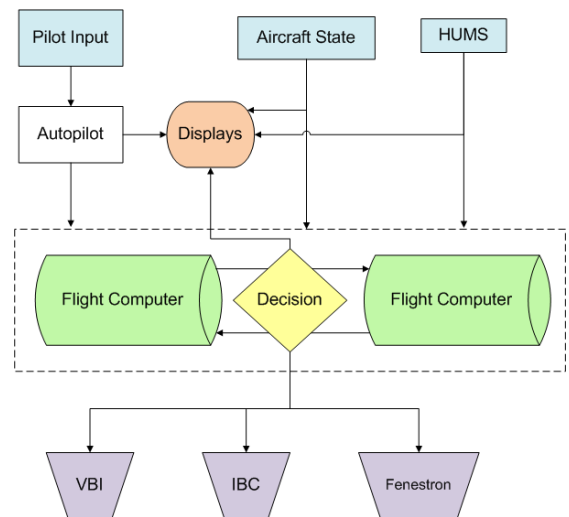
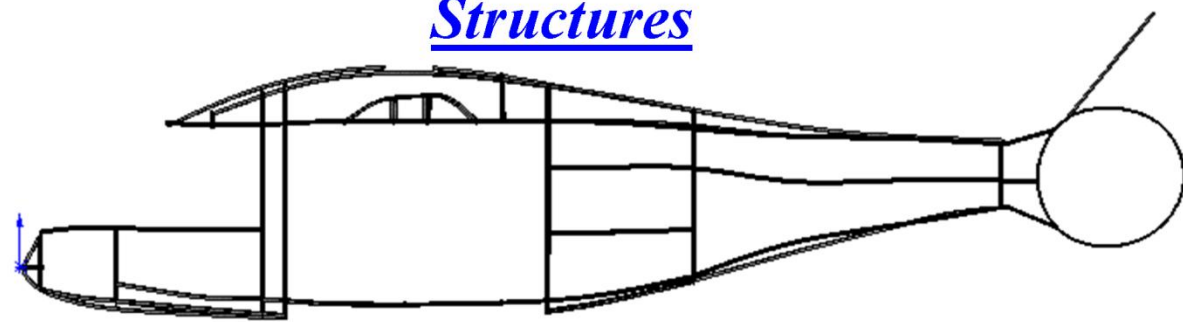


Figure 22: Basic Flight Control System Schematic

The flight control system will use input from the various sensors and avionics systems (detailed in Section 11.0) to provide the pilot with semi automatic takeoff and landing and auto hover capabilities. To take off, the pilot just needs to select desired departure heading. Based upon variables such aircraft loading, obstacles and wind, the Razor Rescue flight control system will select an appropriate takeoff course and then proceed on the selected heading. For landing and auto hovering, the pilot will need to specify the coordinates for the touchdown/hover point. The computer will then plot various approach paths, taking into account the previously mentioned variables and the pilot will select the one he/she wants to execute.

Foldout 6: Razor Rescue Fuselage Structures and Aerodynamics

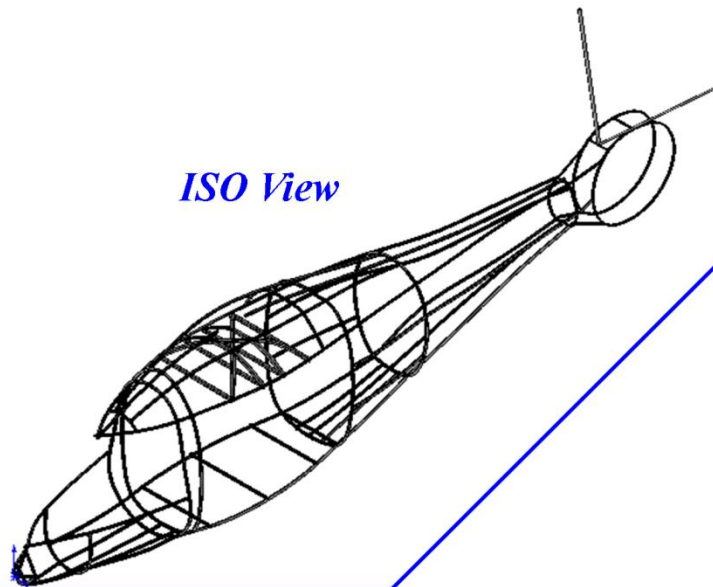
Structures



Side View

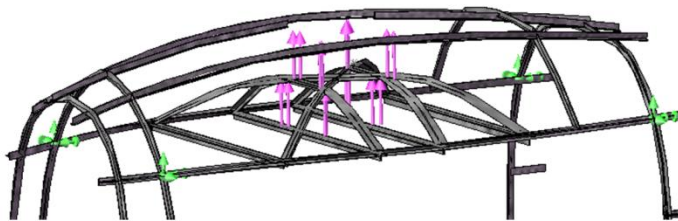
Structure Overview

ISO View

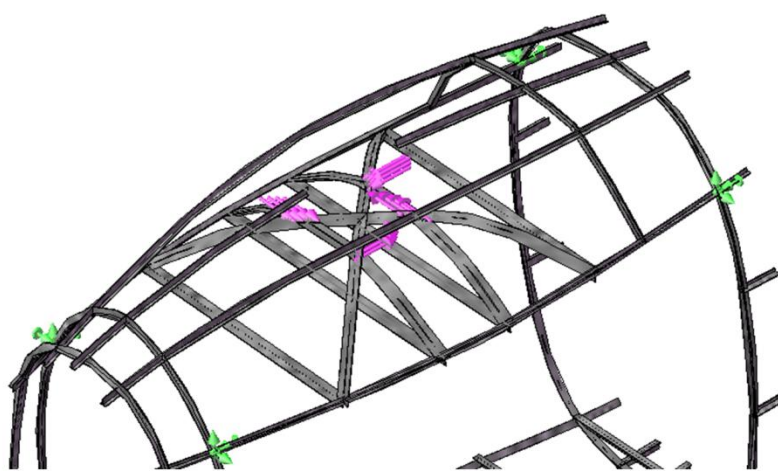


FEA Setup Examples

Rotor Lift

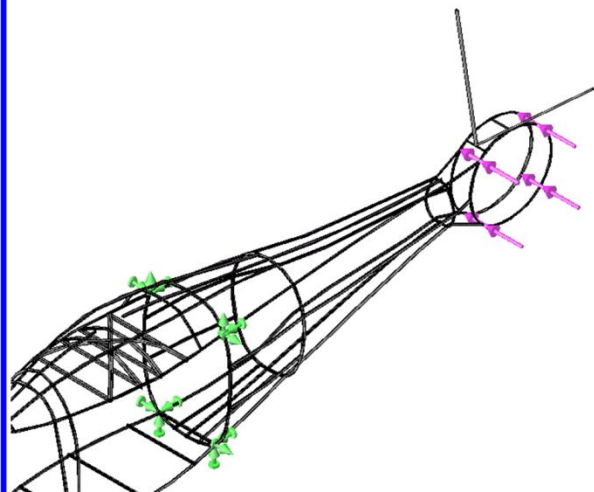


Rotor Torque on Main Fuselage



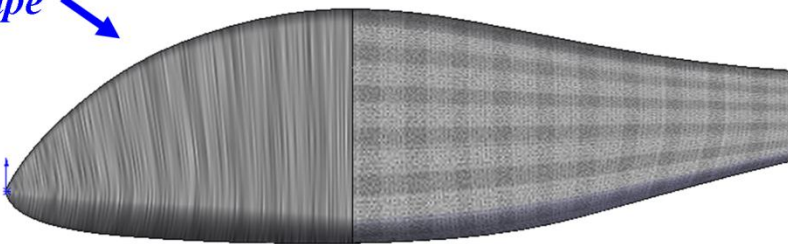
Purple arrows represent loads,
generated by rotor trim program
Green arrows represent restraints

Antitorque Force on Tailboom

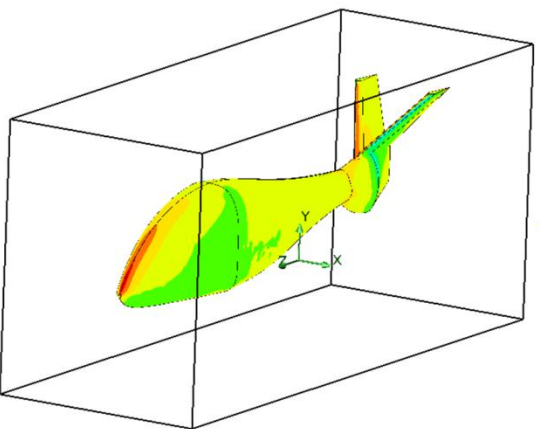
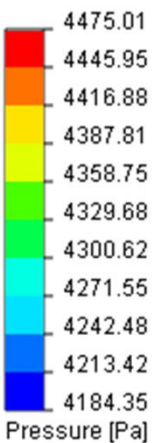
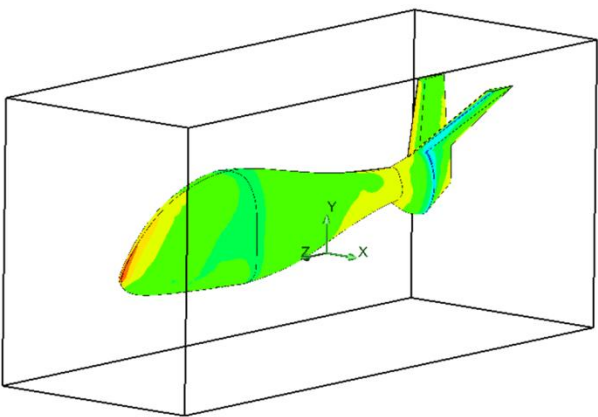
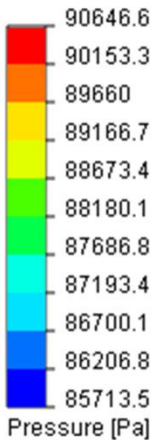


Aerodynamics

Main Fuselage Shape

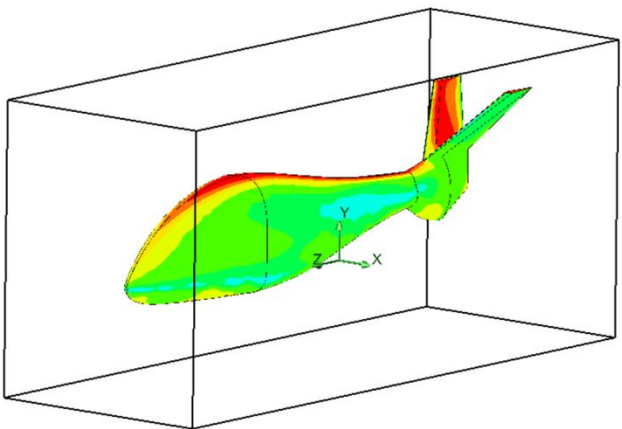
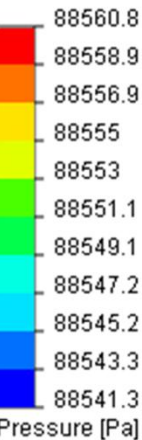


Fuselage 0° AoA



Fuselage -6° AoA
High Speed Forward Flight

Fuselage Hover Download



10.0 Airframe Structure and Aerodynamics

10.1 General Layout

The current layout for the Razor Rescue is one pilot up front with four passengers in the cabin. One of the reasons behind this choice is to limit the bluff body that would be created with the necessary space for two occupants in the nose of the helicopter. This allows for a much more streamlined nose which in turn allows for a decrease in drag. Also, the pilot as much more visibility, as he/she can see out of both sides of the aircraft. Maximizing the internal cabin space to allow for the multiple configurations that might be needed was another consideration used for this judgment. Adding a stretcher is possible by removing two seats on one side of the aircraft. Two attendants can then fly with the patient. Alternatively, all four cabin seats can be removed to use the internal space only to move cargo into the disaster area. A spacious cargo space aft of the main cabin further increases the internal volume of the aircraft. It is accessible from both the inside of the aircraft and through and an external door and is sized to carry the four passengers' luggage.

10.2 General Structural Layout

The structural layout consists of four primary areas: nose/cockpit, central fuselage, tail boom and fenestron. Five primary bulkheads serve to connect the different sections, to support loads and bending moments, and to support the engine and transmission deck. In addition, smaller bulkheads are used to maintain fuselage and tail shape as well as frame openings. Each of the major bulkheads has been placed to strategically take the loads from the major components of fuel, cargo, transmission, engine landing and anti-torque loads.

The first two bulkheads attach the nose to the main body, provides structural stability for the aviation rack and fuel as well as the forward mounting point for the skids. The second and third bulkheads provide support for the transmission deck. The transmission deck as been designed and analyzed to take the lifting and torque loads associated from the rotor as the rotor housing itself will double as a standpipe, further eliminating the need for extra support. The third bulkhead also is the mounting point for the aft section of the landing gear. The third and forth bulkhead provide structural support for the engine mounts as well as the cargo hold. The external shape of the fuselage and support for door openings is provided by secondary bulkheads located between the second and third primary bulkheads. Within the tail boom section are two secondary bulkheads and eight longitudinal stringers. The fifth bulkhead connects the fenestron to the tail boom. The fenestron has two secondary bulkheads supporting the ducted fan. It also has two D-spars supporting the V-tail. Rohacell foam "fingers" located between the second and third primary bulkheads provide the crashworthy structure.

10.3 Structure Analysis

The structure has been analyzed using COSMOS for the following loads: Lift from the rotor, Torque from the rotor, and moment cause by the Anti-torque. The choice behind which loads to analyze came from the trade-off between most important and the amount of time needed to perform the analysis. COSMOS, which is a FEM program coupled with Solidworks, was chosen to perform the analysis because of the ease of use. Changes can be made to the structure of the helicopter without the unnecessary hours that would be spent taking a model drawn using one CAD program and re-defining everything in a separate FE program, though in several circumstances it would take hours to run the analysis within COSMOS. Below in Table 10, the loads as well as factors of safety that were calculated for the different areas of the structure as well as screenshots from COSMOS are shown in the foldout.

Table 10: Results from COSMOS analysis

Load Type	Load	Factor of Safety
Lift	3800 lbs	1.32
Torque	1200 ft-lbs	1.35
Anti-Torque	3700 ft-lbs	1.27

The results show that the structure is more than capable of withstanding the required loads for lift, torque and anti-torque. The factors of safeties fall a little higher than most "standard" aerospace structures. This is optimal due to the decrease in checkups and downtime as well as the possibility to increase the overall lifespan of the helicopter. The longer a helicopter is used for, the more "green" it is towards the environment.

10.4 Exterior Shape Considerations

The external shape of the fuselage is mainly selected from a point of aerodynamic cleanliness as well as maximizing internal cabin space. The cross-section of the fuselage has a box-like shape to provide maximum usable interior space. The exterior shape of the aircraft also allows for clean aerodynamics assessed from the downwash of the rotor. The very gradual upsweep angle is intentional to eliminate the threat of flow separation and thus lowering parasite drag which would further hinder the aircraft's performance(68). This is a direct improvement over the EC-120's upsweep angle (shown in the foldout), which undoubtedly separates flow and causes a large increase in drag.

10.5 Aerodynamic Analysis

The flow around the fuselage was analyzed using FloWorks for the following conditions: Forward Flight at Cruise Speed at zero deg AOA, Forward Flight at Cruise Speed at 6 deg AOA and hover. FloWorks, a CFD program coupled with Solidworks, was used to analyze the flow for the different conditions. This program was used for the same reason COSMOS was used, it allows easy manipulation of the shape of the helicopter's skin without the unnecessary re-defining of it to perform analysis in a different CFD program. Below in Table 11, are listed the different drag loads that are associated with each condition as well as an image from FloWorks showing the calculation being performed.

Table 11: FloWorks analysis results

Type of Analysis	Drag (N)	Cross Sectional Area(m ²)
Forward Flight @ 0 deg AOA	321	2.21
Forward Flight @ -6 deg AOA	330	2.22
Hover	63	6.41

10.6 Crashworthiness

Rohacell foam fingers are being implemented as a means to provide the cabin with extra support and safety during the event of a crash (69). This energy absorbing material is designed to evenly spread the forces of a crash while using complex crushing modes to allow sustainable "g loads" for the helicopters occupants(70)(71)(72). The pilot and cabin crew all have stroking seats, which further absorb the energy from a crash.

10.7 Landing Gear

The selection of the landing gear configuration was driven by several factors including minimal flat plate area in forward flight to reduce drag, landing maneuvers conducted by "semi-professional" pilots and low maintenance.

After conducting a trade study on the major types of landing gear, skids were decided to be the best solution. Although retractable gear reduces total aircraft drag, it is heavier and more maintenance intensive than skids. The forward flight drag associated with skids will be minimal due to shaping them to reduce their equivalent flat plate area.

10.8 Doors

There are four doors for the main cabin and one door for the pilot. These doors open in a clamshell method. This allows for the largest usability of the internal space. In the event that cargo will need to "stick" out of the sides of the helicopter, the doors can be removed quickly with 2 bolts each. This type of construction will also allow the occupants to escape from the cabin in the event of a crash because the doors will not be obstructed as would be the case with sliding doors. The pilot's side windows will also have the capability of being removed from the inside in the event of a side crash.

11.0 Cockpit and Cabin Systems

11.1 Comfort of Passengers

There are five particular areas of interest regarding the overall comfort of the passengers during flight. These areas include: Seating, Environmental Control System, Internal Noise Reduction, Sun Protection, and Vibration Control.

11.1.1 Seating

Martin Baker's crashworthy passenger seat was chosen for the Rescue Razor for multiple reasons. This lightweight seat weighs only 23 lbs, while maintaining the capability to seat a wide range of passenger sizes and shapes. The seats four-point foot assembly allows it to be quickly installed or removed, which is ideal for this type of helicopter. The unique seat structure attenuates crash energy so the net forces acting on the passengers are significantly decreased. Adjustable armrests, headrests, lumbar and thigh support all help to maximize comfort during flight. Martin Baker's passenger seat is used in conjunction with a seat cushion designed by Oregon Aero. These cushions rotate the pelvis, and restore proper lumbar curvature, allowing the body to stay erect without effort, eliminating discomfort (60).

11.1.2 Sun Protection

The Razor Rescue is equipped with a sun protection system that is integrated into the windows themselves. This system, known as ECSmartGlass, consists of two outer glass layers, with two electroconductive coatings in between. These electrochromic windows change light transmission properties when a voltage is applied to them(61). In the "off" mode, the particles are arranged randomly, and the window is transparent. In the "on" mode, the particles arrange in such a way that they actually absorb some of the light, and the window appears tinted.

Changing the opacity can be remotely controlled by the pilot and only consumes two volts when the windows are tinted. The ECSmartGlass effectively blocks 99.5% of damaging UV rays, up to 98% of light, and reduces the cost/power required to heat/cool the passenger cabin(62).

11.1.3 Internal Noise Reduction

The main sources of noise inside the cabin interior stems from the engine and main gearbox. There are two methods to reduce cabin noise; passive techniques (which work best at middle and high frequencies, and active techniques (which work best at low frequencies)(63). For this reason, the Rescue Razor implements both methods in an attempt to maximize passenger comfort. Interior sound proofing material surrounds the main cabin, as well as the engine, transmission, and main gearbox.

Ultra Electronics UltraQuiet system is also used to reduce the low frequency noise levels. A noise cancellation speaker, the main component of the system, emits a sound wave with the same amplitude and opposite polarity to the original sound. The sound wave emitted from the speaker combines with the sounds generated from the helicopter to form a new wave, in a process called interference, and effectively cancel each other out. Microphones and digital signal processors are also imbedded in each of the headrests. The microphones continuously monitor the cabin noise, and the digital signal processor drives the loudspeakers, generating the anti-noise field(64).

11.1.4 Vibration Control

The original concept was to use passive methods such as dampers and shock absorbers. These devices attempt to use friction to convert vibration into heat. The main disadvantage however, is that they only work for a specific frequency. The Rescue Razor uses a variable speed rotor, and thus requires a damping method that will adapt to handle variations in vibration frequency.

Micromega Dynamics has developed an active control method that is capable of introducing structural damping into any vibration mode observed by the sensor. Their Active Damping Device (ADD) can offer better comfort with less weight than traditional passive technologies. The ADD produces an equal force that opposes the force created from external vibration. It consists of a vibration sensor, actuator, and a controller. According to Micromega Dynamics: "...frequency variation of 100% have been observed without performance degradation." These stand-alone systems are placed throughout the helicopter at the multiple sources of vibration(65).

11.1.5 ECS

The Environmental Control System (ECS) is based on the Bell 206 model, produced by Keith Products. Components include; heater, compressor, condenser, aft evaporator blower, and forward and aft evaporators. The bleed air heater,

Foldout 7: Razor Rescue Systems

List of Subsystems

System	Public	Para-Military	Military	Weight (lbs)	Power Req'd (W)
Avionics					
LN-251 Embedded INS/GPS System	X	X	X	12.7	30
TDFM-7000 Multiband Airborne Transceiver	X	X	X	6	62.5
MH-60R/MH-60S Multi-Function Display	X	X	X	23.9 x 2	127.5 x 2
Custom Multi-Function Display	X	X	X	8.74	85
Transponder	X	X	X	1.6	40
KGP560 Enhanced Ground Proximity Warning Sys.	X	X	X	1.5	70
AN/AAR-54(V) Missile Warning System			X		
Sensor			X	3.85	8
Electronics Unit			X	10.5	34
Flight Management System	X	X	X	12.3	60
Lighting					
Forward Facing Recognition Floodlight Triple LED	X	X	X	0.25 x 2	18 x 2
Anti Collision Light	X	X	X	2.5	15
Interior Light	X	X	X	0.86 x 2	23.8 x 2
Cockpit light	X	X	X	0.044 x 2	7 x 2
Landing/Taxi Light w/ Power Supply	X	X	X	3.54	45
Weapons					
Hydra 70 Rocket (M151)			X	9.3 x 7	
MK66 MOD 4 Motor			X	13.6 x 7	
M260 7 Tube Light Weight Launcher			X	73.8	
M240D 7.62mm MG		X		20.48	
M-2.50 Cal MG			X	27	

System	Public	Para-Military	Military	Weight (lbs)	Power Req'd (W)
Other Systems					
Tactical Searchlight		X	X	27.3	140
External Electric Rescue Hoist	X	X	X	80.48	
First Aid Kit	X	X	X	1.43	
F010 Fire Extinguisher	X	X	X	10	
Armored Crew Seat			X	72.25 x 4	
Passenger Seat	X	X		20 x 4	
Armored Cockpit Seat			X	80.75 x 1	
EAD01 External Fast Roping/Rappelling Device		X	X	21.17	
Internal/External Airbags	X	X	X	23	
Foldable Stretcher		X	X	14	
Firewalls	X	X	X	0.002 lb/sq in	
Sound Proofing Interior	X	X		1 lb/sq ft	
Starter Generator	X	X	X	16.15	
Windshield Wipers	X	X	X	8.2	
Auxiliary Battery	X	X	X	24.6	
Polastar Escape Window Lighting Sys. (2 Doors)	X	X		17.64	
Emergency Rotation Gear	X	X	X	76.5	
Wire Strike Protection System	X	X	X	11	
Air Ventilation System / Cabin Fan	X	X	X	6.2	
ECS	X	X	X	81	
Automated external defibrillator	X	X	X	8	
Vibration Damper	X	X	X	6.6	
STS 1400 Radar System	X	X	X	22	

List of Control Panel Gauges/Warning Lights

Gauges	Warning Lights
Vertical Speed Indicator	Low Fuel
Airspeed Indicator	Low RPM
Altimeter	Low Oil
Dual Tachometer	Clutch
Manifold Pressure	MR Chip
Engine Oil	MR Temp
Engine Torque	Starter On
Transmission Oil	TR Chip
Fuel	Engine Failure
Oil Temperature	Engine Fuel Pump inoperative
Generator	Battery Hot
Horizontal Situation Indicator	Secondary Lube Pump On
Clock	Open Door
Compass	Generator Failure
Engine Temp	
Outside air temp	
Battery Temp	
Fuel Flow	

Sub-System Weight and Power Tech Factors

System	Weight (lbs)	% Reduction	New Weight
M260 7 Tube Light Weight Launcher	82	10	73.8
M240D 7.62mm MG	25.6	20	20.48
M-2.50 Cal MG	30	10	27
Tactical Searchlight	39	30	27.3
Armored Cockpit Seat	95 x 1	15	80.75
Armored Crew Seat	85 x 4	15	72.25
External Fast Roping/Rappelling Device	26.46	15	21.17
Starter Generator	19	15	16.15
Emergency Rotation Gear	90	15	76.5
ECS	90	10	81
External Electric Rescue Hoist	100.6	20	80.48
Auxiliary Battery	41	40	24.6
System	Power Req'd (W)	% Reduction	New Power Req'd
MH-60R/MH-60S Multi-Function Display	150 x 2	15	127.5
Custom Multi-Function Display	100	15	85
Tactical Searchlight	175	20	140
Multiband Airborne Transceiver	125	50	62.5

Safety Subsystems

Personal Safety/Passenger Aid

First Aid Kit	Treat personal injury
Firewalls	Protect from on board fire
Automated External Defibrillator	Treat cardiac arrest
Foldable Stretcher	Transport injured passengers
Fire Extinguisher	In case of on board fire

Operational Safety

Snow Baffle	Protects engine against snow intake
Wire Strike Protection	Protects against collision with cables
Top Owl Helmet Mounted Display	Increase pilot situational awareness
Rupture Resistant Fuel Containers	Protects fuel from leaking
Anti-Ice System	Prevents windshield icing
Windshield Wipers	Prevents rain obstruction

Crashworthiness

Energy attenuating seats	Reduces force on passengers during a crash
Armored Cockpit Seat	Protects pilot against small arms fire
Stratoflex Fuel Breakaway Valve	Contains fuel if fuel container and fuel lines separate
Internal/External Airbags	Helps to reduce head/neck injury
Emergency Rotation Gear	Keeps aircraft afloat if crash is in a body of water
Polastar Escape Window Lighting System	Visual aid for disoriented passengers

Sector Specifications

Sector	Weight (lbs)	Power Req'd (W)
Civilian	683.184	992.7
Para-Military	752.134	1132.7
Military	1144.974	1216.7

which is connected to the aft evaporator blower, uses bleed air from the engine mixed with the cabin air. The cooling system is a vapor cycle cooling system using refrigerant 134a. The compressor is driven by a shaft forward of the engine. The condenser draws in air from an intake on the left side of the helicopter, and the forward/aft evaporator blowers provide cool air to the cockpit/cabin respectively(66). Although the avionics are primarily cooled via ambient air from vents in the front of the helicopter, a separate duct routed from the ECS provides additional cooling.

11.1.6 Safety

11.1.6.1 Avionics

The Razor Rescue needs to have the capability of semi-automatic take-off and landing to allow use by non-professional pilots. This is achieved through the integration of five avionics systems to include: Flight Management System, Enhanced Vision System, Synthetic Vision System, Helmet Mounted Display, and an advanced Radar System. These components will significantly increase pilot situational awareness and allow him/her to focus on simply piloting the helicopter.

11.1.6.2 Flight Management System

The Flight Management System (FMS) allows for advanced flight planning with the aid of the internal INS/GPS system and the internal terrain database. Through the use of such features as; parallel offsets, route to an alternate, direct routings, and waypoint insertions, the system can guide the Razor Rescue along specified paths for different missions. The system is based on the Rockwell Collins FMS-4200, which includes the flight management computer, and the control display unit located on the main control panel(67). The FMS will increase situational awareness, decrease pilot head down time, and create simple navigable routes.

11.1.6.3 Enhanced Vision System

Flying an aircraft during normal operating conditions can be challenging enough, and with night operations and/or low visibility, it can become nearly impossible. The Enhanced Vision System (EVS) enables the pilot to see in all directions and conditions, including low visibility, increasing safety and situational awareness (68).

The system uses multiple imaging sensors that are digitally fused together to project an image on a Helmet Mounted Display. The EVS approach is designed to expand the pilot's visual capability beyond the limits of current aircraft windows, canopies, and Heads Up/Helmet Mounted Displays giving the pilot “see-through the aircraft” capability. The EVS is limited however by the viewing range of the imaging sensors (69).

11.1.6.4 Synthetic Vision System/Radar System

The Synthetic Vision System (SVS) essentially paints a picture of the outside world not covered by the EVS. A 3-D image of the area outside the helicopter is created using the terrain database to support the EVS. Although the support of the SVS is very beneficial, and gives the pilot a complete visual image out of the helicopter, the Razor Rescue will be operating in neighborhoods surrounding cities, and areas following earthquakes or other catastrophic events. The SVS is only as good as the terrain database which it is operating off of, and it will not have detailed information of recent changes to local geography (69).

The radar system, located in the nose of the helicopter, is able to correct for this lack of data. The system is based on ICX Radar Systems’ Millimeter Wave Perimeter Security Radar (PSR). It can paint a real time image of the surrounding area, including personnel, up to 1400m away. Scanning a 360 deg field of view every second, it can detect as close as 2m (70). This is critical for warning the pilot of encroaching tree lines and landing area blockage.

11.1.7 Safety Equipment

The Razor Rescue is equipped with a wide variety of safety features ranging from first aid kits to laser missile warning systems. The safety systems are separated into three sections; Personal Safety/Passenger Aid, Operational Safety, and Crashworthiness. A complete list of each section, along with a brief description of each system is located in Foldout 7.

11.1.8 Cockpit Systems

The main flight control panel consists of three Multi-Function Displays (MFDs), the Flight Management System (FMS), the Enhanced Ground Proximity Warning System (EGPWS), communication equipment, a transponder, and 15 warning lights. The lights provide indication of failures in the specified areas; Fuel, Oil, Temperatures and Pressures. The complete list of warning lights and gauges features on the control panel can be seen in Foldout 7.

The side panel is located to the left of the pilot above the collective pitch. It consists of the main circuit board, engine, lighting, vent, heat, hoist power, and anti ice controls. The pilot has the ability to control lighting, cooling, and heating of both the cockpit and the cabin from this panel, although the passengers will have access to vents, which can be opened/closed. Lighting, internal and external, includes; forward facing recognition flood light, tactical searchlight, landing/taxi light, and individual cockpit/cabin lights.



Figure 23: Main Control Panel

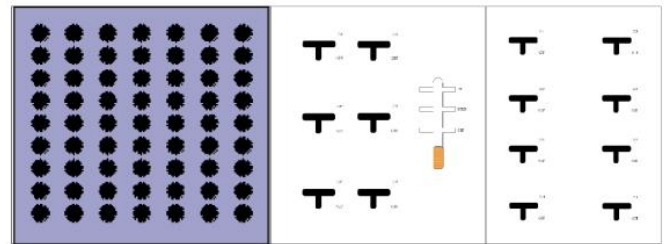


Figure 24: Side Control Panel

11.1.8.1 Multi-Function Displays

There are a total of three Northrop Grumman MFDs on the flight control panel. The lower MFD, and one of the top MFDs will display the primary gauges listed in Foldout 7. The third MFD, while able to display other indicators, is primarily used to display live video feed during rescue missions, hover conditions, weather patterns, or even radar map and windshear. The MFD's Active Matrix Liquid Crystal Display is bright enough for sunlight readability, while sensitive enough for night missions and night vision(71).

11.1.8.2 Enhanced Ground Proximity Warning System

Honeywell's Bendix/King KGP 560 Enhanced Ground Proximity Warning System (EGPWS) utilizes its advanced terrain and obstacle database to help protect against controlled flight into terrain. The look-ahead algorithms use position, altitude, and flight path of the helicopter to detect terrain or obstacles approximately one minute away. The visual and audio warnings ensure the pilot is aware of the threat as soon as it's detected(72).

11.1.8.3 Communication Systems

The Razor Rescue's communication equipment consists of Technisonic's TDFM-7000 Airborne FM transceiver, along with a cockpit to cabin intercom system. The transceiver supports up to four bands, each capable of storing 510 channels with simultaneous operation on each band(73). The intercom system includes throat microphone and earpiece devices. This allows for quick, hands free communication between the cockpit and cabin. This is crucial during rescue operations in which wounded civilians/soldiers are being transported and cared for.

11.1.8.4 GPS

The Northrop Grumman LN-251 is an integrated, lightweight, embedded INS/GPS System that provides superior positioning performance to other compatible systems. Its open architecture system allows for easy adaptation to changing mission requirements(74).

11.1.8.5 *Mission Specific Equipment*

The Razor Rescue is designed for multi-purpose transport missions in areas of high congestion/devastation where ground transport is not feasible. Transportation could potentially range anywhere from food or other materials to wounded civilians or soldiers. Important equipment necessary to complete this mission includes; searchlight, radar system, and rescue hoist.

11.1.8.5.1 *Radar System*

Locating individuals in disaster areas, potentially during night missions with limited visibility makes this no easy task for the pilot. The STS 1400 Perimeter Surveillance Radar System is located in the nose of the helicopter, and can detect moving vehicles and personnel anywhere from 2m - 1400m away. It can effectively operate in virtually any climate, weather, or lighting condition(70).

11.1.8.5.2 *Searchlight*

The TrakkaBeam Tactical Searchlight is ideal for military, law enforcement, and search and rescue applications. It uses a Xenon lamp half the size of traditional searchlights to project a more intense and concentrated beam on the intended target(75). The system is located in the storage compartment beneath the engine, and is retractable to reduce drag during forward flight.

11.1.8.5.3 *Rescue Hoist*

Goodrich's Electric Rescue Hoist is located in the cabin above the passengers head. There are two different set ups depending on the application. The hoist cable will either be directed through the cabin floor for sling loads, or over a pulley on the doorframe. With the capability of hoisting up to 600 lbs, the system can effectively lift/lower a wide range of people and materials(76).

11.1.9 *Sub-Systems*

The complete list of Sub-Systems can be seen in Foldout 7. This table includes the overall weight and volume of each sub-system, as well as a breakdown of which systems appear in each of the three sectors to include: Civilian, Para-Military, and Military. Foldout 7 details the specifications regarding overall weight and volume for each of the three sectors. The foldout also references tech factors applied to specific system weights and power required respectively. These numbers are based on changes made and additional information gathered during the research phase, and well as predicted drops in weights regarding new materials and advancements potentially available by 2020.

12.0 Multiple Sectors

The Razor Rescue is designed for all conceivable Civilian, Para-military, and Military missions. Due to the potential differences in mission goals/conditions, there are several mission specific systems that do not appear on the Civilian version, which is specifically designed to deal with multi-purpose transport missions. The only real conceivable danger to the helicopter and crew consists of the surrounding terrain upon landing, weather, and potential collisions with obstacles such as terrain or other aircraft. These threats have all been compensated for through the use of specific avionics equipment to help increase safety and pilot situational awareness. The Razor Rescue's Para-Military version may have to deal with such situations as search and seizures in coordination with local law enforcement. The Military version may conduct short to medium range reconnaissance missions in hostile areas surrounding these cities. For this reason, the defensive capabilities of these versions is essential.

The Civilian version is not equipped with weapon systems. The Para-military version has an M240D machine gun mounted on the underbelly of the helicopter, between the landing skids. The Military version has an M2 machine gun, and an M260 Lightweight Launcher, capable of firing seven Hydra 70 Rockets. These weapon systems are mounted on struts on either side of the fuselage. Both the Para-military and Military versions also have a missile warning system, an armored cockpit seat, and a rappelling device. The armored seat will protect the pilot from multiple rounds of ammunition no larger than 7.62 mm. This is important when landing troops or supplies in hostile areas. The

rappelling device allows for the crew to evacuate the helicopter fast, easy manner without the need for the helicopter to land. The engine is up-rated to deal with potential increases in performance demands. Details each aircraft versions' installed systems can be found in Foldout 7.

13.0 HUMS

The Health and Usage Monitor System (HUMS) is utilized by the Razor Rescue to reduce maintenance costs and increase safety. Sensors are located throughout the helicopter to monitor the current health of critical mechanical systems. The pilot will be able to access this information from the cockpit. Once on the ground, the maintenance crew will be able to get an even more detailed analysis, including prognostics. This predictive software will allow for the crew to order parts on a need basis, instead of a simple time table for the critical parts. This will greatly reduce the cost of parts as well as the time spent searching for problems.

13.1 Sensors

Sensors will be mounted to areas of the rotorcraft that typically need careful inspection before flight or need maintenance often. Accelerometers are

Table 12: HUMS Sensor Information

Location	Sensor Type	Description
Each blade root	Accelerometer	Auto blade tracking for controls
Each blade flex beam	Strain gauge	Monitors loads on flex beam
Pitch housing	Rotation sensor	Monitors relative position
Blade grip	Rotation sensor	Monitors relative position
Main hub	Rotation sensor	Monitors relative position
Transmission input	Torque meter	Torque data for prognostics
Transmission output	Torque meter	Torque data for prognostics
Main gearbox	Accelerometer	Vibration data for prognostics
Fenestron gearbox	Accelerometer	Vibration data for prognostics
Engine mounts	Accelerometer	Monitors vibration for balance
Turbo compounder	Accelerometer	Vibration data for prognostics
Turbo charger	Accelerometer	Vibration data for prognostics
Electrical generator	Current sensor	Monitors output current
One fenestron blade	Strain gauge	Monitors loads on blade
V-tail	Creep sensor	Creep data for v-tail research
V-tail	Strain gauge	Load data for v-tail research

used to measure vibrations throughout the aircraft, and strain gauges are used to detect stresses and loads. Table 12 shows a list of sensor locations for the Razor Rescue and a short description of its purpose. Some sensors send information to the flight control computer so that in case a catastrophic failure occurs, the computers can make compromises in controls to ensure a safe landing. The health of these critical areas will also be displayed in the cockpit for the pilot's convenience.

13.2 Ground Station

The HUMS information gathered during flight is then stored on board the Razor Rescue. Soon after landing, the information is downloaded into a ground station PC on the ground. This ground station uses software to identify areas for maintenance and special attention. The ground station will have a user-friendly graphical user interface (GUI) highlighting the areas for maintenance. The GUI will also have technical manuals on file for the entire aircraft, and will automatically attach the proper manual to all work orders. The ground station will also access the parts inventory to check for availability, and order parts if needed.

The HUMS ground station also uses previously recorded data to train prognostic software that predicts future failures throughout the Razor Rescue. If a certain part has a particularly long lead time, the prognostic software will predict the remaining life of the part and place an order so that it's on location when it needs replaced. This greatly increases efficiency and reduces down-time for the aircraft. The ground station also has a quick critical areas check option to give the Razor Rescue a "walk-around" before take-off. This helps keep the take-off time below 10 minutes after being positioned on the heli-surface, which is a requirement in the RFP. Overall, the HUMS system will greatly increase safety and reduce maintenance costs for the Razor Rescue

14.0 Acoustics

“A helicopter is a one man band, its turbine exhaust blaring a piercing wine, the fuselage ski’s vibration rumbling like a drum, the tail rotor rasping like a buzzsaw.” (77) Helicopters are typically louder than similarly sized fixed wing aircraft due to the nature of their rotor systems. In addition, helicopters are perceived to be louder by the public because they operate much closer to populated areas due to their runway independence. Since the Razor Rescue will be performing disaster relief, police, and military missions, the noise is of utmost importance.

14.1 General Noise

Many communities and airports have enacted standards against excessive noise. The current International Civil Aviation Organization (ICAO) has a limit of 85.4 dB, but some towns have tougher standards. Davis City, CA has a limit of 65 dB, which is much higher than current helicopters.

14.2 Noise Reduction

14.2.1 General

The comprehensive solution to reduce noise was modeled after the Quiet One, a highly modified OH-6 Loach used during the Vietnam War to place wiretaps on the North Vietnamese phone lines. Modifications included an extra main rotor blade, swept tips, reduced tip speed, scissors tail rotor, and exhaust muffler. These adaptations reduced noise so much that one operator remarked “I’d stand on the [landing pad] and try to figure out the first time I could hear it and which direction it was coming from. I couldn’t place it until it was one or two hundred yards away” (77).

Many of the features of the Quiet One were retained on subsequent designs. The MD-500 series of aircraft (descendents of the Hughes 500) retained the 5 bladed main rotor and the AH-64 Apache features a scissors tail rotor. Today, the MD-520N is one of the quietest helicopters in the world due to the combination of Quiet One and NOTAR technology. However, the project engineer for the covert helicopter at Hughes, Rod Taylor, recently remarked that “There is no helicopter today as quiet [as the Quiet One]” (77). The Razor Rescue aims to achieve noise levels on par with the Quiet One, much quieter than the current EC-120B, which produces 78.7dB in hover. This goal is achievable because both aircraft are in the same weight class.

14.2.2 Main Rotor

14.2.2.1 BVI Noise

The Razor Rescue reduces noise in a variety of ways. The most important feature is the very low tip speed during low speed and hovering flight. This greatly reduces the noise while the aircraft is closest to an objective and when noise is most critical. Although this increases the drive system weight, this tradeoff was considered to be good.

At higher forward speeds, the rotor speeds up to improve aircraft performance by reducing retreating blade stall. This increases overall noise, but in this flight regime it is not as important because the aircraft will be farther from persons on the ground. In addition, the atmosphere can attenuate a significant portion of the noise.

In addition, the Razor Rescue features five main rotor blades. This lowers the loading and subsequent pressure disturbance caused by each individual blade, spreading out the noise to higher frequencies. Also, the blade tips have significant anhedral. The anhedral increases the “miss distance” between a rotor tip and the vortex shed by a previous blade, which further reduces BVI noise.

14.2.2.2 Thickness Noise

The RC(4)-10 and RC(5)-10 airfoils, which comprise most of the blades, are relatively thin. At the tips, the even thinner RC(6)-8 airfoil is employed. Using these airfoils, thickness noise is minimized.

14.2.2.3 Loading Noise

Variable twist modifies the blade loading distribution by offloading the tips. The control system, aided by tapered tips, maintains this loading throughout the flight regime, which reduces the loading noise.

14.2.3 Tail Rotor

The tail rotor has often been identified as one of the loudest helicopter components because it operates in the highly unsteady and turbulent wake of the main rotor. In addition, the tail rotor operates at a high rpm, so the noise that it generates is particularly annoying to humans because it is in the band of frequencies that the ear is most sensitive.

The Razor Rescue features a fenestron anti-torque device. This system offers significantly lower noise than a conventional tail rotor because the shroud protects the blades from interacting with the rotorwake. Furthermore, the 10 blades are unevenly spaced, which spreads out the noise over a larger range of frequencies, reducing the perceived noise level.

14.2.4 Engine

The SCRT exhaust cleaning system functions as a muffler for the engine. The exhaust is vented upwards, so while the aircraft is flying overhead, the fuselage reflects most noise away from the ground.

15.0 Green Design

The most important aspect of the Razor Rescue is its friendliness to the environment. High focus was taken into minimizing fuel consumption and, therefore, reducing pollution to the atmosphere during operation. Materials also played a role because manufacturing is a point of high concern in pollution emissions. Recommendations on manufacturing processes, treatments, and recyclability will be given to help reduce overall emissions, harmful health hazards, and minimize overall energy consumption.

15.1 Local Pollution

Local pollution is the pollution emitted from the exhaust of the engine while in operation. The most harmful emissions of local pollution are:

1. Carbon Monoxide (CO) – is a colorless, odorless, poisonous gas. It often oxidizes in to carbon dioxide and contributes to greenhouse gases and global warming.
2. Hydrocarbon (HC)- contribute to depletion of ozone and causes smog.
3. Nitrous Oxide (NOx)-cause a variety of health and environmental problems. One example of a health effect is NOx particles causing emphysema. Environmental impacts are smog, acid rain, water deterioration, and climate change(78).
4. Particulate Matter (PM)-has less environment effect but is the unhealthiest of the pollutants. It has been linked to asthma, lung cancer, cardiovascular diseases, and premature death.
5. Sulfur Oxides-have strong and unpleasant odors in high concentrations. Because they are concentrated near ground level, they often contribute to vegetation damage. They also have been linked to causing respiratory ailments (79).

15.1.1 B20

The Razor Rescue will be featuring a biodiesel blend of 20% biodiesel and 80% ultra-low sulfur diesel. Ultra low sulfur diesel will meet U.S. regulation emission standards for 2014 for non-road vehicles such as helicopters. It features a 97% reduction of sulfur compared to present diesel. The black soot exhaust from diesel engines will no longer be a problem. It also comes from almost no extra energy consumption for refineries and will only minimize when put into mass production(80). The 20% biodiesel used to mix with the ULSD will help with operational pollution. It will reduce emissions of Carbon Monoxide, Hydrocarbons, Particulate Matter, and Nitrogen Oxides(81)(82). However, nitrogen oxides increase about 2% with biodiesel blend.

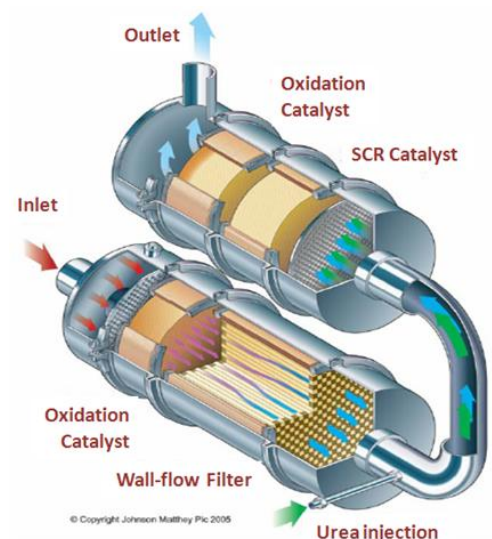


Figure 25: SCRT System (16)

15.1.2 Selective Catalyst Reduction (SCRT)

SCRT system is an exhaust emission control system that combines a particulate filter system with a selective catalytic reduction catalyst. The CRT particulate filter reduces particulate matter by 85%. The SCR catalyst reduces nitrogen oxides by 90% and reduces carbon monoxide and hydrocarbons between 85 to 95 percent.

This system will be placed right outside the engine exhaust rather than within the engine, which would minimize overall performance. As Figure 25 shows, the exhaust would first flow through the CRT diesel particulate filter to reduce CO, HC, and PM. This component only requires urea injection coming from a tank size of 7.5 gallons(83). This urea is injected in a controlled amount into the exhaust prior entrance into SCR component.

15.1.3 Pollution Reduction

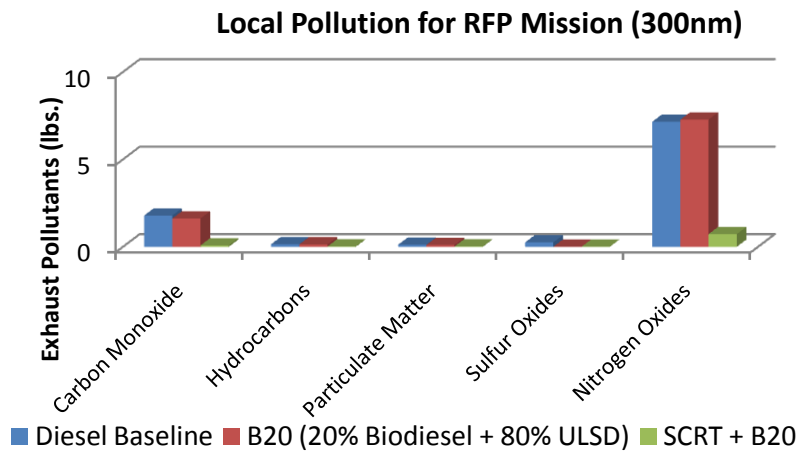


Figure 26: Local Pollution Comparison

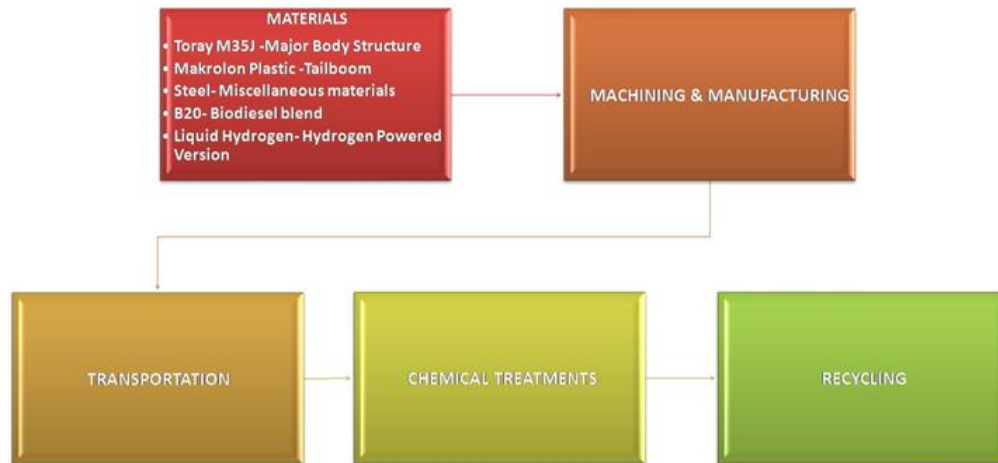
Table 13: Pollution Reduction

Emission	Overall Percent Reduction
Carbon Monoxide	95.46
Hydrocarbons	86.10
Particulate Matter	82.72
Sulfur Oxides	97.52
Nitrogen Oxides	89.82

Figure 26 displays the results of using B20 fuel and an SCRT system and their effects on the overall local pollution. Knowing how much exhaust pollution was within diesel exhaust in pounds per horsepower per hour, a comparison could be made with baseline diesel exhaust(84). The basic mission of the Razor Rescue was used for this comparison where an average of 233 horsepower was used for 2.9 hours. B20 caused minor change in exhaust pollutants but did manage to reduce CO and SO₂. The SCRT had enormous effects on the pollutants. All harmful emissions were reduced to almost to the hundredths of pounds and nitrogen oxide was reduced to point where it would have minimal effects on atmosphere. The overall percent reductions are shown in Table 13.

15.2 Complete Pollution Chain

This pollution will take into account in detail of possible effluents discharged and health hazardous materials that could come from manufacturing, treatments, transportation, and recycling. Some possible solutions will be given to rid or minimize some of these problems.



15.2.1 Machining & Manufacturing

15.2.1.1 M 35J Carbon Composites

Electron beam curing is a future development to manufacture carbon composites. Using a linear accelerator, a stream of electrons is able to cure epoxy resins. Most Aerospace grade composites are normally made through autoclaves at a temperature of 350°F. This requires high energy with often nitrogen gas filled tanks. E-beam curing ultimately requires less energy and will not produce any emissions during process(85). The mechanical properties are still comparable and the same high-grade epoxies can be used.

15.2.1.2 Makrolon Plastics

Makrolon is made through process of thermoforming where sheets of plastics are heated to a certain temperature. Then, they are pressed onto a specific mold to create the wanted shape. Makrolon has no ozone depleting substances such as chlorofluorocarbons, halons, or carbon tetrachloride. It is also has no harmful heavy metal compounds such as lead or mercury. However, Makrolon plastics do contain small traces of hydrocarbons but it is less than .02% (86).

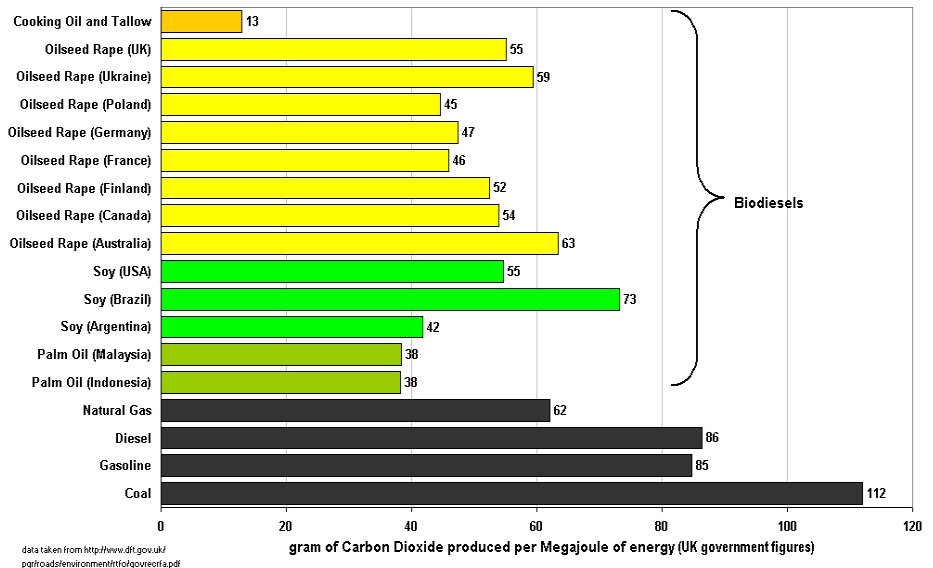


Figure 27: Biodiesel Production Emissions

15.2.1.3 B20 Fuel

Biodiesel are a form of solar energy, as plants use photosynthesis to convert solar energy into chemical energy stored in the forms of oils, carbohydrates, and proteins. The more efficient a particular plant is at converting solar energy into chemical energy, the better biofuels are as a source of energy(87). The most photosynthetically efficient plant is algae. Lots of research is being performed to test mass production of biodiesel in algae farms. An algae farm the size of Maryland could replace all the petroleum in the world(7). However, this process has not necessarily been proven, so biodiesel production will be assumed to be from the next best plant, soybeans. The overall lifecycle emissions of carbon dioxide from biodiesel are 78% lower than the overall carbon dioxide emissions from petroleum diesel as shown in Figure 27. The reduction is a direct result of carbon recycling in soybean plants. Carbon monoxide life cycle emissions are 35% lower in biodiesel than regular diesel and particulate matter is 32% lower too.

15.2.1.4 *Hydrogen (2040 option)*

The emissions and energy consumed in the production of hydrogen is holding this option back. By 2040, there should be an efficient infrastructure in hydrogen production. Hydrogen will be assumed to be produced using the power from wind turbine farms in 2040. Wind turbine farms are becoming popular and mass production of them using composites is being investigated, which will reduce the overall emissions in the complete pollution chain. Wind turbine farms will minimize any manufacturing emissions produced from other power generators(88).

15.2.2 Chemical Treatments

15.2.2.1 *Gear Superfinishing*

A process currently in research to improve helicopter gears in durability. Due to intense and constant friction, gears are worn out and need to be replaced resulting in more energy usage and chemical treatments for gears. The process is done through a ceramic medium on a vibratory surface. This process could emit possible harmful chemicals into the air that advises the person in charge to wear mask filters. The gear lifespan has increased by 22% (89).

15.2.2.2 *Oil Lubrication*

Current problem of oil systems is that extra oil is wasted after each mission. A device called Allen VP30-1S portable filtering system can purify unused oil for reuse. It can be implemented after the helicopter returns and lands on its home base.

15.2.3 Transportation

It is assumed that not all of our products will be manufactured by the same company, so there will be pollutions during transportation. If regular gasoline or Jet-A fuel was used during transportation, then there will be some amount of carbon monoxide, sulfur dioxides, particulate matter, carbon dioxide, and nitrogen oxides emissions as a result. It is recommended that environmental forms of transportation be used when possible. Railways and boats provide efficient ways of transportation for mass transport with minimal emissions.

15.2.4 Recycling

Large advancements have been made to the recycling of carbon composites. Milled Carbon Ltd, has a new process, which turns rejected carbon parts into a valuable reusable material. The process includes pyrolysis that removes any resin or binder from the carbon. The result is material with just slightly lower in mechanical properties than new products (90)(91).

Makrolon is recycled by means of careful separation from other materials. It is, then, regranulated and reintroduced into the extrusion process. The quality of Makrolon plastics can be very high as long as the original material was close to clean. Makrolon can also be incinerated because it only contains carbon, hydrogen, and oxygen, which burn very cleanly. Its high calorific value makes it very advantageous to generate energy.

Steel will have the ability to be recycled. 100% of the steel will be melted down and recreated into new products. Steel does not lose any of its inherent physical properties during the recycling process, and has drastically reduced energy and material requirements than refinement from iron ore. The energy saved by recycling reduces the annual energy consumption of the industry by about 75%, which is enough to power eighteen million homes for one year(92).

15.3 Overall Energy Consumption

15.3.1 Carbon Composites

Optimally designed, the high stiffness-to-weight ratio of carbon fiber composites enables weight savings of 75 to 80 percent versus steel, 30 to 40 percent versus aluminum, and up to 50 percent versus fiberglass SMC. This weight savings saves amount of installed power from the engine and thus reduces overall energy from fuel production and consumption. Carbon composite fatigue life saves energy of maintenance as compared to an aluminum fuselage, which would require frequent part replacements. Composite versus aluminum or steel structures often experience similar amount of maintenance for the first 15 years, but thereafter maintenance costs begin to rapidly soar with the onset of steel corrosion and aluminum fatigue cracking(91).

15.3.2 B20

The total fossil energy efficiency ratio of biodiesel compared to diesel is 3.215% versus .8337% respectively. The ratio is based on total fuel energy divided by total fossil energy used in production, manufacture, transportation, and distribution. This means biodiesel is four times as efficient as diesel fuel. Biodiesel is able to produce 3.2 units of fuel for every unit of fossil energy consumed in the lifecycle as compared to diesel's .83 units of fuel(87).

15.3.3 Hydrogen (2040 option)

The main concern with hydrogen fuel is the high-energy costs of creating and implementing it. There is current research into developing a viable infrastructure for hydrogen(93). It is estimated that this system can be created by 2030, so a 2040 outlook is promising for the Razor Rescue. The liquid hydrogen will be produced by means of wind turbine power as shown in Figure 28Error! Reference source not

ound.. Wind turbines transfer energy from wind to mechanical power. This will reduce the large power requirement for electrolysis(94).

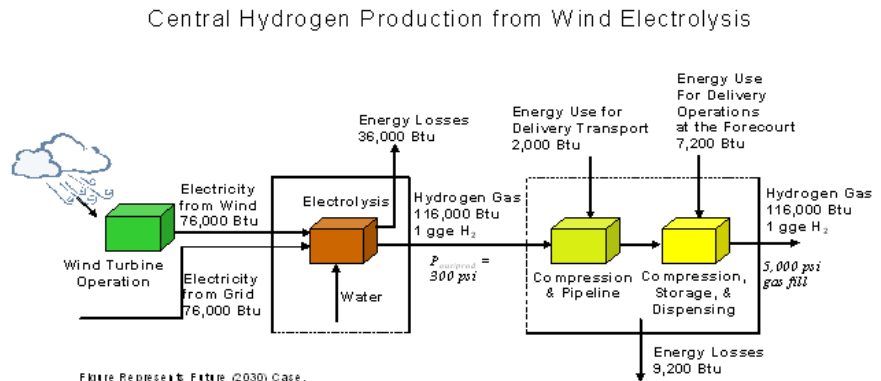


Figure 28: Hydrogen Life Cycle (95)

15.3.4 Makrolon Plastics

Bayer has been making Makrolon plastics for many years now. Their process of thermoforming is very efficient in energy terms. Their recycling has also improved over the years as well.

Table 3 displays a rough estimate of the overall energy consumption for the life cycle of Razor Rescue. Only the biggest components of fuel and materials were taken into account for production and operation. By knowing the Btu per gallon for the fuel, a rough estimate of fuel energy was calculated for a 300 nautical mile mission at cruise speed. Electronic operation and HUMS on the helicopter were also factored in for operation and maintenance energy costs. It was assumed that 70% of carbon composites could be recycled, so the process of recurring by means of E-beam was estimated.

Table 14: Estimated Overall Energy Consumption		B20	Hydrogen
		Btu/hr	
Manufacturing			
Composite (E-beam)	50 KW/hour for 4 hours curing	682,400	682,400
Fuel (B20 soybean)	1.214 Btu per Btu of Fuel	7,162,600	-
Hydrogen Production	206400 Btu/gge	-	37,152,000
Operations			
Electronics	1000 Watts	3,142	3,142
Fuel			
Diesel (B20)	118,000 BTUs/gallon	5,900,000	-
Liquid Hydrogen	227,850 Btu/ft^3	-	5,502,578
Maintenance			
HUMS	1000 Watts	3,142	3,142
Recycling			
Composites	70% Recovered Composite	477,680	477,680
Totals			
Estimated Total Energy Consumption	with B20	14,228,964.00	43,820,941.50

16.0 Weight Analysis

16.1 EC-120 Weight Prediction

As an initial weight estimation, the weight prediction equations from Prouty (30) were used. These equations use a trend analysis to determine the weights of specific components. The next iteration in the weight breakdown used technology factors from the AHS forum to update the equations from Prouty's book, which were based on 1984 technology. For comparison and validation purposes, these modified equations were used to predict the weight of the EC-120, since its MTOW is known. As is shown in the table, the weight equations were accurate to within 2%.

Table 15: EC-120 Weight Prediction

Breakdown	Weight	Tech Factor	Adj. Weight
Main Rotor Blades	134.03	0.79	105.88
Main Rotor Hub	123.50	0.70	86.45
Horizontal Stabilizer)	29.84	0.70	20.89
Vertical Stabilizer	66.21	0.75	49.66
Tail Rotor	12.44	1.00	12.44
Fuselage	599.41	0.77	463.94
Landing Gear	212.92	0.70	149.04
Nacelles	0.00	1.00	0.00
Engine Installation	227.00	1.00	227.00
Propulsion Subsystem	49.10	0.69	33.88
Fuel System	23.98	1.00	23.98
Drive System	136.73	0.67	91.61
Cockpit Controls	19.96	0.40	7.98
System Controls (non-boosted)	19.59	0.30	5.88
Auxiliary Power Plant	150.00	1.00	150.00
Instruments	21.00	0.73	15.33
Hydraulics	24.67	0.70	17.27
Electrical	265.31	0.87	230.82
Avionics	150.00	1.00	150.00
Furnishings and Equipment	78.00	1.00	78.00
Air Conditioning and Anti-Ice	31.74	1.00	31.74
Manufacturing Variation	15.87	1.00	15.87
WE	2391.31		1967.67
Pilot	220.00		220.00
Passengers/Payload	1100.00		1100.00
Fuel	585.00		325.00
Contingency	119.57		98.38
GW ESTIMATION	4415.88		3711.06
EC 120 LISTED MTOW			3780.00

16.2 Razor Rescue Weight Buildup

Once the actual components of the helicopter were designed using Solid Works, weights could be assigned to them using material properties, allowing for a more accurate weight break-down than the trending equations. A chart showing the components' weights as percentages of the maximum weight is shown below. The empty weight is approximately 2,130 pounds, while the MTOW is 3,800 pounds.

In the table below, the numbers highlighted in blue were generated using material properties, and not using Prouty's trending analysis, while the numbers in black were a result of those trends.

Table 16: Razor Rescue Weight Buildup

Breakdown	Weight
Main Rotor Blades	165.00
Main Rotor Hub	100.00
Tail Rotor	60.00
Body (Fuselage / Empennage)	357.00
Landing Gear	60.00
Engine Installation	240.00
Propulsion Subsystem	35.01
Drive System	174.16
Cockpit Controls	7.85
System Controls	4.67
Urea Tank	80.00
Instruments / Avionics	90.64
SCRT Tanks	20.00
Electrical / Lighting	150.25
Furnishings and Equipment	568.00
Manufacturing Variation	15.22
WE	2127.80
Pilot	220.00
Passengers/Payload	1100.00
Fuel	250.00
Contingency	106.39
GW ESTIMATION	3804.19

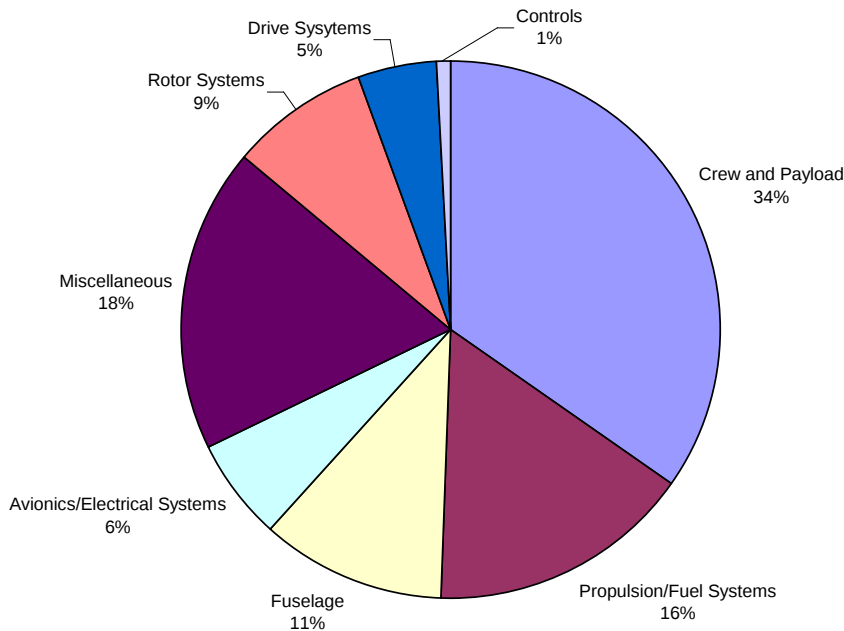


Figure 29: Weight Distribution

16.3 C.G. Estimation

The center of gravity was found by summing up the majority of the components used within the aircraft. The mean locations are as follows:

$X = 0.325$ ft behind the rotor, $Y = 0.02$ ft right of the rotor, $Z = 3.59$ ft below the rotor.

The picture below illustrates the center of gravity with respect to the X and Z locations; the Y offset is not shown because it is minimal.

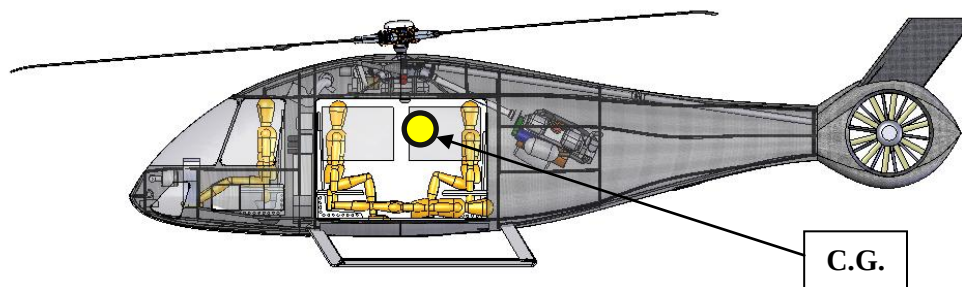


Figure 30: CG Location

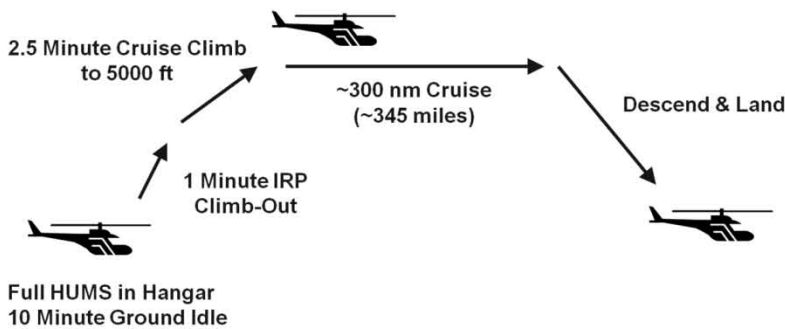
16.3.1 CG Range

The C.G. envelopes were tabulated by changing the seating configuration, as well as the amount of fuel being carried. By removing the front two passengers, and reducing the fuel load down to 25 lbs, the X location of the C.G. moves to a full foot behind the rotor. Likewise, removing the two back passengers, and carrying a full 250 pounds of fuel places the X location at only 0.04 feet behind the rotor. To effect the C.G. location in the Z direction, two of the passengers

Foldout 8: Razor Rescue Performance

Mission 1: Civilian Transport

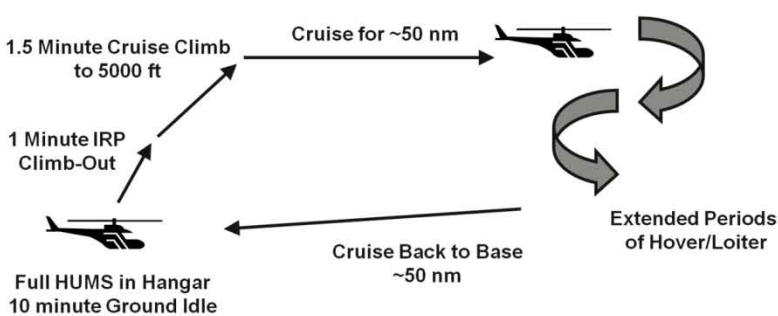
Full Payload at Takeoff



Ground Idle	10 minutes
IRP Takeoff	1 minute
Cruise Climb (~5000 ft)	3.65 minutes
Cruise (150 nm)	77 minutes
IRP Hover-Land-Takeoff	1 minute
Cruise Climb (~5000 ft)	3.4 minutes
Cruise (150 ft)	78 minutes
Total Mission Time	174 minutes (~2.9 hours)
Total Razor Rescue Fuel Required	234.3 lbs (~35 gallons)
EC-120 Fuel Required	420.2 lbs (~62 gallons)

Mission 2: Military Recon

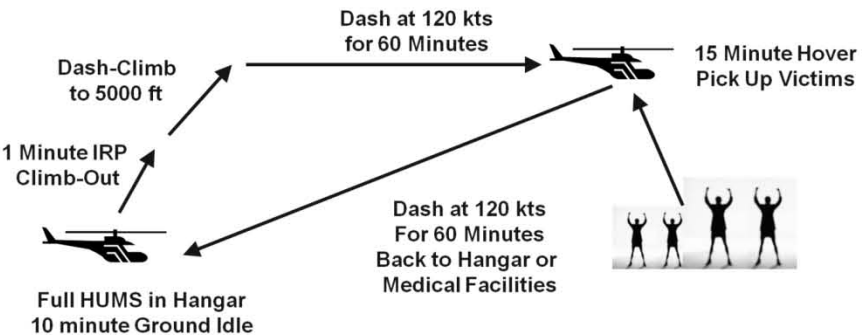
Half Payload for Duration



Ground Idle	10 minutes
IRP Takeoff	1 minute
Cruise Climb (~5000 ft)	2.4 minutes
Cruise (50 nm)	27 minutes
Loiter	30 minutes
Hover	5 minutes
Loiter	30 minutes
Cruise (50 nm)	28 minutes
Total Mission Time	132 minutes (~2.2 hours)
Total Razor Rescue Fuel Required	161.2 lbs (~24 gallons)
EC-120 Fuel Required	258.6 lbs (~28.59 gallons)

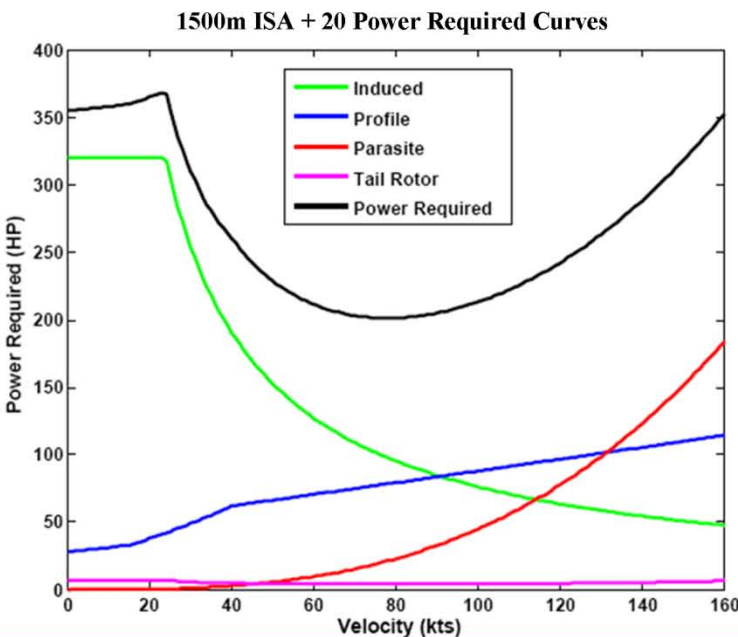
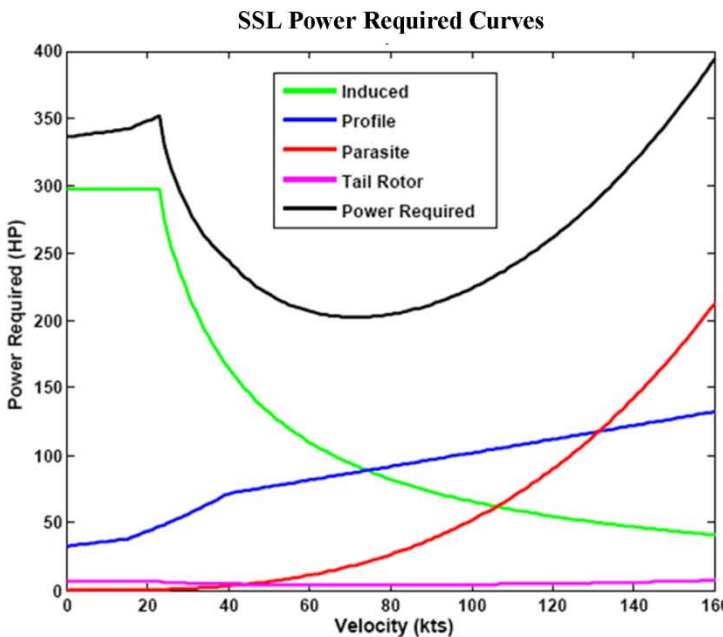
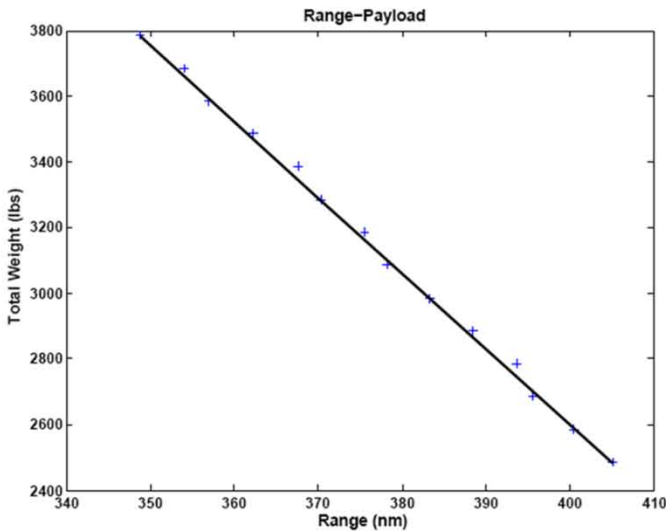
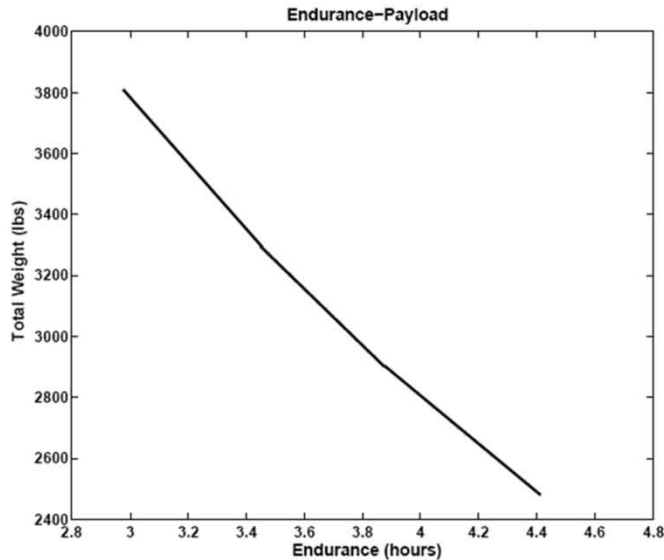
Mission 3: Disaster Relief

No passengers at takeoff, Pick up full passenger and luggage load at midmission hover



Ground Idle	10 minutes
IRP Takeoff	1 minute
Dash Climb (~5000 ft)	5.2 minutes
Dash (60 nm)	60 minutes
Hover	15 minutes
Dash (60 nm)	60 minutes
Total Mission Time	151 minutes (~2.5 hours)
Total Razor Rescue Fuel Required	239.6 lbs (~35 gallons)
EC-120 Fuel Required	450.1 lbs (~70 gallons)

All mission include the following constraints: MTOW = 3804 lbs, WE = 2127 lbs, Pilot Weight = 220 lbs, Passenger Weight = 275 lbs (each, including luggage), Biodiesel Weight = 6.7 lbs/gallon, Takeoff at SSL, Cruise at 1500 meters (~5000 ft), ISA + 20 degrees C, 10% Reserves



are removed, and one is left lying on a stretcher on the floor, causing the Z location to be 3.75 feet below the rotor. The mean location is also the max height for the Z direction, at 3.59 feet below the rotor. In the Y direction, removing the two passengers on the right side of the vehicle shifts the Y C.G. to 0.09 feet to the left of the rotor. Removing the two passengers on the opposite side of the vehicle produces a Y C.G. location of 0.14 feet to the right of the rotor. In summary, the travel for the X location of the C.G. is 0.96 feet, 0.16 feet for the travel in the Z direction, and 0.23 feet in the Y direction.

17.0 Performance Analysis

17.1 Required Power

Two of the main, performance-driven metrics given in the RFP are: 1) minimizing fuel consumption for a one hour flight at 120 knots target speed, and 2) Hover-Out-of-Ground-Effect for 15 minutes with Maximum Take-Off Weight at 1500 meters (~5000ft). Both of these objectives were able to be accomplished, as shown in the figures on the Performance Analysis foldout.

The figure in the bottom, center-right position represents the power required breakdown for a flight at sea-level at MTOW. With these conditions, the cruise speed is approximately 118 knots. The figure in the bottom, right-hand corner represents the power required breakdown for a flight at 1500 meters, also at MTOW. This configuration leads to a cruise speed of nearly 124 knots. With these two situations bracketing the normal operating range of the aircraft, the RFP requirement for a cruise speed of 120 knots is well met. The high altitude configuration leaves the aircraft capable of hovering while maintaining a sufficient power margin for maneuvers, but during the transition to forward flight the altitude would need to be decreased in order to maneuver safely.

17.2 Mission Analysis

Also stated in the RFP, the aircraft must be designed for use in Military / Para-military / Public multipurpose transport missions. As such, 3 different “example” missions were created for use in sizing fuel tanks and determining approximate mission durations. These three missions are as follows:

17.2.1 Military Recon

The aircraft weight is set with half-payload for the duration of the mission. This allows for up to two soldiers, or extra electronic surveillance equipment. The mission layout begins with a warm-up period of approximately 10 minutes during which the aircraft is inspected and all of the systems readied for flight. Next is a climb-out at the Intermediate Rated Power, or IRP, lasting one minute, followed by a cruise climb to the desired altitude (1500m, in this case). After reaching cruise-altitude, the helicopter flies at cruise speed to the location of the mission. The reconnaissance mission is accomplished with periods cruise, loiter, and a minimal amount of hovering, after which the aircraft makes the return trip to base, about 50 miles in this example. The total mission time for this set-up was around 2.2 hours, during which approximately 24 gallons, or 161 lbs, of fuel was consumed. This is approximately 100 lbs less fuel than the EC 120 takes to perform the same mission.

17.2.2 Maximum Range

To show that the Razor Rescue was capable of meeting the RFP requirement calling for a maximum range of 300 nautical miles, another mock-mission was drawn up. This mission uses an aircraft weight with the full payload for the entire mission, to ensure that the requirement can be met at full-load. This mission’s start is similar to the recon mission, as it begins with 10 minutes of ground idle, followed by 1 minute of IRP climb-out, and then a cruise climb to 1500 meters. After this portion, the aircraft then travel for 150 nm, lands, repeats the IRP and cruise-climb, and then cruises the 150 nm back to station. The total time for this situation was approximately 2.9 hours, and nearly 235 lbs, or 35 gallons, of fuel was used. The EC 120 takes approximately 420 lbs of fuel to accomplish the same mission.

17.2.3 Disaster Relief

One of the primary uses for this helicopter, as suggested by the RFP, is in a disaster relief support role. For this scenario, the aircraft begins without any payload. This mission starts with the usual 10 minutes of ground idle /

startup, and the IRP climb-out, but instead of a cruise climb, the aircraft performs a “dash-climb,” enabling the aircraft to maintain a 120-knot forward speed while reaching the cruise altitude. The helicopter then proceeds to maintain that 120-knot speed for one hour before reaching its destination. It then hovers at its 1500-meter altitude while performing a pickup of 4 passengers, bringing the payload up to its maximum value. Next, the Razor Rescue makes a return trip at 120 knots to the hospital from which it is assumed to have been deployed, taking another hour to do so. The mission duration is about 2.5 hours and the fuel consumed was again nearly 35 gallons, or about 240 lbs. A comparison was made with this mission, using the EC 120, to evaluate the effectiveness of the Razor Rescue’s unique design characteristics. The EC 120 completed the mission in about the same amount of time, but the gas-turbine engine used twice the amount of fuel as Razor Rescue, at nearly 70 gallons, or 470 lbs. This comparison highlights the RFP parameter asking for minimized fuel consumption at the targeted cruise speed of 120 knots.

On the Performance Analysis foldout, the Endurance-Payload and Range-Payload curves are located at the bottom of the page. These show a maximum endurance of approximately 4.4 hours, and a maximum range of nearly 405 nautical miles, with only the pilot present. The endurance may be vastly increased if the payload is replaced by fuel of the same weight, however, such long flights may be more efficiently accomplished with the use of a fixed wing aircraft.

18.0 Cost

The cost model selected for our aircraft was given in the 2002 RFP (94). This model was originally created for use in estimating the cost of upgrading a light, 4-6 place helicopter. It has since been modified to suit our requirements by altering the percentages used, as described by previous year’s cost models in an effort to match the approximate costs of the EC-120. Table 17 shows the approximate cost breakdown:

Table 17: Cost Estimation

Component	2006 USD
Main Rotor	\$521,000
Final Assembly	\$110,000
Furnishing / Equip	\$81,200
Tail Rotor	\$79,800
Engine	\$68,500
Instruments	\$65,500
Drive System	\$56,700
Airframe	\$44,000
Electronics	\$31,500
Avionics	\$22,200
Propulsion Subsystems	\$15,100
Landing Gear	\$12,700
Flight Controls	\$3,660
Air Induction	\$1,660
Air Conditioning	\$138
Total Cost	\$1,110,000
+ 35% Profit	\$1,500,000

19.0 Conclusion

The Razor Rescue is a highly efficient multi-purpose transport helicopter intended to operate in devastated areas and urban environments. The aircraft is designed with utility in mind while meeting all RFP performance requirements. The large passenger compartment can be quickly and easily reconfigured to fit a stretcher or other outsized cargo. Also, advanced systems allow inexperienced pilots to safely use the aircraft to aid those affected by a disaster.

It features an OPOC turbocompound diesel engine fueled by energy efficient B20 biodiesel. The smaller total fuel consumption combined with an SCRT system makes Razor Rescue’s propulsion system a lot more environmental friendly. Furthermore, when a hydrogen infrastructure has matured, the Razor Rescue will have the ability to run on liquid hydrogen fuel. With minimal changes to the engine, the aircraft will have a smaller environmental footprint while running on hydrogen.

The advanced rotor system improves system performance while reducing total power required with an innovative control system. Variable speed rotor technology reduces aircraft noise, especially at low speeds where it impacts communities the most. The Razor Rescue also features a fenestron tail rotor, as well as a rotor tip speed as low as 600 ft/s during hover to minimize acoustic signatures in and around neighborhood areas.

Overall, performance and utility exceeds that of the EC-120, while offering significantly lower lifespan energy consumption. It is an attractive aircraft for civilian, paramilitary and military operators due to its many features designed to improve aircraft usability and pilotability.

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