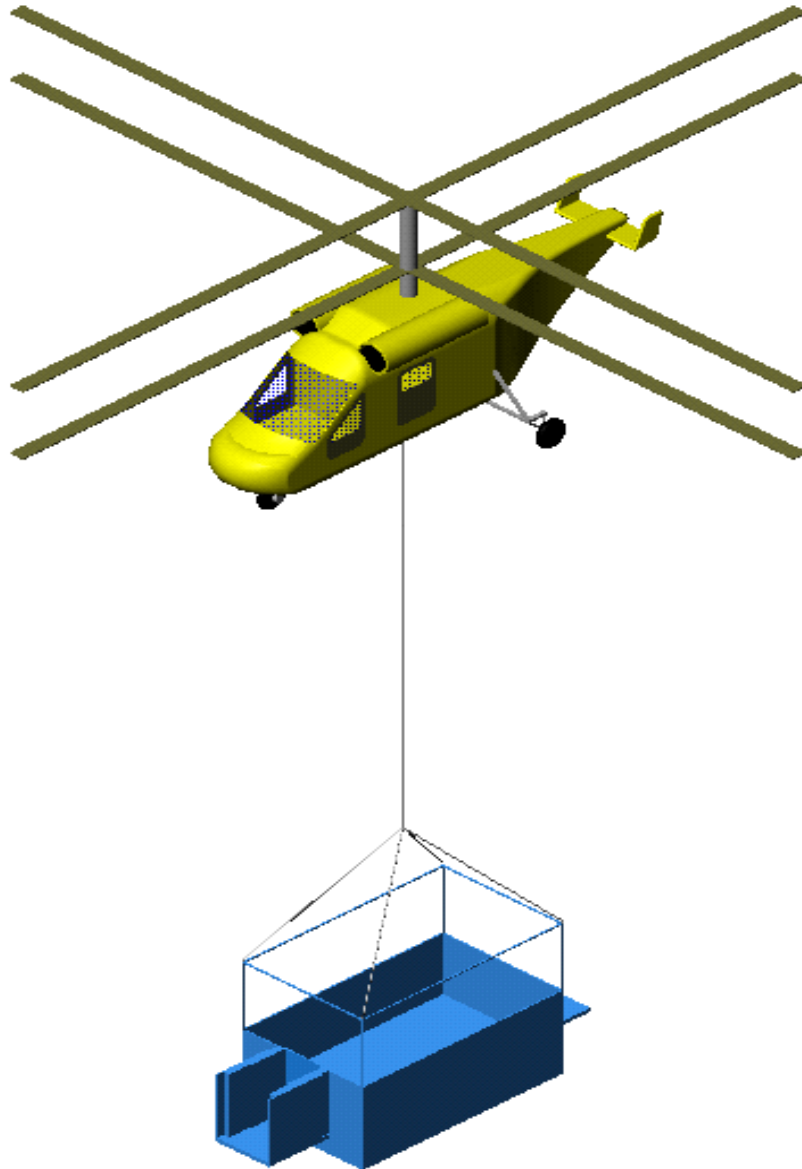


# ***EXTRICATOR***

*THE MULTI-ROLE VTOL URBAN DISASTER RELIEF VEHICLE*



Department of Aerospace Engineering  
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June 1, 2003

# Rensselaer Polytechnic Institute



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## EXTRICATOR

### THE VTOL URBAN DISATER RESPONSE VEHICLE

In response to the 2003 American Helicopter Society Student  
Design Competition – Undergraduate Category  
1 May 2003

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## **ACKNOWLEDGEMENTS**

We would like to thank Professor Nikhil Koratkar for establishing the helicopter design course at the Rensselaer Polytechnic Institute and his continuous guidance and advice throughout the duration of this course.

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## Compliance Matrix

Mission Requirements		Result
<b>High rise Firefighter deployment</b>	·Deliver (15) 300 lb firefighters to rooftops up to 1500 ft in 2 minute cycles	<b>YES</b>
<b>Rooftop Occupant Extraction</b>	·Transport 1200 people/hr from rooftops to the ground or adjacent rooftops.	<b>NO System can transport 900 people/hr</b>
	·Air vehicle or rescue subsystem “landing” on congested rooftops.	<b>YES</b>
<b>Building face penetration and occupant recovery</b>	·Enable penetration of building windows at any floor	<b>YES</b>
	·Extraction of 800 occupants/hr from windows at any floor	<b>NO System can transport 400 people/hr</b>
<b>Ground pump water cannon fire fighting</b>	·Provide lift for 5 in diameter water hoses capable of pumping 1500 gallons per minute to a minimum of 100 stories using ground mounted pumps or pumps positioned on adjacent rooftops.	<b>YES</b>
<b>Self contained tank water cannon fire fighting</b>	·Refillable under one minute from standing sources/supplies in adjacent buildings.	<b>YES</b>
	·Engagement of fires on any floor with directed water cannon	<b>YES</b>
<b>Removal of debris</b>	·Carry at least 5000 lbs. to supply relief materials or aid in removal of debris.	<b>YES</b>
<b>Disaster command and control</b>	·4 personnel for simultaneous multiplexed communication on 6 communication frequencies	<b>YES</b>
	·Endurance not less than 2 hours. 1 hour hover and 1 hour cruise at 60 knots.	<b>YES</b>
	·Navigation systems shall enable rapid and accurate response to street addresses.	<b>YES</b>
	·Sensor systems locate occupants in zero visibility conditions. Thermal maps of building structures.	<b>YES</b>
	·Sensor data transmitted to other disaster relief systems on the ground and in the air	<b>YES</b>

<b>VTOL Important Requirements</b>	·Safe and prolonged hover operations within between high rise buildings	<b>YES</b>
	·Precision hover - maintain lateral separation within 1 ft of pre-selected distance and altitude within 1 ft.	<b>YES</b>
	·Sustain position hold hover is zero visibility conditions	<b>YES</b>
	·The system shall be easy to operate and mission manage.	<b>YES</b>
	·Perform all missions at ambient conditions (Denver Colorado on a 95 <sup>th</sup> percentile summer day)	<b>YES</b>
	·The system shall be transportable on a wide load flat bed truck on urban roadways.	<b>YES</b>
	·The system shall be re-configurable from one mission configuration to another in less than 20 minutes.	<b>YES</b>
	·Execute any missions following a 20 nm deployment from a home base.	<b>YES</b>
·System endurance for firefighter deployment and extraction not be less than 1 hour.	<b>YES</b>	

# **Executive Summary**

## **Introduction**

The Extricator, a high-lift multi-role urban disaster response helicopter, has been designed in response to the 2003 American Helicopter Society Student Design Competition (sponsored by Sikorsky Helicopter). The Request for Proposal (RFP) identified the need for disaster relief VTOL vehicle for saving lives and also to assist the existing ground disaster relief vehicles. The primary goal for this design is to produce a relatively compact aircraft with heavy lift capabilities, with subsystems equipped for victim extraction and firefighting mission in a high density urban high rise environment.

## **Mission requirements and design objectives**

The RFP specifies a number of required mission elements. Chief among those is the requirement of rate of victim extraction per helicopter of 1200 people per hour from the rooftop and 800 people per hour from the building face. Due to power, weight and required rate of climb considerations, it was decided to reduce the rate of victim extraction to be 900 people per hour from the rooftop and 400 people per hour from the building face. A plug and play concept was used in order to meet the requirement of quick reconfiguration from one mission to the other. The bottom of the Extricator has an external subsystem attachment bay and various subsystems such as the external water tank, passenger extraction basket and additional cargo bay can be attached or released quickly. A wide range of missions such as firefighter deployment, debris removal, command and control can be successfully achieved because the Extricator's design is based on the most demanding mission, which is the victim extraction of 900 people per hour from the rooftop to ground.

## **Aircraft configuration trade-off study**

An extensive study of various aircraft configurations was conducted. The co-axial helicopter emerged as the best candidate, whereas the conventional, tandem helicopter, compound helicopter, tilt rotor, among others, were eliminated due to size, payload considerations and hover performance. Trade studies indicated that a co-axial helicopter is the most compact and elegant solution for the mission and provides the best trade-off between the need for compactness and the need to carry heavy lift, hover efficiently (low disk loading) and achieve the required rates of climb needed to accomplish the mission.

## **Extricator: design features**

The Extricator is a co-axial helicopter. The design is dominated by the conflicting trade-off between its high lift capabilities and its physical size. Extricator was designed to carry the maximum load of 5500 kg (50 people per trip) while keeping its size to a minimum. The equipped subsystems make the design highly versatile and are designed to complete the mission efficiently and safely. Here are some highlights of the design:

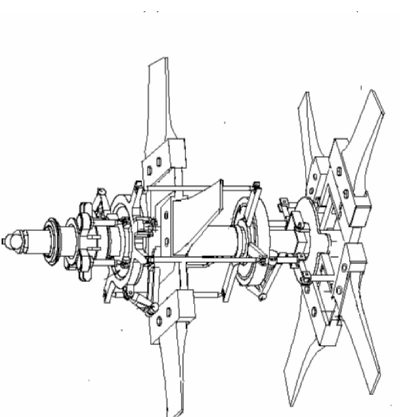
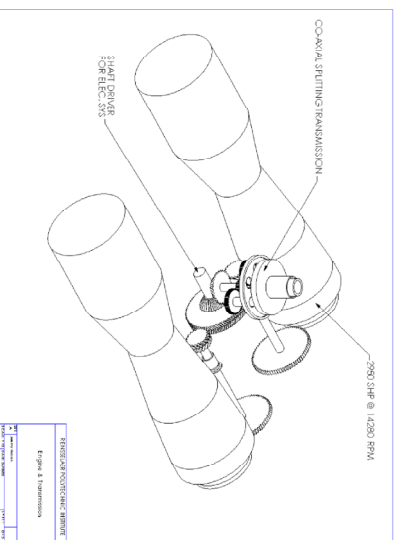
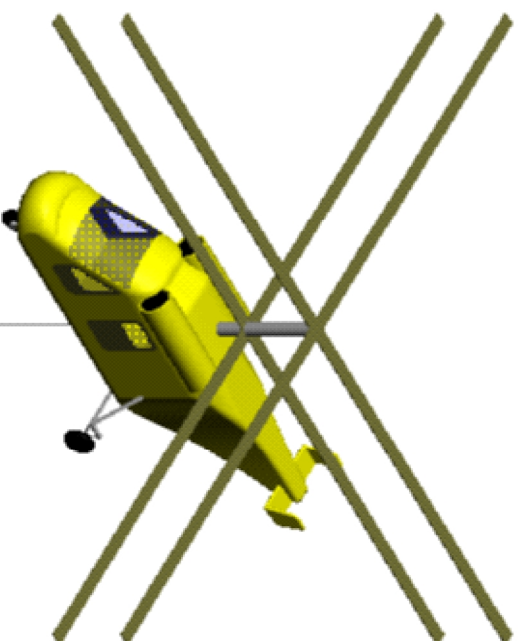
- The Extricator uses the co-axial rotor configuration with 4 blades on each rotor, it eliminates the need for a tail rotor and allows a compact design (main rotor diameter: 14.65 m) while still generating the required amount of thrust (aircraft weight: 11,792 Kg) at a reasonable disk loading ( $35 \text{ Kg/m}^2$ ).
- Specially designed airfoil meets the requirements of high lift. Three different types of airfoil were used on different sections of the blades. The RAE9648 airfoil was used from the root to 50% of the blade span, the OA312 airfoil was used from 50% to 77.5% of blade span, and the remainder of the blade all the way to the tip was the OA309 airfoil.

- Bearingless rotor hubs with elastomeric lag dampers are used to minimize part count and maintenance costs. Collective and cyclic blade pitch control is achieved through the use of an interconnected dual-swashplate mechanism. A special yaw-control mechanism is also integrated with the swashplates to provide differential pitch to the rotors in order to achieve yaw control.
- The fuselage houses the pilot cabin, the command and control module and on-board water tank. Passengers from the disaster site are rapidly extracted into a basket system. This enables a relatively short fuselage to minimize the overall size of the helicopter (compactness). The basket is tethered from a bulkhead located close to the vehicle center of gravity to minimize cg travel issues.
- Subsystem attachment bay enables quick configuration of the helicopter from one mission to another. Subsystems such as external tank, passenger basket, cargo-bay can be conveniently attached so that the same basic design fulfils all the missions.
- Retractable bridge on the passenger basket enables safe extraction from the building face. A stabilizer device underneath the basket is used to counteract the moment created by the victims rushing into the helicopter during face extraction.
- A fixed tricycle landing gear system is used in this aircraft. Since the design cruise speed is only 60 kts, drag due to the wheels will not be significant enough to warrant a retractable system.
- The design is driven by two 2950 HP engines, whose inputs are combined by the transmission system and sent to a single shaft, which connects to the co-axial transmission that engages the individual rotor systems.

*A fold-out showing aircraft level description is provided on the next page.*

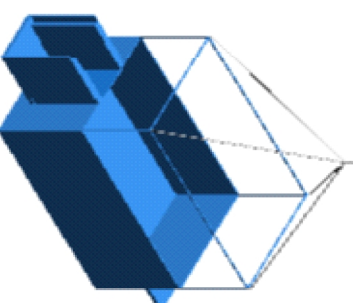
# THE EXTRICATOR

Performance		Weights	
Range	220 km	Take-off Gross Weight	11800 kg
Maximum Climb Rate	18.3 m/sec	Empty Weight	4755 kg
Cruise Speed	60 knots	Disk Loading	35 kg/m <sup>2</sup>
Induced Velocity	13.4 m/sec	Fuel Capacity	1300 kg
Hover Power	3487 hp	Maximum Payload	5500 kg
Max Power (Climb)	5900 hp		
<b>Airframe and Rotor Geometry</b>			
Landing Gear	Fixed	Number of Blades per Rotor	4
Overall Length	23.5 ft	Rotor Diameter	14.65 m
		Blade Chord	0.42 m
Overall Width	8.9 ft	Hover Tip Speed	240 m/s
Tail Stabilizer	U-tail	Co-axial Rotor Spacing	1.75 m
		Rotor Solidity	0.0724



**Engines & Transmission**

**Swashplate Control System**



## Chapter 1 Introduction

Disaster response in urban environments is challenging due to the density of buildings, building heights, and access road congestion. Current response is provided largely by ground vehicles and systems installed within the buildings, however these systems have many shortfalls.

The purpose of the Industry/NASA/AHS student helicopter design competition is to challenge rotorcraft designers to perform the concept design of a vertical takeoff and landing vehicle (VTOL) capable of saving lives and protecting property in demanding urban high rise environments.

VTOL systems offer great potential to address many of the shortfalls of current urban response systems. Several experiments have been conducted to explore new ways of firefighting with VTOL systems. These technologies integrated into platforms suitable for urban operations offer great promise to save lives and protect property in the future.

The VTOL system shall be tasked to perform the following missions:

- High rise firefighter deployment
- Rooftop occupant extraction
- Building face penetration and occupant recovery
- Ground pump water cannon fire fighting
- Self contained tank water cannon fire fighting
- Removal of debris
- Disaster command and control

A break down of these missions, provide the following operational environment and mission requirements.

### **High rise firefighter deployment**

- Enable delivery of teams of 15 firefighters weighing 300 lbs each with gear to rooftops up to 1500 ft in no more than 2-minute cycles.

### **Rooftop occupant extraction**

- Safely transport a minimum of 1200 people per hour from high-rise rooftops to either the ground or adjacent rooftops.
- Enable air vehicle or rescue subsystem “landing” on congested rooftops.

### **Building face penetration and occupant recovery**

- Enable penetration of building windows at any floor
- Enable extraction of not less than 800 occupants per hour from windows at any floor when equipped with a window extraction mission kit.

### **Ground pump water cannon fire fighting**

- Provide lift for 5 inch diameter water hoses capable of pumping 1500 gallons per minute to a minimum of 100 stories using ground mounted pumps or pumps positioned on adjacent rooftops.

### **Self contained tank water cannon fire fighting**

- The internal water tank when installed shall be refillable in under one minutes from standing water sources or water supplies in adjacent buildings.
- Enable engagement of fires on any floor with a directed water cannon drawing from either the air to ground hose or by drawing from an optional onboard water tank of 500 gallons.

### **Removal of debris**

- The system must have the ability to carry external cargoes of at least 5000 lbs. to supply disaster relief materials or aid in the emergency removal of debris.

### **Disaster command and control**

- Provide a command and control platform to disaster response decision makers to coordinate all aspects of disaster response. A minimum of 4

personnel is required with capability for simultaneous multiplexed communication on 6 different communication frequencies.

- When configured for command and control the vehicle must have an endurance of not less than 2 hours. 1 hour of which is in a hover and 1 hour of which is in cruise at 60 knots.
- Navigation systems shall enable rapid and accurate response to street addresses.
- Sensor systems shall have the ability to locate occupants in zero visibility conditions. Sensors shall be capable of developing thermal maps of building structures.
- Sensor data shall be able to be transmitted to other disaster relief systems on the ground and in the air.

### **VTOL Important Requirements**

- Enable safe and prolonged hover operations within “urban canyons” ... between high rise buildings
- Perform precision hover, maintaining lateral separation from glass, steel, or concrete vertical surfaces within 1 ft of a pre-selected separation distance while maintaining altitude within 1 ft.
- Ability to sustain position (hover) in zero visibility conditions.
- The system shall be easy to operate and mission manage.
- The system shall be capable of performing all missions at ambient conditions represented by Denver Colorado on a 95<sup>th</sup> percentile summer day.
- The system shall be transportable on a wide load flat bed truck on urban roadways.
- The system shall be re-configurable from one mission configuration to another in less than 20 minutes.
- The system shall be capable of executing any of the defined missions following a 20 nm deployment from a home base. System endurance for firefighter deployment and occupant extraction missions shall not be less than 1 hour.

## **Chapter 2 Detailed Mission Profiles**

### **High Rise Firefighter Deployment:**

The mission of fire fighter deployment encompasses the ability to deliver teams of 15 firefighters weighing 300 pounds each with gear to rooftops up to 1500 ft in no more than 2-minute cycles. A crew of 15 firefighters at 300 pounds each is calculated to weigh approximately 2800 kg. The firefighters will be carried in the precision lift basket to the height of 1500ft. The time allotted for each firefighter to enter or exit the basket would be 1.25 seconds and the time for a trip to the top would be 35 seconds with a climb rate of 13.06 m/s. The mission would then take a total of 2 minutes for a total round trip.

### **Rooftop Occupant Extraction:**

In the rooftop occupant extraction mission, the helicopter needs to be able to pick up building occupants on the roof and transport them to a safe location. There will be two scenarios for this type of occupant extraction. The first scenario is where there is a building adjacent to the one that has the emergency. The helicopter will then transport the rooftop occupants from the one building to the safe building close by. In this scenario it is calculated that the helicopter will be able to carry 50 people in a precision lift basket at a time and make 22 trips in an hour, which means it will be able to transport 1,100 people in an hour. The time for loading and unloading was figured to be 1.5 seconds per person. The payload for 50 people was figured to be 5500 kg. The power required in this case is 5866 Hp with a necessary climb rate of 18.3 m/s

The second scenario is when there is no building near the building that has the emergency. In this case the occupants would have to be lifted all the way to the ground. In this case they occupants would still use the precision lift basket. The total number of people that would be able to be carried in an hour in this fashion would be 900 per hour. In this case the time for loading and unloading is still 1.5 seconds per person. The payload for 50 people is 5500 kg. The power required is 5866 Hp with a climb rate of 18.3 m/s.

### **Building Face Penetration and Extraction:**

In this case the mission requires that the helicopter fly close to the building and extract the occupants from the face of the building through a window for example. To do this the precision lift basket will be fitted with an extendable bridge that will be used to extract the buildings occupants. The occupants will be extracted through a large window on the floor that is large enough to allow adequate room for the procedure. This would typically be a large hallway window in the building as opposed to using an office window which is usually smaller and in which case there is not as much room to move around. The extendable bridge will telescope out from the precision lift basket and allow the extraction team to open the window and extract the occupants to safety.

With this mission there will also be three scenarios as well. The first scenario is if the fire or emergency occurs in the lower 15 percent of the floors. The next scenario would be extracting people from 50 percent of the building height. And the final scenario is extracting people from 85 percent of the building height. Calculations show that

extraction at 85% building height is the most demanding scenario for all three cases considered. We show that with trips of 50 people each, a total of 400 people can be extracted per hour.

### **Ground Pump Cannon Fire Fighting:**

The ground pump cannon fire fighting mission will include the helicopter being able to carry a fire hose up to 1500 feet and fight the building fire in that fashion. This would mean the fire hose would weigh around 1020 kg (the weight of the water column is assumed to be supported by the ground based pumping station) and the helicopter would be able to carry the weight of the system to fight the fire and would be able to extinguish fires from the air using ground pumps.

### **Self Contained Water Cannon Fire Fighting:**

The mission of fighting fires from the air using the self-contained system consists of carrying 500 gallons of water in a self contained tank in the helicopter or attached to it. The weight of the water would be 1556 kg, which is within the limit of the payload that is set for this helicopter of 5000 kg, which means this helicopter would be able to perform this mission. Note that the Extricator can perform both the ground pump cannon fire fighting and the self-contained water canon firefighting mission simultaneously.

**Command and Control:**

The command and control mission includes the helicopter to fly for 2 hours with 1 hour in hover and 1 hour a cruise. The helicopter has been designed with a range of 220 km, which covers the 2 hours in cruise and the 1 hour in hover. The helicopter will also have systems on board for navigation through conditions typically found in a disaster situation. This mission setup will also allow the helicopter to find people in the building using advanced imagery equipment, so as to increase the effectiveness of the rescue efforts.

### **Chapter 3 Concept Evaluation and Down-selection Process**

In the initial design phase of the Urban Disaster Response Vehicle, several different designs were considered: the conventional single main rotor single tail rotor design as well as the more complicated tandem, intermeshing and co-axial configurations. Other existing helicopter designs such as compound helicopter and tilt-rotors were not considered because of poor hover performance [Leishman-2000]. In order to determine which of these four configurations would best suit our needs as stated in the RPF, several key requirements were considered. These key requirements included heavy-lift capability, hover performance, climb speed, compactness, maneuverability, versatility, complexity, cost and ease of operation. Each of these characteristics was compared among the four candidate helicopter configurations, resulting in the final general design choice.

A design matrix was tabulated in order to determine which configuration is most suitable for this design. First, the set of criteria as stated above were given a multiplication factor or weighing factor (1 to 8) based on the relative importance of that criterion. Then, each of the criteria was compared among the four chosen helicopter configurations and corresponding points (1 to 4 points) were assigned based on the ability of the candidate configuration to satisfy the criterion. Next, these points were multiplied by the weighing factor of that criterion and then summed up to give the total score for each of the helicopter configurations. This methodology provides a convenient mechanism to qualitatively compare the relative merits of the chosen configurations. Our analysis indicated that the co-axial helicopter configuration was the most suitable

configuration for the RFP mission profile due to its compactness, good hover performance, high-lift capability, and excellent maneuverability.

An air-borne rescue vehicle must be able to carry heavy loads; debris must be removed from disaster sites, personnel and victims carried and water transported. Thus, this category was assigned a maximum weighting value of eight. In heavy lift, the traditional helicopter design performed poorly, while the other three candidates were rated about the same. This difference in lift capability can be attributed to the duality of the rotors, which helps to reduce the disk loading, thereby improving performance. Furthermore, since there is no tail rotor required in the co-axial design, full engine power can be used to carry the payload.

Compactness of a rotorcraft is mainly determined by the size of its rotor and, for the urban purposes of this design, compactness is crucial, and was thereby given the highest weighing factor of eight. Taking rotor sizes into account, the co-axial obviously scored the highest, followed by the intermeshing and the single rotor. The tandem scored the lowest, considering that, in that design, there are two separate rotors placed next to each other with as little overlap as possible.

In a rescue mission, time is of the essence and the maximization of climb rate is critical. Knowing this, this category was also given the maximum possible weighting factor of eight. Climb rate is directly related to the thrust of a helicopter, which is similar to the dual-rotor tandem, co-axial and intermeshing designs. Climb rate is significantly less for the single rotor design due to tail rotor losses.

In order to meet certain requirements as stated in the RPF, the rotorcraft needs to be able to maintain stable hover. Due to its importance, this category was assigned a

weighting factor of seven. The hover efficiency of the intermeshing design is the best, as reflected in the matrix below. This is because, unlike the tandem and the co-axial, there are no losses to consider from overlapping rotors and, unlike the conventional, there are no tail rotor losses.

In an urban situation, the maneuverability of the helicopter is important; the rotorcraft must be able to move around the sharp corners of high-rise buildings. Thus, this category was given a weighing factor of 6. The tandem design is the largest and most awkward and therefore received the lowest score. The co-axial, as the most compact, received the best score.

As listed in the RPF, the rescue helicopter must be able to perform more than one mission. It must therefore be of versatile design. This category was assigned a weighing factor of 4. The tandem, due to mainly its large fuselage, was given a higher score than the other three configurations.

Minimizing the complexity of the design, though not critical to our design requirements, should still be considered. The weighing factor for complexity was determined to be 2. The fact that most helicopters built today are of the conventional design resulted in a higher score for that configuration. Also, the single rotor design does not have the complications of the other three, such as the dual hub design of the co-axial or the careful spacing of the intermeshing blades.

The cost and maintenance of a product always needs to be considered during the design project. This helicopter is no different. Though the helicopters would theoretically be used sparingly, only during emergency rescue situations, and therefore would not require relatively high maintenance costs, they would still be an expense that a

city's budget would have to support. This category was given a weighting cost of 1. Due to the relative simplicity and multitude of existing technology of the conventional configuration, it was given the highest rating. The other three designs are much more complex, with respect to components such as the rotor hubs, swashplate and transmission, and therefore were given lower scores.

The design matrix in which these categories were tabulated is presented below.

Criteria	X	Tandem	Co-axial	Intermeshing	Single Rotor
Heavy Lift Capability	8	4	4	4	1
Compactness	8	1	4	2	2
Climb Ability	8	4	4	4	2
Hover Efficiency	7	3	3	4	3
Maneuverability	6	1	4	3	3
Versatility	4	4	3	3	3
Complexity	2	2	1	1	4
Cost/maintenance	1	2	2	2	4
Total		121	157	142	103

Table 3.1: Design Matrix

Based on the above matrix, it is clear that the co-axial helicopter performs the most favorably out of the four considered configurations.

There were two more important factors that needed to be taken into consideration in addition to all the above-mentioned parameters. The co-axial helicopter is compact; how, then, are supplies and people going to be transported in such a small fuselage? Also, loading and unloading people directly into the fuselage can introduce large cg travel, offsetting the equilibrium of the helicopter. These issues were resolved with the inclusion of an external basket into the design, onto which people and loads can be placed. This basket allows the fuselage to remain at a relatively small size while still transporting a large load. Also, since it can be tethered to the bottom of the helicopter at a location that is close to the center of gravity, this external basket will not seriously affect the helicopter's static stability. The basket design also allows for a physical separation between the rescuers (crew, command and control staff located in fuselage) and the victims (located in the basket). We believe that it is important to separate the victims who are likely to be in a highly emotional and panicked condition from the rescue stall, so that they may perform their duties calmly and efficiently.

Note that there will be a destabilizing moment introduced, that will offset the equilibrium of the basket itself while people are loading and unloading. This will be accounted for via an auto-stabilizer device consisting of a gyroscope that controls the position of a stabilizing weight in order to compensate for these new moments.

## Chapter 4 General Aircraft Layout and Weight Breakdown

### Aircraft Weight Breakdown

The weight can be broken down into a several key components, some of which are always part of the helicopters gross weight, and others that are mission dependent. The location of these weights can be seen in Table 4.1 and Figure 4.1. The dimensions for longitudinal cg are referenced with respect to the nose of the helicopter (origin). The vertical cg is referenced with respect to the base of the fuselage. Positive dimensions signify locations above this plane, while negative dimensions (e.g. basket) signify locations below this plane.

Components	Mass (lb)	Long. CG (ft)	Vert. CG (ft)
<b>Permanent</b>			
Pilot/Co-pilot	400	6	3
Fuselage	1940	11	4
Avionic System	122	2	1.5
Electrical System	100	13	6.25
Front Landing Gear	210	3.3	0
Rear Landing Gear	441	14.5	0
Fuel System	122	14.6	1.5
Engines	1200	9.9	6.5
Main Gear Box	1323	11.25	6.5
Rotor Blades	750	11.25	12.7
Rotor Hub	1818	11.25	8.5
Swash Plates	276	11.25	8.5
<b>Variable</b>			
Fuel	2866	14.9	3.8
Water	4172	9.3	0.7
Basket (with 50 people)	12125	11	-20

Table 4.1: Weight Breakdown and CG locations

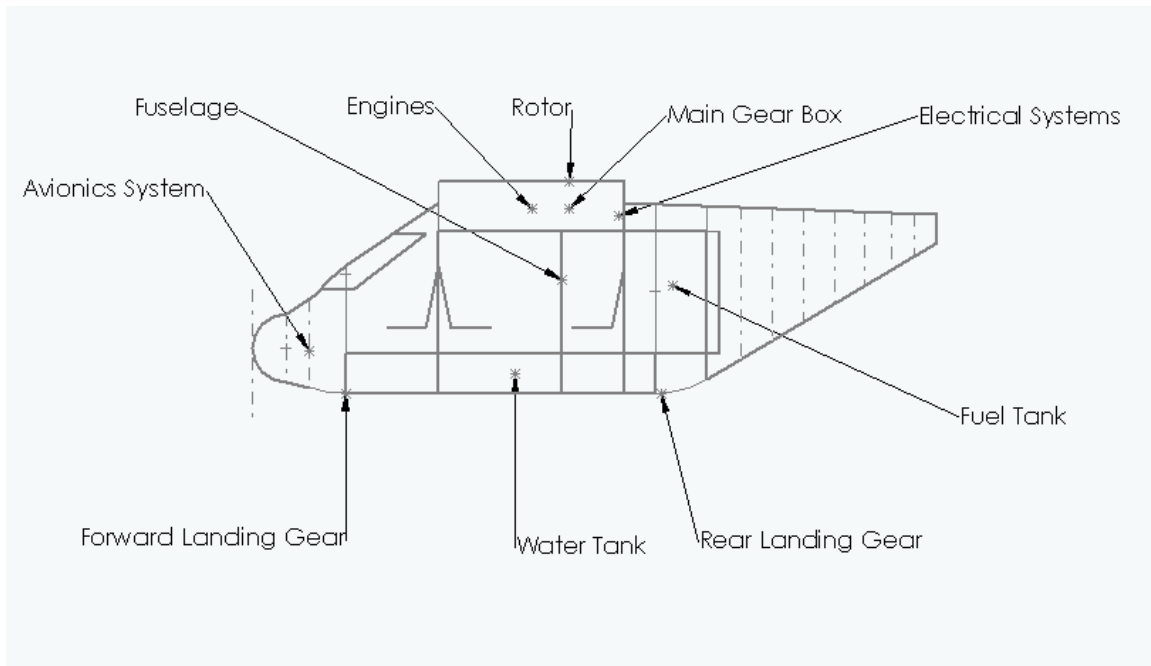


Figure 4.1: Key component locations

## Fuselage

The majority of the fuselage weight is from the airframe. This frame is made up of primary bulkheads to support the heavy component loads. All of the major components of the helicopter (such as the engines and the transmission deck) must be fixed to primary bulkheads. Secondary bulkheads are another component of the airframe. They are able to support smaller component loads (such as the battery). See Figure 4.2 for bulkhead placement. These bulkheads are fastened together via stringers running horizontally along the helicopter frame. The fuselage houses most of the helicopter's substructures, with the exception of the rotor group and the landing gear (as can be seen in Figure 4.1).

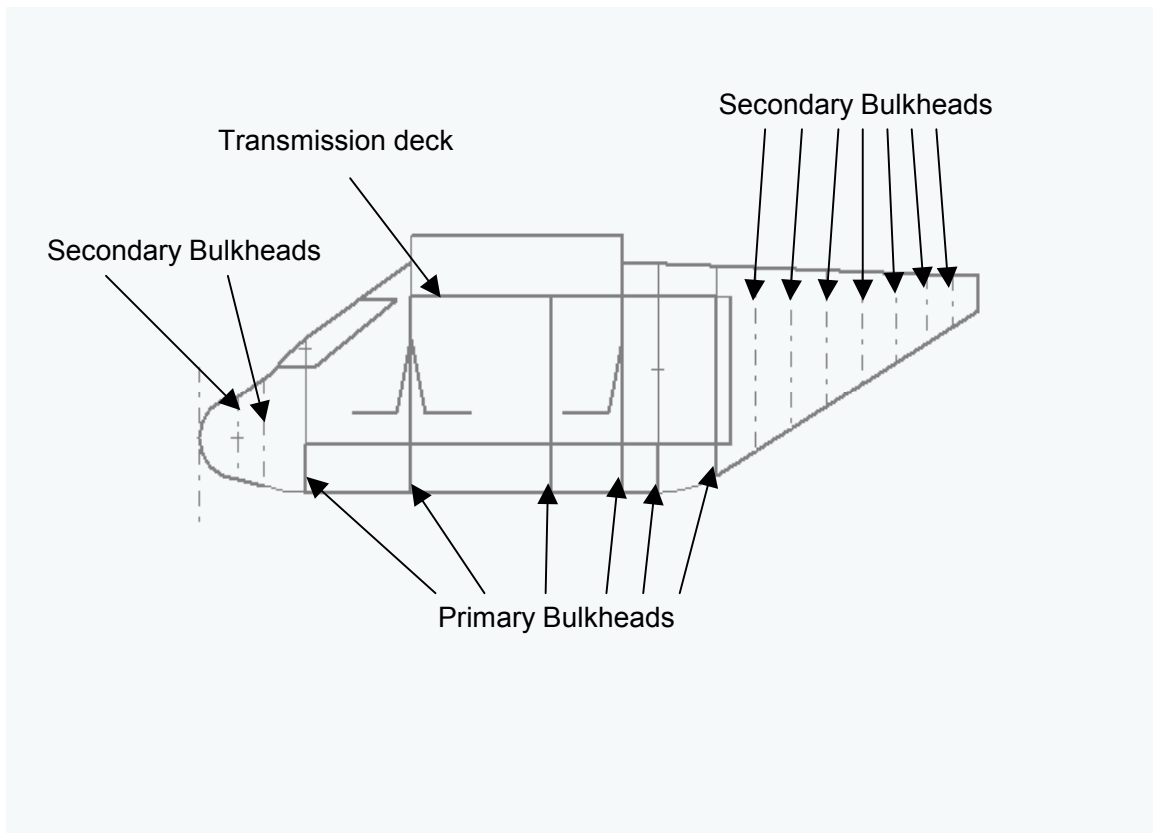


Figure 4.2: Bulkhead placement for fuselage

### Center of Gravity

Most of the components have fixed centers of gravity and unchanging weight, however there are a few factors, which change the location of the CG throughout a mission. The first is the burning of fuel. The helicopter will start each mission with a full tank of gas, but as the mission progresses (and fuel is used), the CG will travel forward. Also, the CG can vary location depending on the mission at hand. For example, while firefighting, the helicopter will start with a full tank of gas and water, both of which will be used during the mission, causing the CG to move. Also, while extracting victims, a substantial load

will be added to the helicopter, which will cause the CG to travel depending on the number of people being extracted and also the fuel being used. For stability and control reasons, the CG travel must be limited during flight to 2.5% of the rotor radius forward of the shaft and 1.5% aft of the shaft [Koratkar-1999]. The worst-case CG travel can be seen in Figure 4.3.

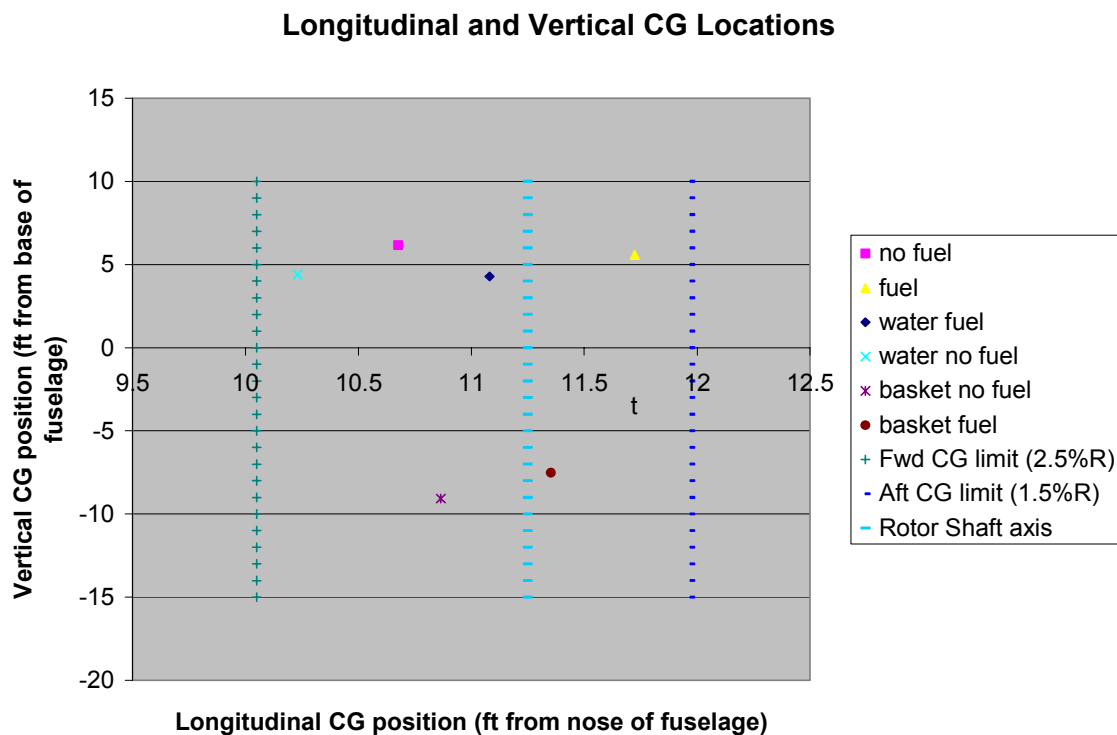


Figure 4.3: CG Travel

Overall dimensions of the fuselage are provided in Figures 4.4 and 4.5. Note that the maximum length and width of the fuselage are limited to 23.5 ft and 8.9 ft respectively. Therefore with a blade folding mechanism the helicopter can be transported on a flat-bed truck.

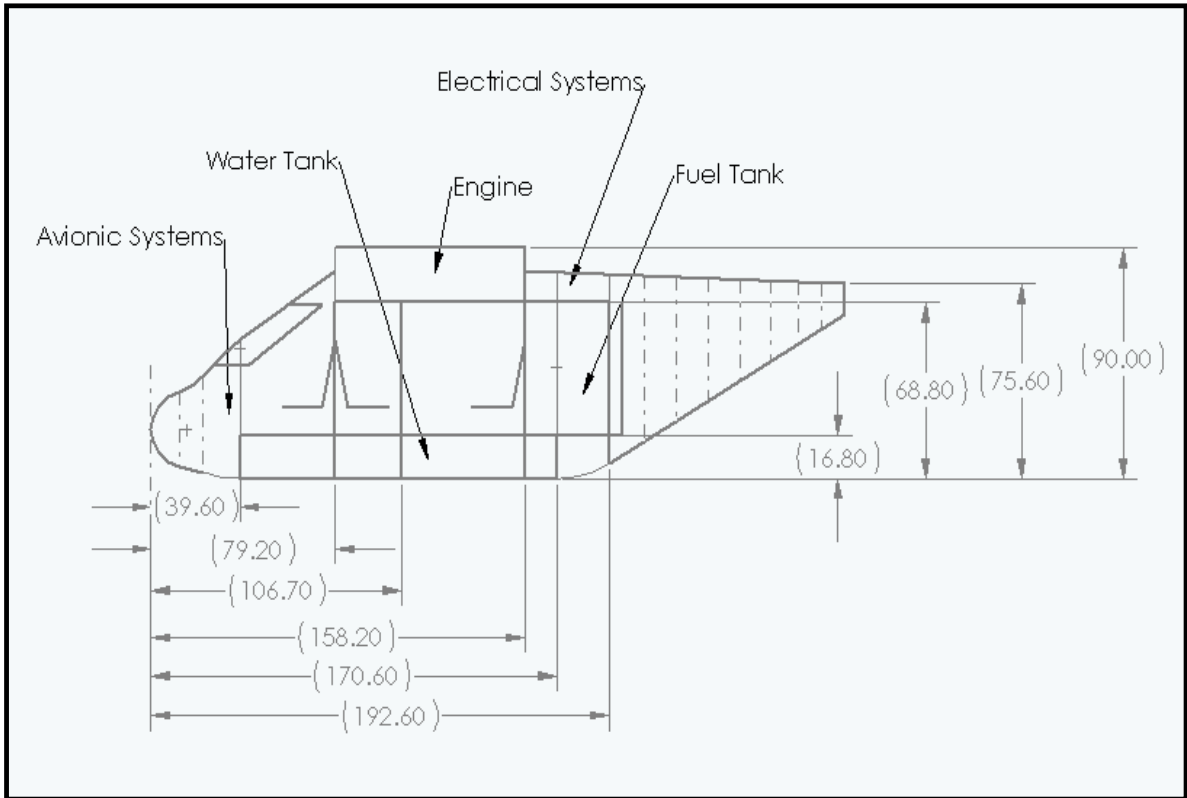


Figure 4.4: Fuselage side view (all dimensions marked are in inches)

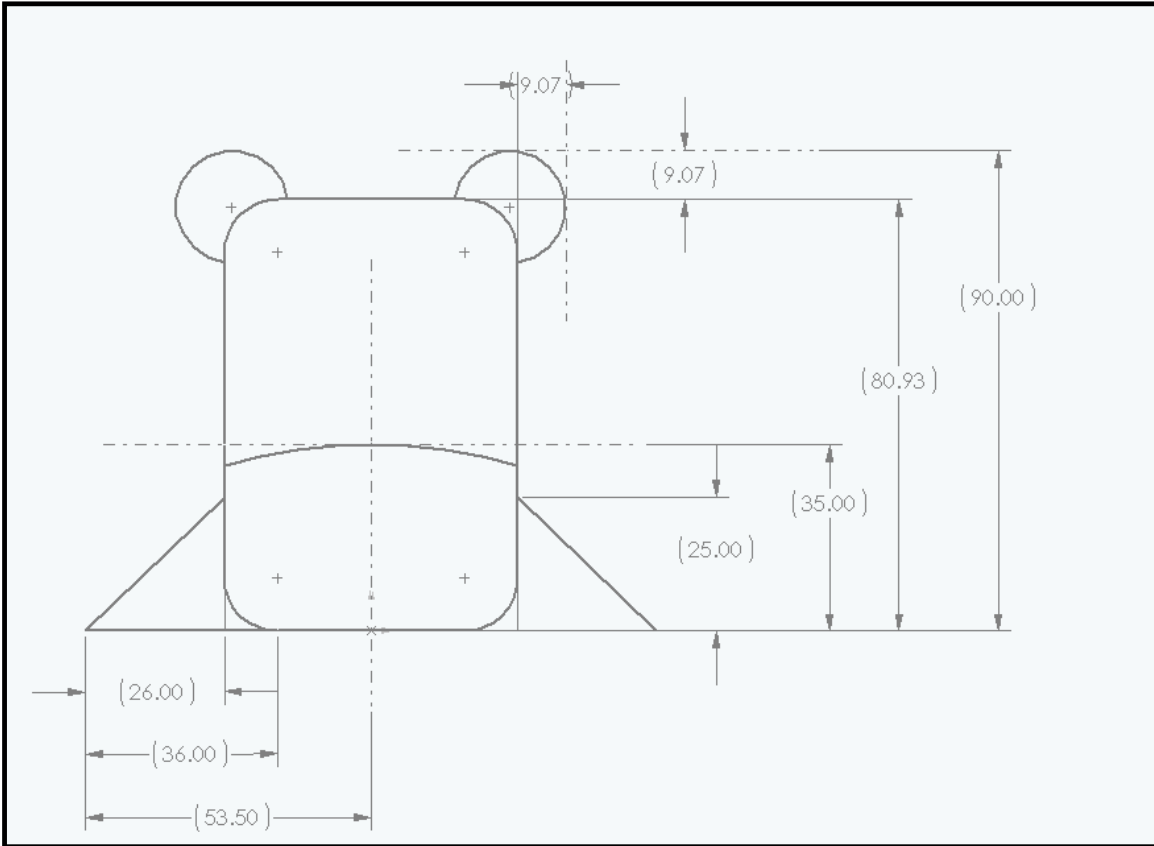


Figure 4.5: Fuselage front view (all dimensions marked are in inches)

## **Chapter 5 Detailed Design of Sub-Systems**

### **5.1 Fuselage**

#### **5.1.1 Substructure**

The design uses six primary bulkheads and several smaller bulkheads for load transfer and maintaining structural shape. The forward primary bulkhead is 39.6 inches behind the nose, in front of the pilot and supports the nose gear, avionics, and pilot instrumentation. The second primary bulkhead, 76.3 inches from the nose, supports the pilot, copilot and two crew seats as well as the transmission deck and is the forward anchor point for the engines. The third intermediate primary bulkhead at 103.3 inches is placed 28.7 inches in front of the main rotor mast. Its purpose is primarily to support the weight of the basket, directly beneath it. Its secondary role is to provide additional support for the transmission deck, engines, main rotor support beams, belly tank and cabin instrument console. The placement of this bulkhead is important as the primary payload weight will be placed on it. The closer the bulkhead can be to the rotor mast, the less center of gravity travel there will be. The fourth primary bulkhead, 158.4 inches behind the nose, is the rear anchor for the engines. It also exists as the anchoring for the rear-forward facing crew seats, and the rear mount point for the engines. The fifth primary bulkhead, 167 inches from the nose, supports rear fuel tanks and support for the rear landing gear. The sixth bulkhead, at 192.7 inches, is the rear support for the transmission deck and fuel tank. Spaced in between all of these and in the tail boom are the secondary bulkheads. The skin is attached to both primary and secondary bulkheads.

### **5.1.2 Tail Boom**

The co-axial design lends itself to having a very short and minimal tail section. The tail boom is a semi-monocoque structure with only secondary bulkheads to support the weight of the empennage. Stringers are used to transmit the loads to the primary structure along with the skin and secondary bulkheads. The rear stabilizer is a U-tail, which carries some weight penalties, but because there is no tail rotor or thrust compounding devices, the weight of the tail will be relatively small in comparison with traditional designs.

### **5.1.3 Interior Layout**

The cockpit layout is a standard two seat side-by-side configuration. The cockpit houses all the controls needed to fly the aircraft and operate the onboard water cannon. Primary command and control is carried out by the crew in the main cabin. The length of the cabin is 82.1 inches with a ceiling height of 52 inches and a width of 54 inches. The four crew are seated facing each other with a central console between them. This console houses all the needed instrumentation for operation of the command and control role.

Four doors are used to allow access for the crew. The pilot and copilot access through the standard hinged doors. The other four crew members access through “clam-shell” doors on either side.

## **5.2 Drive System**

The design is driven by two 2950 hp engines input to a transmission where their powers are combined and sent to a single shaft, which connects to the co-axial transmission.

### **5.2.1 Engine Configuration**

The engines will be fastened to both the transmission deck and bulkheads. The drive shafts will connect with the transmission via two shafts running back along half the length of the engine and will apply power through spring-type overrunning clutches [Kish-1978]. Expected size of the engine will be approximately 70 inches in length, 20.5 inches in diameter and weigh approximately 550 lbs. The design calls for two 2950 hp engines. The expected output will be at approximately 14280 RPM based on currently available turbo-shaft engines.

### **5.2.2 Transmission Configuration**

The main transmission is fairly simple in design, though very hardy in construction. It takes input from one or both engines (2950 hp @ 14280 RPM) from the respective clutches, separated by 48 inches and delivers this to the main step-down gear. This main gear drives both the electrical sub-systems alternator and the bevel gears for changing the angle of rotation to 90 degrees from the original path. The initial gears from the load point of the engine to the intermediate shafts have a reduction ratio of 10:1. From these two shafts is the main pinion-gear reduction set [Dudley-1984]. The 2, 20-tooth double-spur pinions, at 1428 RPM, connect with the 456-tooth double-spur gear, at 62.575 RPM, leading to a reduction ratio of 22.82:1. Each of these contacts can safely

deliver 9324 Hp each. The output shaft of this gear, directly drives the electrical systems and the bevel gear leading to the co-axial splitting transmission. The bevel gears are both 5-pitch 35-tooth which have a maximum power transfer of 6700 Hp. Because of the design of the splitter transmission, both rotors are locked in phase and will maintain the same RPM.

The shaft from the primary transmission runs directly to the co-axial splitting transmission. The input gear, 30 teeth, drives the outer and inner transmission gears, 150 teeth, giving a reduction of 5:1 leaving the rotation rate at 1056 RPM. The inner transmission shaft drives the inner shaft with a 25 tooth pinion and 85 tooth gear, reduction ratio 3.4:1. The outside shaft is driven by a 35 tooth pinion and 119 tooth gear, reduction ratio 3.4:1. This leads to a total step down of 17:1 through the co-axial transmission and output rate of 312 RPM.

Safety was an important consideration in our decision to go with a two engine design. Both rotors are driven by a single input from both engines. This is done because of the possibility of engine failure in flight. If each rotor were driven by one engine, an engine failure would mean a loss of power and torque to one rotor. Without a tail rotor this would mean catastrophe. Having two engines means an added factor of safety and reliability over a single engine design.

Figures 5.1 to 5.3 show the details of the engine and transmission system for the Extricator.

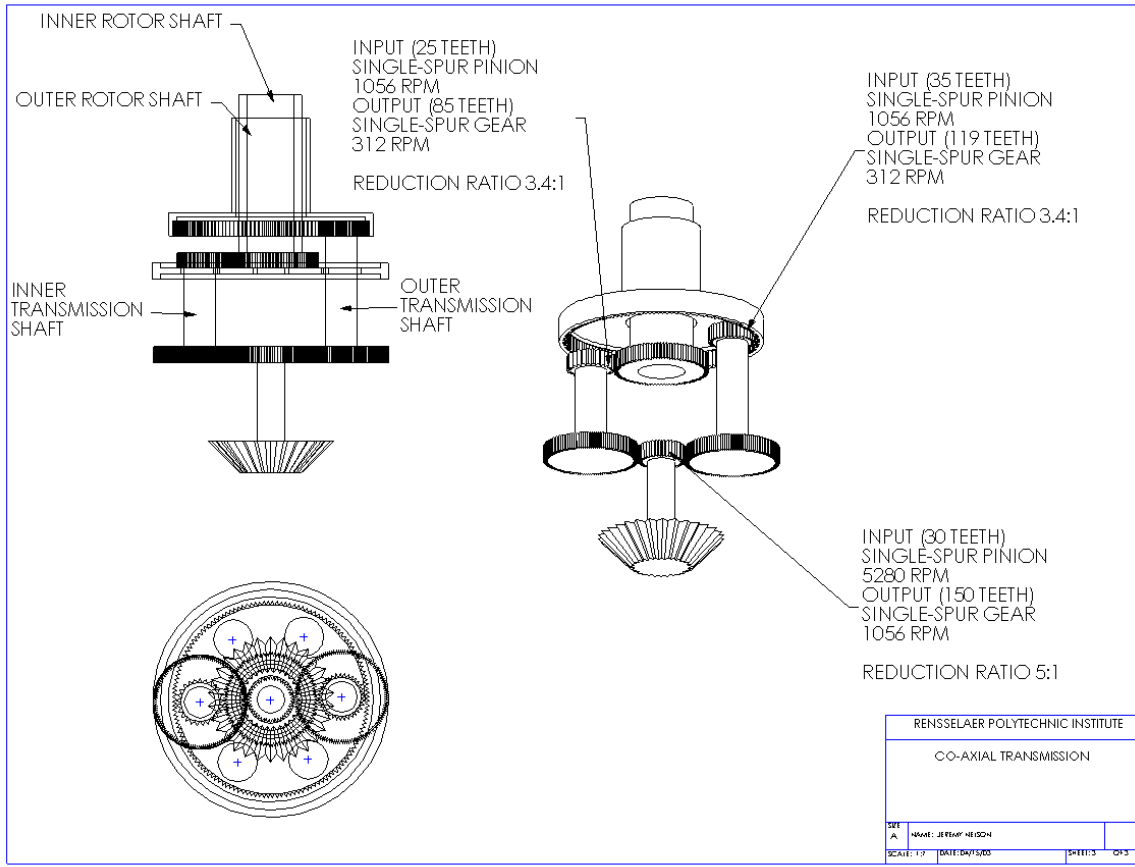


Figure 5.1: Upper transmission system

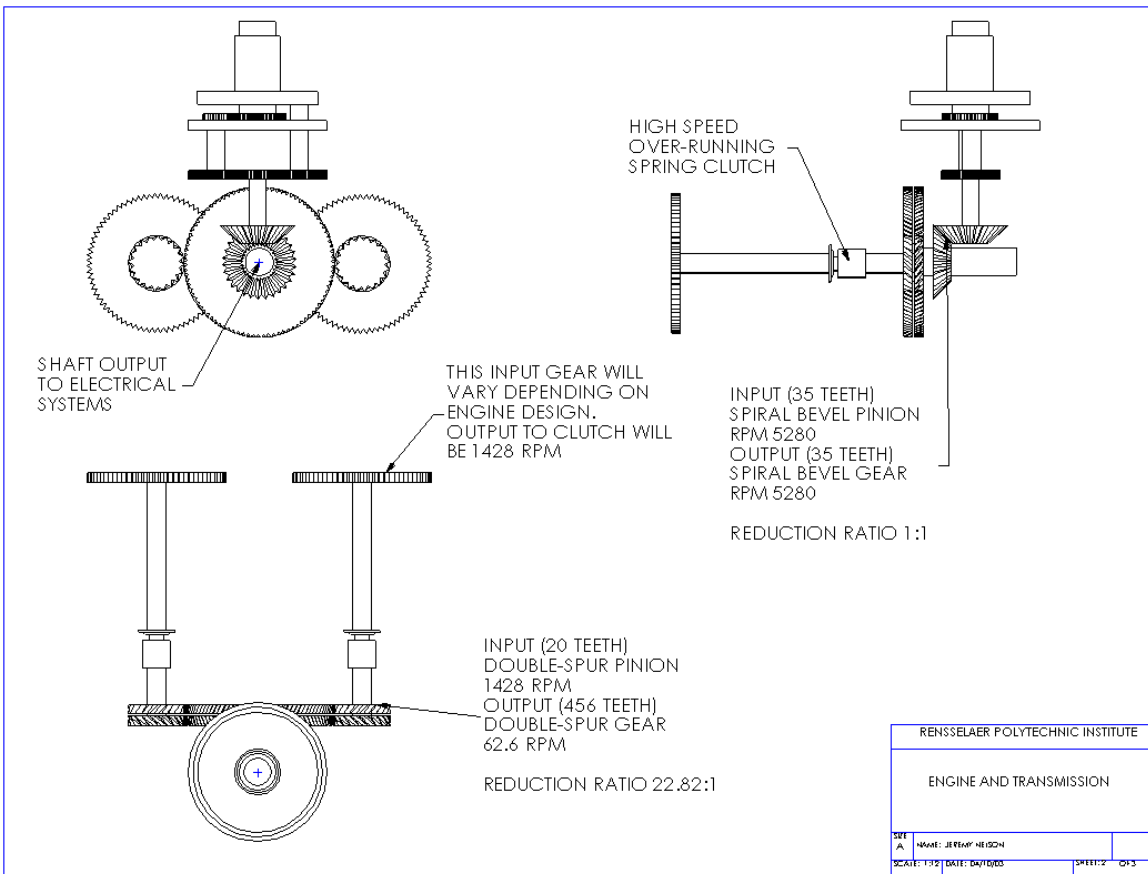


Figure 5.2: Lower transmission system

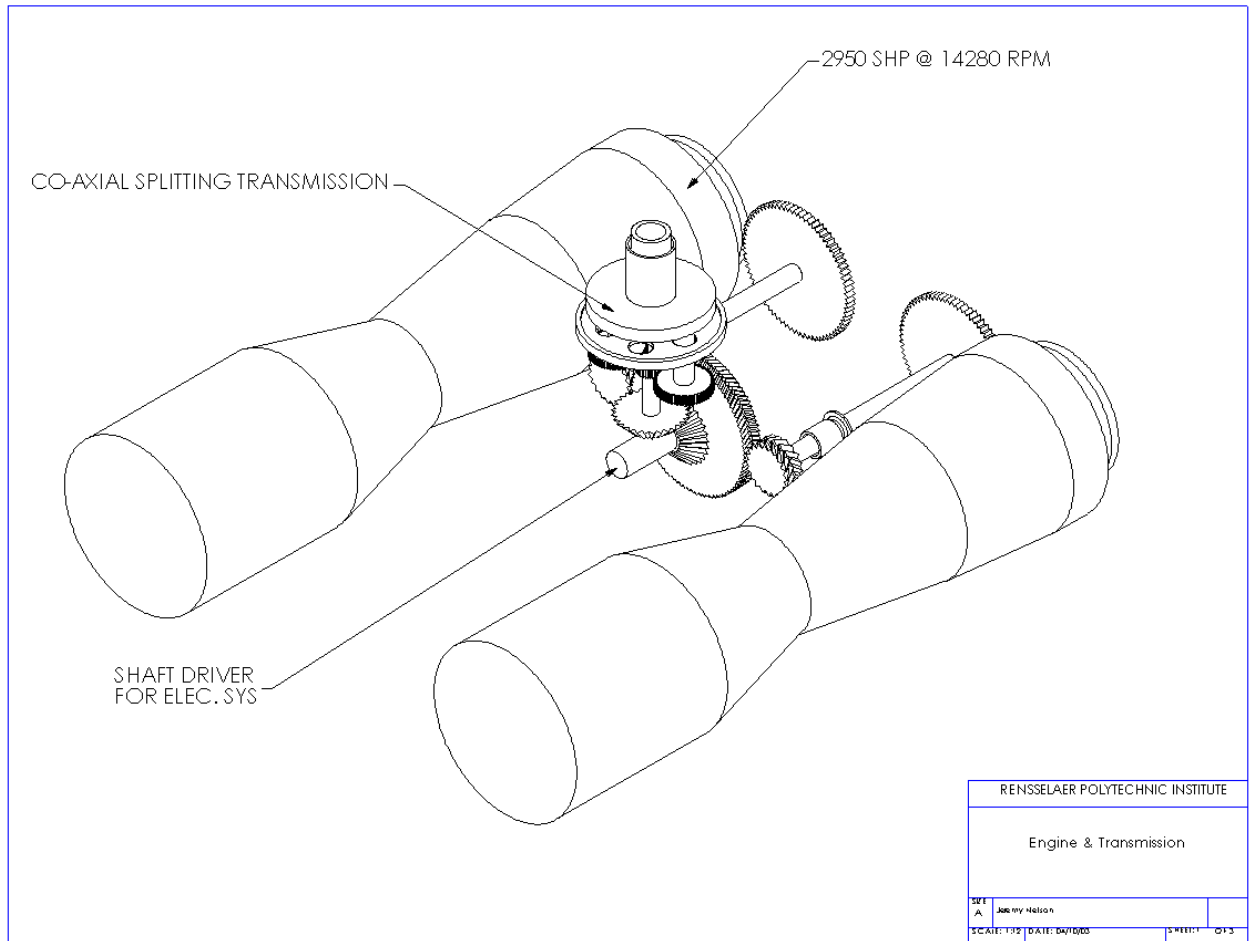


Figure 5.3: Complete transmission system and engines

### 5.3 Structural Integration

Typically, rotor loads are transmitted to the bulkheads through the transmission housing. However, the mission parameters imply severe loading conditions and moderate impact loading. Because of the shaft within a shaft design of co-axial rotors, only one of the rotors can offload to the fuselage via a thrust bearing supported by four pylons attached to the intermediate primary bulkhead and transmission deck. Though

only half of the weight can be offloaded, it is still a significant and important improvement. When looking at a total mass of 11800kgs, reducing the weight carried by the transmission by half will have obvious advantages in terms of component lifetime, reliability and overall safety.

## **5.4 Landing Gear**

The craft will have three fixed wheel type landing gears, two at the rear under the furthest bulkhead, and one at the front under the forward bulkhead. For the mission requirements, it was decided that retractable landing gear would merely cause excess weight and complication to the design. Also the design is tailored around a cruise speed of 60kts, so drag due to the wheels will not be significant [Wood-1968]. The fixed-wheel type landing gear was preferred over a fixed skid system because of superior cushioning effect in case of hard landing, ability to taxi on the ground and ease on deployment on debris ridden roof-tops.

### **5.4.1 Configuration**

Dimensions for rear gear. Disc brakes are installed on the rear gear for stopping and controlling ground rolls and keeping the aircraft stationary while parked.

Steering will be accomplished through the rudder pedals as in most aircraft. The maximum turning angle will be 60 degrees so that ground maneuvers can be accomplished within a reasonable area.

The nose gear and main gear have a distance of 10.9 ft between their centers. This keeps the center of gravity well within limits. The width between the rear landing

gears is 10.6 ft. This wide stance was used because of the rather top-heavy design, and the impending danger of tipping in high winds.

#### 5.4.2 Tire Sizing

Because of the variable surfaces that the helicopter may land on, a low pressure tire is used. Three 20 x 11.5 – 14.5 bias-ply tires [Currey-1988] are used, chosen because there is a possibility of heavy landings and shock loading and bias-ply tires have been shown to withstand low pressure testing better than radial ply tires. Pressure in the tires is a recommended 1.7MPa (245 psi), which will provide adequate support and impact cushioning for a fully loaded layout. The tire specifications are summarized in the table below.

##### Tire Characteristics:

Size:	20 x 11.5 – 14.5
Ply rating:	24
Weight kgs (lbs):	27.7 (61)
Rated Vertical Load, kN (lbs):	111.2 (25,000)
O.D. unloaded m (inches):	0.76 (30)
Max. width unloaded m (inches):	0.2 (8)

Table 5.1: Tire specifications

### 5.4.3 Oleo Sizing

Single oleo-pneumatic shock absorbers are used for both main and nose gear. Each gear must be able to withstand a 13 inch drop test, equivalent to a touchdown velocity of 8.35 ft/s. The estimated stroke for each shock absorber is a vertical 4 inches.

The design requirements are as follows:

- Internal Pressure: 1800 psi
- O.D: 1.3 I.D.
- Length: 2.5 max stroke

Resulting specifications: nose gear O.D. 1.54 inch, length 12.52 inch and main gear O.D. 3 inch, length 7.1 inch.

## 5.5 Main Rotor and Hub Design

In Chapter 6 (Performance) we discuss the procedure used for selection of main rotor diameter and disk loading. This section will discuss the details of hub design and selection of rotor geometry, planform and airfoils to be used on the main rotor.

### 5.5.1 Rotor System

The helicopter has two co-axially oriented counter-rotating rotors (diameter 14.75 m) separated by 1.75 m (12% of rotor diameter). The helicopter's counter torque producing scheme is provided by the counter-rotating rotors of equal size. The rotor hub incorporates a bearingless main rotor design made extensively out of composite materials and is designed for 4 blades. The blade attaches to a flexbeam integrated to the hub that allows blade flapping and lead-lag motion. Blade pitch control is achieved through the use of conventional pitch links and swashplates. The pitch links are connected to a

specially designed cuff that transfers torque to the flexbeam. Elastomeric lag dampers will be used to ensure aeroelastic stability. The rotor hub supports four fiberglass flexbeams firmly attached to the hub at the root. They are designed with correct bending stiffness and cross section geometries to allow for necessary blade deflection.

Elastomeric dampers incorporate flat elastomeric elements that are selected for simplicity and ease of maintenance. The rotor blade has a constant chord of .42m all the way up to 90% of blade radius, and then tapers down to the blade tip. The tip Mach number for the system is 0.7 in hover with a blade tip speed of 240 m/s and increases to an operating Mach number of 0.85 on the advancing side at a cruise speed of 60 knots. The rotor solidity of each rotor is calculated as .0724.

### **5.5.2 Airfoil Selection**

Airfoil selection is crucial to the performance and efficiency of the helicopter rotor system. Different blade sections along the rotor-span experience differing flight conditions based on location along rotor-span as well as a function of the azimuth angle of the advancing and retreating blades. Since there is no single current airfoil that can achieve ideal performance requirements along the entire blade, we must use multiple airfoils [Vuillet-90] to achieve desirable effects along the blade span. Suitable airfoils should have the following characteristics: a high lift coefficient with low drag, a moderate amount of camber to achieve high maximum lift coefficients, and low pitching moments.

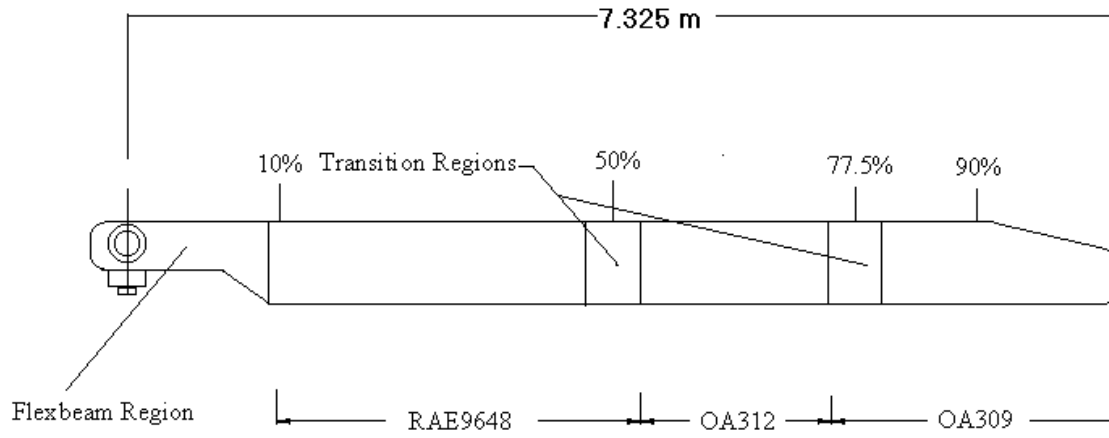


Figure 5.4: Blade schematic and distribution of airfoil sections

Three types of airfoils are used in the design of the rotor: RAE9648, OA312, and OA309. The RAE9648 was used from the root to 50% of blade span (Figure 5.4). It was chosen because of its reflexed camber configuration, which aids in reducing the nose down pitching moments of both outboard airfoils. On the inboard sections close to the blade root of the retreating blade, reverse flow occurs in forward flight resulting in negative lift production. These reflexed camber properties of the airfoil help in retarding this effect as well. The OA312 airfoil was used from 50% to 77.5% of blade span. This airfoil is perhaps in the most critical area, since the majority of the lift is generated in this region. This airfoil provides a maximum coefficient of lift of 1.5 and has a 12% camber. In addition to its excellent lift capability, this airfoil provides a high drag divergence

Mach number (0.78) as well as low pitching moment coefficient. The airfoil chosen for the remainder of the blade all the way to the tip was the OA309. This airfoil possesses a 9% thin cambered airfoil with good lifting properties and a drag divergence mach number of 0.85. The profiles of the OA312 and OA309 airfoil sections as well as a comparison of these airfoils against other typical airfoils are shown in figures 5.5 and 5.6. Note that for a given drag divergence number, both of these airfoils have higher maximum lift coefficients than most commonly used airfoil sections (see Figure 5.7).



Figure 5.5: OA312 airfoil  
(from 50% and 77.5% of blade radius)



Figure 5.6: OA309  
(from 77.5% of blade radius to blade tip).

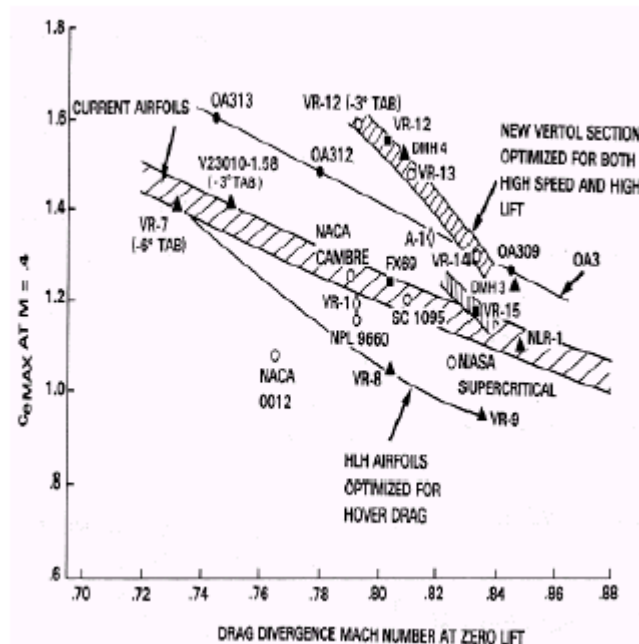


Figure 5.7: Comparison of rotor airfoils

## 5.6 Swashplate control system

The control system that supplies the collective and cyclic inputs to the rotors is similar to other co-axial configurations. The two swashplates are connected by linkages such that they behave in unison. When collective control is applied, the end result will be that the two swashplates will have the same vertical movement and thus the same pitch change will result to both rotors. Similarly tilting the lower swashplate (cyclic control) will result in the same tilt being imparted to the upper swashplate. Below is a diagram of the swashplate mechanism proposed for the Extricator

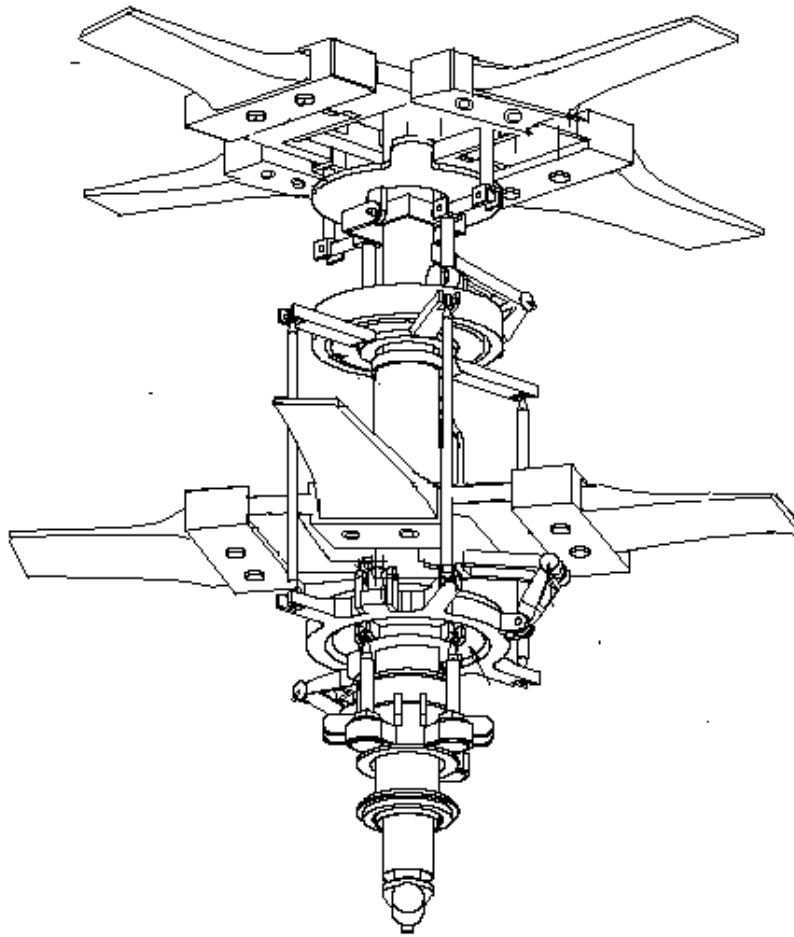


Figure 5.8: Interconnected swashplate control system

There must be a special mechanism that allows for differential pitch to the rotors so as to produce a yawing moment. This allows the helicopter to yaw while remaining at a constant altitude. The scheme [Datta-2000] used to accomplish this is illustrated below.

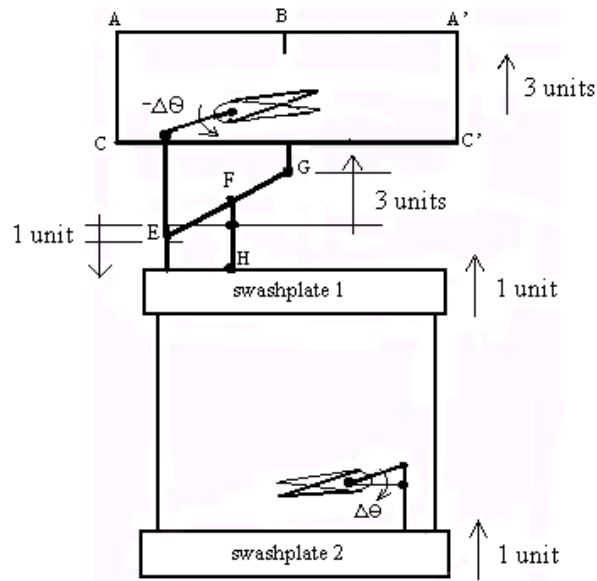


Figure 5.9: Yaw control system

The top lever AA' is connected to a control link at point B. This control linkage passes through the interior of the inner shaft that drives the upper rotor. Lever AA' is also connected to the disk CC' by means of linkages AC and A'C'. The plate CC' is connected to the top swashplate (swashplate 1 in figure 5.9) via a lever mechanism (E-G) that is pivoted at point F, which is rigidly connected to swashplate 1 at point H. Note that it is point E that is connected to the rotor blades on the top hub and not swashplate 1. For the lower rotor, the blades are directly connected to swashplate 2 (see figure 5.9).

When collective input is supplied, the inner most control linkage connected to AA' at point B is given the same vertical motion as swashplate 1 and swashplate 2. Since both the swashplates receive the same vertical displacement, they result in the same pitch change for both the rotors. Since the point B has the same vertical motion, the plates AA' and CC' also have the same motion as the swashplates. Therefore the lever E-G remains horizontal and therefore no differential pitch is introduced between the rotors.

When we need to yaw the Extricator, the inner control linkage that connects to point B on the disc AA', is given a displacement that is greater than the bottom swashplate in order to generate the differential pitch. For example, when collective input is supplied for one unit of upward displacement to the lower swashplate, three units of upward displacement (via the control linkage) are applied to point B that connects to the plate AA'. Therefore plate AA' and CC' have 3 units upward displacement, causing the lever E-G to tilt such that the point E displaces down by one unit (assuming that the lever arm ratio is 2:1) resulting in a differential pitch input. The above manipulation achieves an equal and opposite pitch change of one rotor compared to the other. One rotor will create lower thrust, counteracting the increase in thrust from the other rotor. Since the net change in thrust is zero and the torque created by one rotor is higher, the helicopter will change its heading while maintaining its altitude.

## **5.7 Basket Design**

In order to maximize the amount of passengers that could be rescued in one trip and minimize the time necessary to load and unload these passengers, it was decided that an external basket would be utilized.

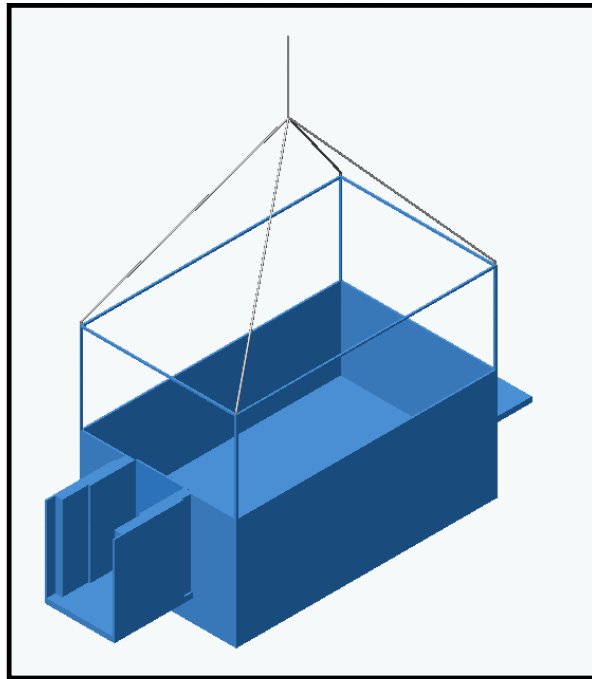


Figure 5.10: Layout of basket for roof-top extraction mission

For the roof-top extraction mission, the basket configuration is shown above. (Figure 5.10). For building face-extraction the configuration will appear as shown in Figure 5.11.

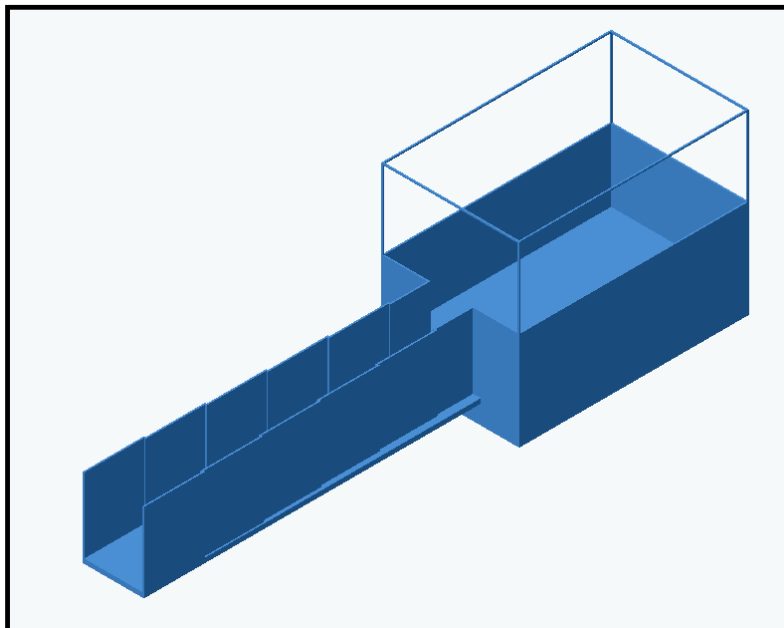


Figure 5.11: Layout of basket for face extraction mission

The bridge shown above has a one-piece base, which slides into and out of the base of the basket. The walls of the bridge are connected to the base at the end of the bridge. When the bridge extends, these walls telescope out, giving the passengers a railing to hold on to, as well as a much-needed sense of security, as they enter the basket.

When the basket is filled to capacity with people, a door that is able to slide in and out of the side of the basket can be closed. A sliding door ensures no extra space is needed to swing open and shut.

When fully extended, the end of the bridge shall be hooked into the window from which people are being extracted, adding stability to the system. This hook also helps counteract the moment created by the weight of the passengers as they cross the bridge. Also counteracting this moment shall be an auto-stabilizing actuator, located in the base of the basket, which shall automatically control the position of a weight along a linear track in order to keep the system level as the victims rush into the basket.

The basket shall be hooked to bottom of the fuselage, as close as possible to the vehicle cg, so that the basket does not create a destabilizing moment on the rotorcraft itself. It shall be hooked and unhooked via cables easily, which will minimize time between missions.

## **5.8 Avionics –System Descriptions**

### **5.8.1 Command and Control**

A minimum of 4 personal are going to be part of the command and control group. Each Control Operator is trained to a very high standard to deal with any incident, and to cope with often distressed and panicky callers, in a calm and competent manner.

As the scope of information becomes increasingly important for the rescue commanders, for example information on hazardous substances, injured people, personnel etc. It is important to acquire and process this information in real-time. One of the purposes of the urban disaster response vehicle, is to enable the option of being able to move experts to the rescue commander in a fast and virtual manner by means of video, data sound sensors and 3-D models of the accident scene.

The rescue commanders needs vast amounts of real time information. They have to keep an eye on their personnel, on others at the accident scene, on resources, buildings and structures, chemicals and much more and at the same time make operational decisions and weigh up risks. They also have to be able to communicate their understanding of the situation and their general decisions to those who need that information. At major accidents there is a big risk that the rescue commanders can fall prey to information overload, i.e. that they receive more information than they are able to manage or to disseminate. In those situations the rescue commanders on the Extricator should be able to take assistance from ground command staff, so that the load can be shared. Personnel and experts at the accident take part in different types of rescue operations (air, sea, land, environment etc.) nationally and internationally where different agencies and nations have different responsibilities. Command, control, and communication systems on the Extricator will be designed to allow personnel at the accident scene, rescue commanders, and experts to use the same equipment and the same systems regardless of which agency or nation is responsible for the operation.

## 5.8.2 Component description

### Thermal imaging camera

The Thermal Imaging Camera (TIC, Figure 5.12 ) and its infrared technology offers firefighters the ability to locate trapped or injured occupants and to move through dark, smoke filled environments. With this device firefighters now have the ability to locate victims quickly, perform rescue and extrication of the victims, locate the seat of the fire and extinguish the fire expeditiously. TIC's read infrared radiation wavelengths. Different objects including the human body give off varying heat levels. The TIC can differentiate heat levels in fractions of degrees allowing firefighters to distinguish between hot, warm and cool surfaces. Infrared travels in longer wavelengths than visible light, therefore in dense smoky conditions the TIC allows firefighters to see objects that are not visible with the naked eye. A bigger unit of the TIC is going to be directly installed into the front of the helicopter and smaller units are going to be handled by individual firefighter.



Figure 5.12: Thermal imaging camera, Mb320

### **5.8.3 human-detecting devices**

LifeGuard, manufactured by DielectroKinetic Laboratories, LLC, of Washington, is marketed as a device to detect the faint electrical signal of a human heartbeat--at distances of up to 500 feet, and through metal, concrete and water. The company says the device, which comes in three models costing \$6,000 to \$14,000, can pinpoint victims in the rubble of a demolished building. "People can be localized through concrete and steel walls, earthen barriers, inside stationary or moving vehicles and underwater," the company's literature says. "There are no known electronic or other countermeasures."

Los Angeles narcotics task force says it has been 100% successful in using the device. This system will be installed on the extricator.

### **5.8.4 Robot to the rescue**

It takes a long time to find victims in a collapsed structure, and often it is impossible to get to them. Robots help in finding victims in a collapsed building (Figure 5.13). Search robots can find victims, map out their location, and send it back to the main computer so rescuers can find the potential survivors. Robots can also send food and first aid to the trapped victims.

There are certain tasks that need to be performed in order to save victims. One of the tasks is to examine the collapsed site and see what points are safer to enter into. Robots make this job easier and safer by mapping out points with its sensors. A rescuer who is searching for victims has to leave the site often for an inspector to come in and check for weak spots and possible collapses. Robots make this job easier also by traveling ahead of the rescue worker and warning him/her of danger spots.

Other tasks are mapping out where victims are located and sending it back to the main computer so firefighters are able to find the victims easily. Robots are also able to travel into tight spots unlike humans and rescue dogs. This makes it easier to map spots, find survivors, and warn of any danger spots.



Figure 5.13: Picture of a robot in a disaster site

Robots will also eventually aid in finding deadly chemicals. The robot is equipped with miniaturized bio-chemical agent detectors that can sense toxic materials and mark the spot so they can be removed properly. Robots can also cover more area in the site of disaster than people. Two such robotic systems will be available to the Extricator to help with search and rescue operations.

### **5.8.5 Automated translation systems**

Speech-recognition technologies could play a key role by helping firefighters transcribe and translate conversation with non-English-speaking disaster victims. For instant, if a victim who can't speak English clearly is rescued by a firefighter; he could have valuable

information about the people left behind. The main challenge is developing solutions that can overcome different language dialects, accents and noisy environments. Current portable computer platforms are not powerful enough to support advanced translation capabilities.

### **5.8.6 The On-Scene commander**

The On-Scene Command and Control (OSC) system is the hub of G-M's overarching Command, Control, Communication, Computers & Information (C4I) initiative.

Although designed for The Coast Guard, the system will be capable of being utilized any multi-agency for example, it can be used for the disaster response vehicle, Incident Command System (ICS)-based response to a natural or man-made disaster. OSC will support and complement the Incident Command System, serving as the platform for the integration, display, and redistribution of real-time, or near real-time, response and planning information for use by the Unified Command and the Planning and Operations sections of the ICS.

**COMPONENTS** - The initial prototype will include the following functions:

**Electronic ICS Forms** - A Microsoft Access relational database processes information among the 30-plus standardized forms used by the ICS.

Response personnel will enter information once and it will automatically "map" to other forms that use the information. This will facilitate the creation of the Incident Action Plan, Situation Display and other reports.

**Situation Display** - Large-screen display will be generated with a Geographic Information System (GIS). This GIS will be capable of importing commercial-off-the-shelf nautical charts, digital maps, and other government or industry-produced geo-referenced data and contingency plan information. There will be graphical display and linkages to the ICS-managed resources. An oil spill trajectory model will be a key component of the Situation Display.

**Information Dissemination** – A web-based Intranet will be linked to the network in order to disseminate completed ICS forms and situational display information to all members of the Unified Command. This Intranet will have the capability to be accessed from outside the Command Post; either through controlled access for other unit, District or HQ use or, if desired, access via the Internet.

## **5.9 Sketch of future urban fire station**

Figure 5.14 shows a conceptual sketch of the proposed fire station. Shown in the figure is a helipad on the roof of the station, designed to enable the Extricator to land and take-off as an when needed. Also space is earmarked for the spare water tanks and spare passenger extraction baskets. This is in addition to conventional systems such as fire engine, fire hose etc that are needed for regular firefighting operations.

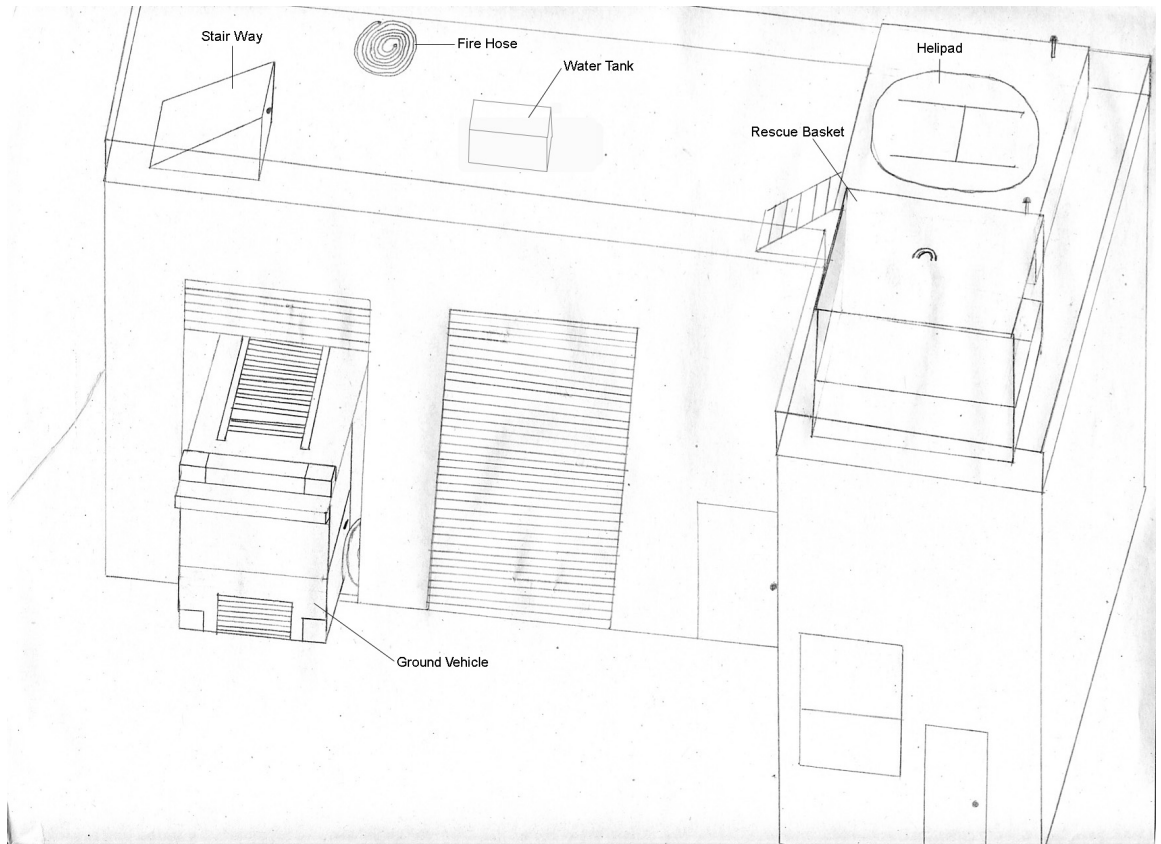


Figure 5.14: Conceptual sketch of urban fire station

## Chapter 6 Performance

### 6.1 Determination of Optimal Vehicle Parameters

A preliminary design code (PDC) was developed for determining the total gross weight, component weights, and basic rotor sizing. The PDC is developed using the formulation presented by Prof Marat Tischenko [Tischenko-2003] in a recent issue of the AHS journal. Parametric studies were also carried out to choose appropriate parameters such as the main rotor disk loading, number of blades, and also the number of engines. The disk loading of a helicopter main rotor is defined as the operating weight of the helicopter divided by the disk area of the rotor. Since the co-axial design has two equal diameter rotors, half the weight of the helicopter will be the effective weight for this calculation. One of the key criteria for the success of an urban rescue vehicle lies in its ability to get close to the building from which it will extract victims. If the helicopter has a large rotor diameter, this can be hazardous when rescuing victims. It is advisable to reduce the rotor diameter in this situation, however from the definition of disk loading; a decrease in rotor diameter reduces the disk area, which then increases the disk loading. This effect has important implications such as an increase in the weight and power required to create a given amount of thrust. From an efficiency point of view, it is desirable to decrease the disk loading of the rotor. Therefore there is a trade-off between the rotor diameter (and thus disk loading) and the power and weight contributions that result from the size of the rotor. In order to achieve the optimum disk loading, a parametric study was conducted for disk loadings from 15 to 50 kg/m<sup>2</sup>. The trade-offs between the total weights, total power and the main rotor diameter were studied and plotted against the disk loading and number of blades.

### 6.1.1 Disk Loading Selection

As the disk loading increases, the total weight and power increases (Figures 6.2, 6.3) while the main rotor diameter decreases (Figure 6.1). Based on our desire of compactness of the design, the disk loading was chosen to be  $35 \text{ kg/m}^2$ . Above this value the reduction in rotor diameter tapers off (Figure 6.1) while the weight (Figure 6.2) and power (Figure 6.3) continue to increase rapidly. Therefore to further increase disk loading above 35 will result in severe weight and power penalty for a minimal saving in terms of compactness.

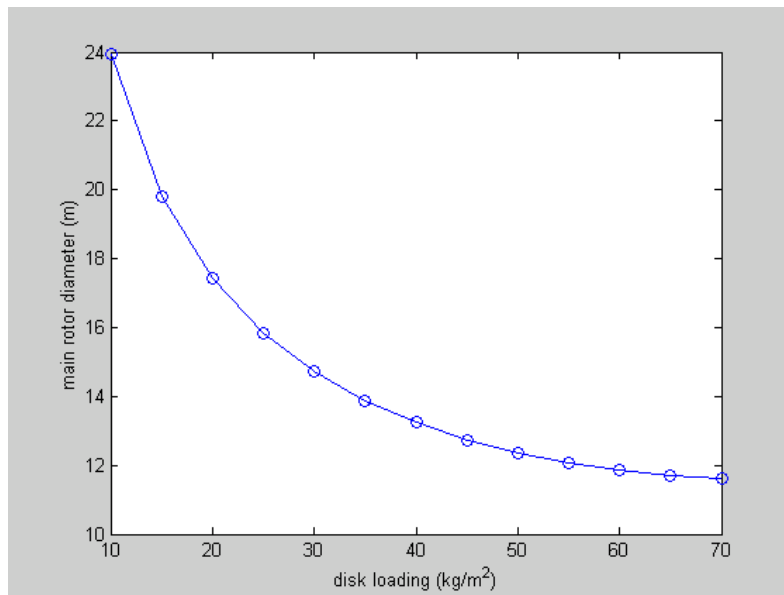


Figure 6.1: Disk loading vs. main rotor diameter

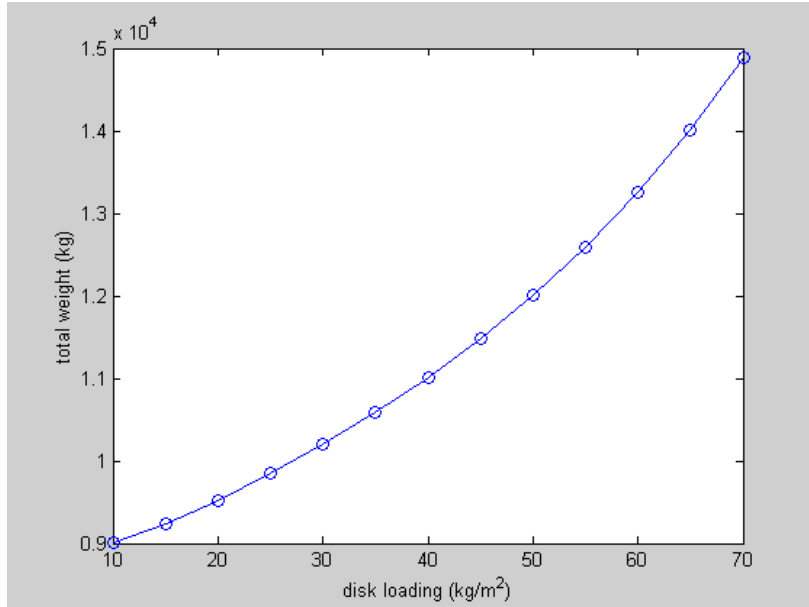


Figure 6.2: Disk loading vs. total weight

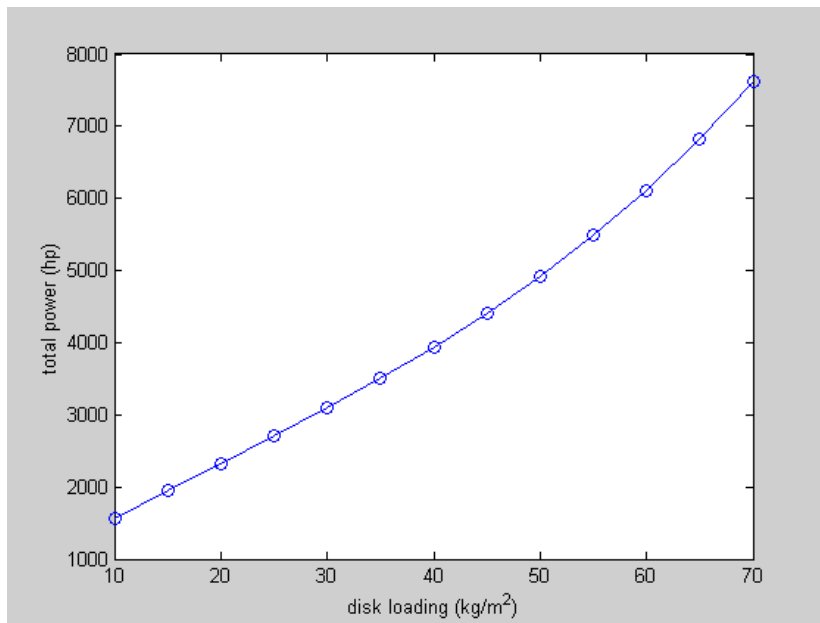


Figure 6.3: Disk loading vs. total power

### 6.1.2 Selection of Number of Blades per Rotor

A study was conducted in order to analyze the effect of the number of blades per rotor on performance indices such as power required, rotor diameter, and total weight. The disk loading was selected as 35; the payload was 5000 kg and no. of engines was set at two. As the number of blades for each rotor increases, the total weight, total power and main rotor diameter all decreases (see Figures 6.4-6.6). However, having more than four blades per main rotor does not have a very significant impact on reducing the main rotor diameter, power and total weight; it is also important not to use too many blades because it adds complexity to the rotor swashplate mechanism and manufacturing cost as well as results in a massive hub. After taking these figures under consideration, it was decided that 4 blades per rotor would be used for the Extricator.

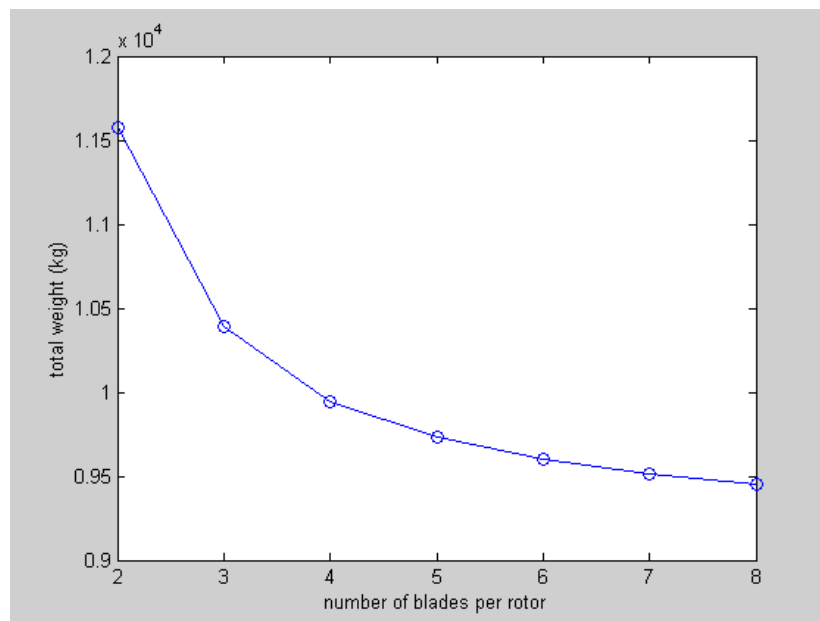


Figure 6.4: Number of blades vs. total weight

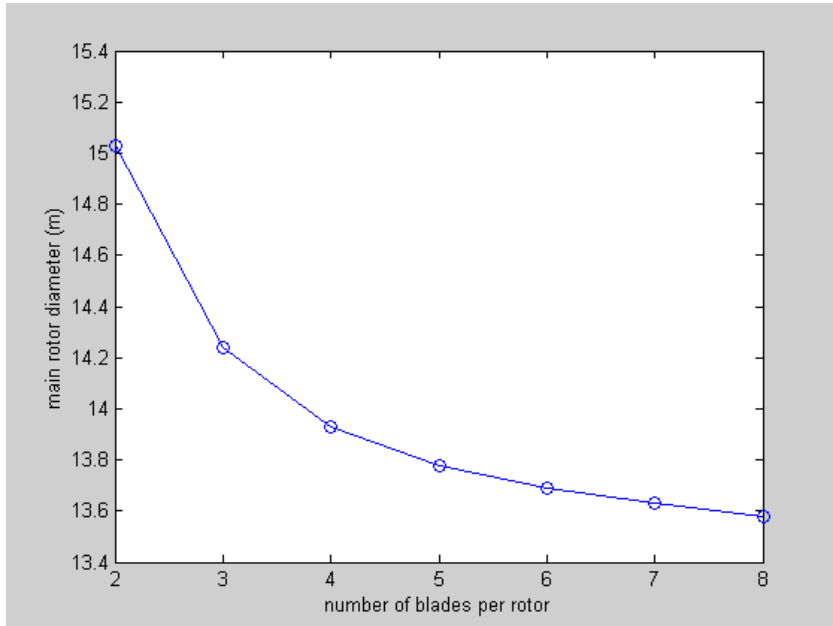


Figure 6.5: Number of blades vs. main rotor diameter

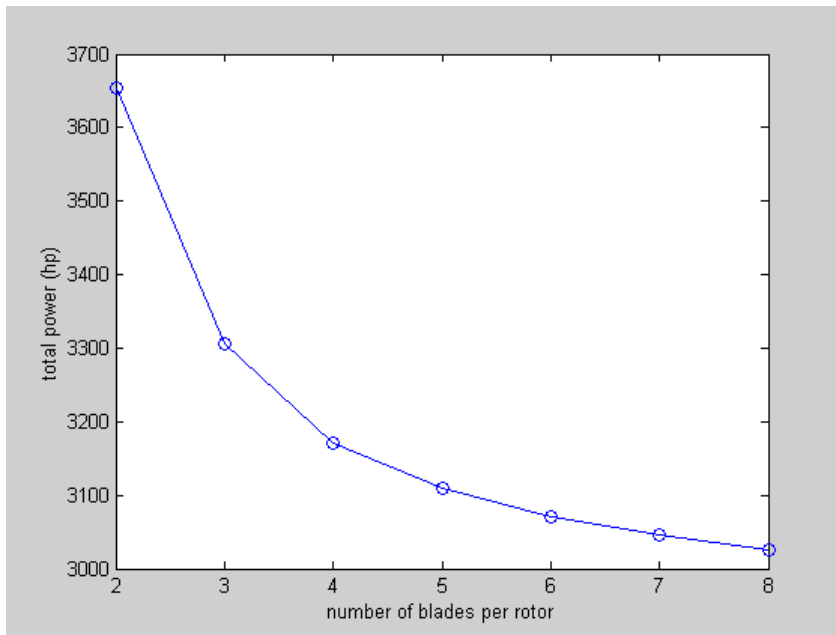


Figure 6.6: Number of blades vs. total power

### **6.1.3 Selection of Number of Engines**

The number of engines to use on our design was influenced heavily by the mission requirements that need to be accomplished. Two of the most important attributes that will allow the helicopter to successfully complete its various missions are high payload capabilities and rate of climb. In order to accomplish this, sufficient of power must be supplied to the co-axial drive-shafts. Using two engines will allow us to meet this high power requirement. Also, the additional engine provides extra safety margin of the design because it enable the helicopter to land safely by reducing the rate of descent when the helicopter is in one engine inoperative (OEI) condition. Based on the preliminary design code (PDC) results, having more than two engines does not have significant effects on the three main parameters: weight, total power, and main rotor diameter. Therefore the number of engines on the Extricator were set at two.

## **6.2 Empty Weight Determination**

The empty weight of the aircraft was calculated according to the formulation presented by Tishchenko et al [Appendix A of the report]. The empty weight took into the account the various weights of the individual major parts of the helicopter as well as the subsystems that make the helicopter function. Most of the aircraft structure materials used in the analysis is steel or aluminum alloys. The weight was reduced by constructing the rotor blades out of composite materials. A reserve weight of 5% [Tishchenko-2003] was added to the empty weight to provide an additional safety margin. The above weight mentioned plus the fuel weight, payload, and weight of additional furnishings is equal to the total weight of the aircraft.

### **6.3 Power Requirements**

Calculating the takeoff weight based on the various mission specifications such as payload, range, cruise speed, and reserve time gave us the information we needed to calculate the power required, which were separated into preliminary engine power and adjusted engine power. The only difference between these two formulas was that the preliminary power equation used a constant main rotor power conversion efficiency, which does not take into account the different flight modes that the rotor will be under such as hovering, forward flight, etc. The adjusted engine power equation used a hover power efficiency factor that was in terms of the preliminary power required and contains other losses in power to run DC functions that will be needed when the helicopter is operating. These two equations used a baseline density that is equal to the density of Denver with cruise density at altitude of 3000 feet above Denver, as a worst case scenario. Furthermore, the nominal engine power is finally calculated using the adjusted power and nominal engine power factor. Hover power and total power in climb were calculated for each mission; please consult the individual mission studies for more information on the numbers.

### **6.4 Performance Estimates for Various Mission Profiles**

The payload is largely dictated by the requirements that need to be met in the RFP. Some of the main payload requirements for different missions are as follows: Safely transport a minimum of 1200 people per hour from high rise rooftops to the ground, enable delivery of teams of 15 firefighters weighing 300 pounds each with gear to

rooftops up to 1500ft in no more than 2-minute cycle, and carry an onboard water tank of at least 500 gallons. For mission requirements involving rates, one can either satisfy the requirement by either carrying a large amount of cargo at once, at a lower climb rate, or one can invest in using that power for high vertical climb rates and make more rescue trips in a shorter amount of time. The payload study is separated into five categories, they are:

1. **Passenger Extraction** – Removing victims from high rise rooftops and side windows.
2. **Firefighting Mission** – Lift for an internal 500 gallon water tank and 5 inch diameter water hoses to a minimum altitude of 100 stories.
3. **Removal of Debris** – Carry external cargoes of at least 5000 pounds.
4. **Command and Control** – Provide a platform to disaster response decision makers to coordinate all aspects of disaster response.
5. **Deployment of Firefighters** – Deliver teams of 15 firefighters to high rise rooftops.

## **6.5 Passenger Extraction**

### **6.5.1 Case 1: Rooftop Extraction (From rooftop to ground)**

The helicopter must be able to transport as close as possible to 1200 people per hour from high rise rooftops to either the ground or adjacent rooftops. These two cases were studied separately. For the passenger extraction from rooftop to ground, a height of 1500 feet for the helicopter to climb and descend was selected as a safe approximation for the highest building rooftops. In order to achieve the goal of extracting 1200 people

per hour, the necessary climb rate was calculated for each payload, which consists of the number of people per trip and the weight of the necessary subsystem. We assumed that the climb rate is equal to the descend rate and the time for loading and unloading passengers from a rooftop is the same, 1.5 seconds per passenger, and proportional to the total number of passengers. The density of air used in the calculations is based on the standard atmosphere properties [Raymer-1999] at 5500 feet (Denver altitude). Based on an unloading and loading time of 1.5 seconds per passenger, it was found that it does not appear feasible to extract 1200 people per hour from the rooftop to the ground. This extraction rate would result in a very large climb rate, with associated climb power requirements that are unrealistic. The following study assumes a more realistic rate of extraction of 900 people per hour. The rate of climb, total power in climb, total weight and also the main rotor diameter were plotted against the no. of passengers per trip (see Figures 6.7-6.10).

As the no. of passengers per trip increases, the climb rate required to meet the goal of extracting 900 people per hour decreases while the total power, total weight, and the main rotor diameter increases rapidly. The no. of victims extracted per trip was chosen to be 50 because this value corresponded to a realistic rate of climb of 18.288 meters/second (Table 6.1 and Figure 6.7), while keep the weight, size, and power penalties due increasing no. of victims per trip at a reasonable level. For 50 people per trip the loading time is 75 seconds (1.5 sec per passenger), the total time for each trip is 200 seconds (to enable 900 people to be extracted in 18 trips (50 people per trip)). The necessary climb rate (based on 75 sec loading and unloading time) required to

accomplish each trip in 200 sec is 18.288 m/sec with a resulting climb power of 5866 hp. The total aircraft gross weight for this case is 11,792 Kg (25,990 lbs). The main rotor is sized at 14.65 m and the resulting induced velocity in the plane of the rotor is 13.4 m/sec.

# of victim each trip	payload (Kg)	loading time (sec)	total time each trip (sec)	climb time (sec)	climb rate (m/sec)
35	4000	52.5	140	17.5	26.1257
40	4500	60	160	20	22.86
45	5000	67.5	180	22.5	20.32
<b>50</b>	<b>5500</b>	<b>75</b>	<b>200</b>	<b>25</b>	<b>18.288</b>
55	6000	82.5	220	27.5	16.6255
60	6500	90	240	30	15.24
70	7500	105	280	35	13.0629
80	8500	120	320	40	11.43
90	9500	135	360	45	10.16
100	10500	150	400	50	9.144

hover power (hp)	Climb power (hp)	Rotor Diameter (m)	Gross Weight (kg)	induced velocity (hover) (m/sec)
2630	5192.551457	12.57	8690.1	13.406683
2912.5	5395.59808	13.29	9714	13.406589
3198.2	5621.998026	13.98	10748.1	13.406114
<b>3487</b>	<b>5866.521724</b>	<b>14.65</b>	<b>11791.9</b>	<b>13.399805</b>
3778.6	6122.67046	15.29	12845	13.399969
4072.9	6387.592649	15.9	13907.1	13.408043
4669.1	6944.226988	17.09	16057.1	13.40404
5274.8	7523.216325	18.21	18239.9	13.407429
5889.6	8121.878583	19.29	20454	13.402972
6512.9	8734.487626	20.32	22698.3	13.403468

Table 6.1: Passenger Extraction Mission @ 900 victims/hour

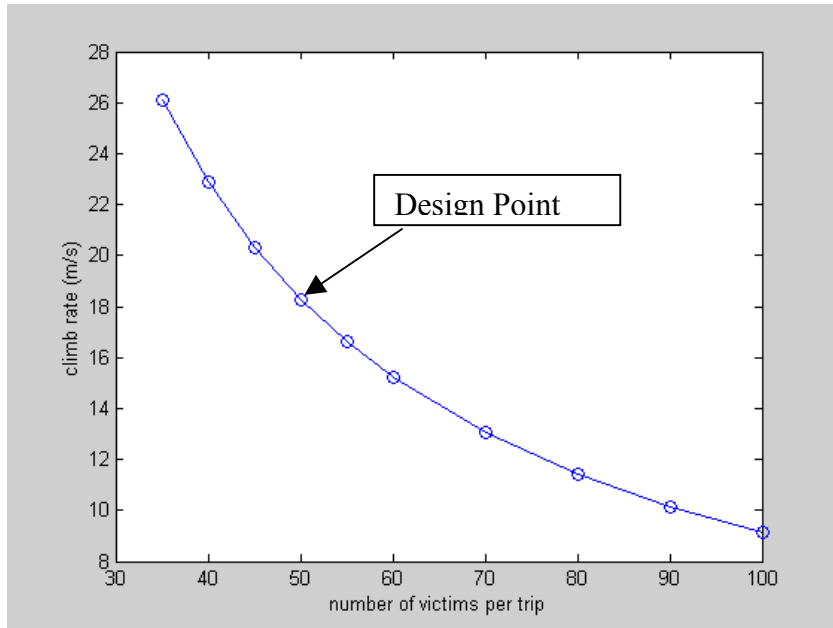


Figure 6.7: No. of passengers/trip vs. required climb rate

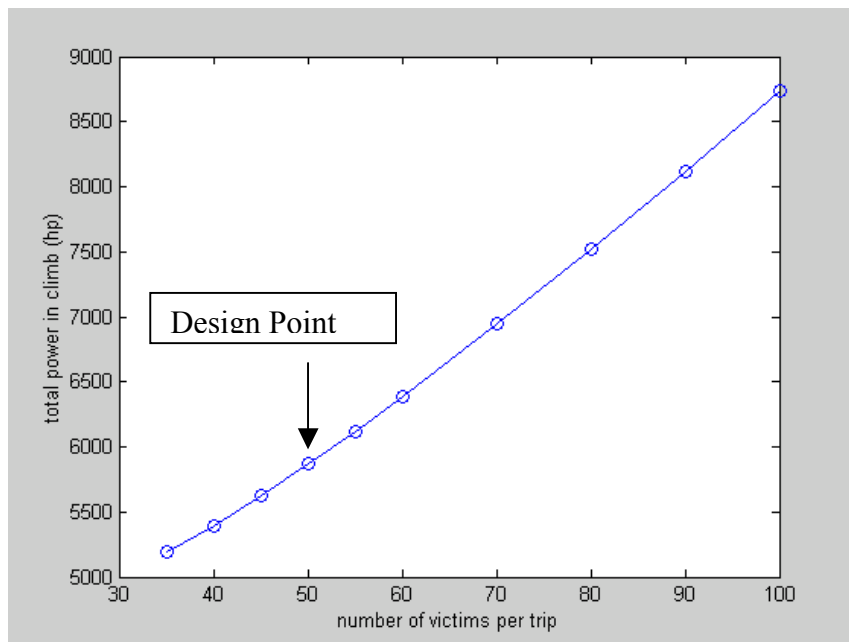


Figure 6.8: No. of passengers/trip vs. total required climb power

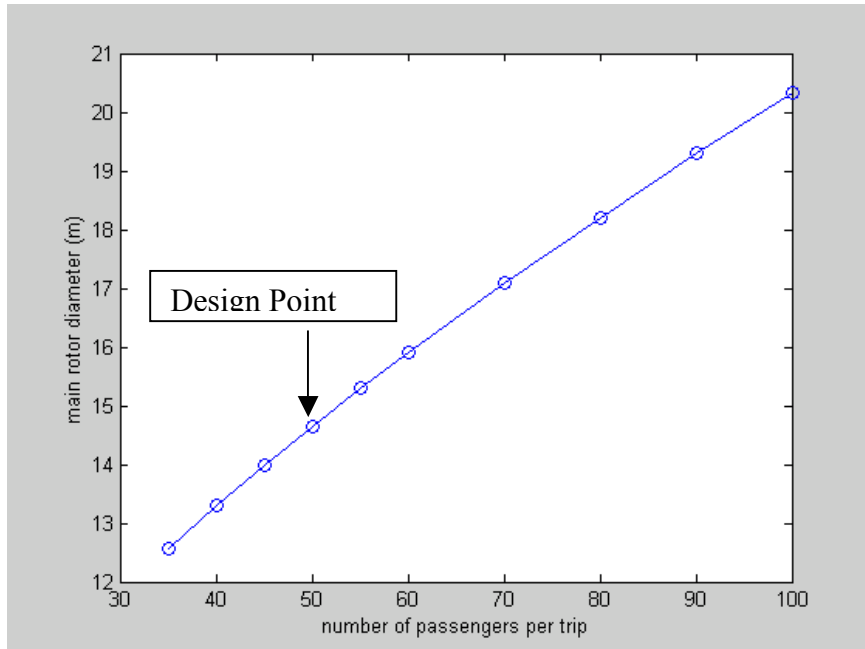


Figure 6.9: No. of passengers/trip vs. main rotor diameter

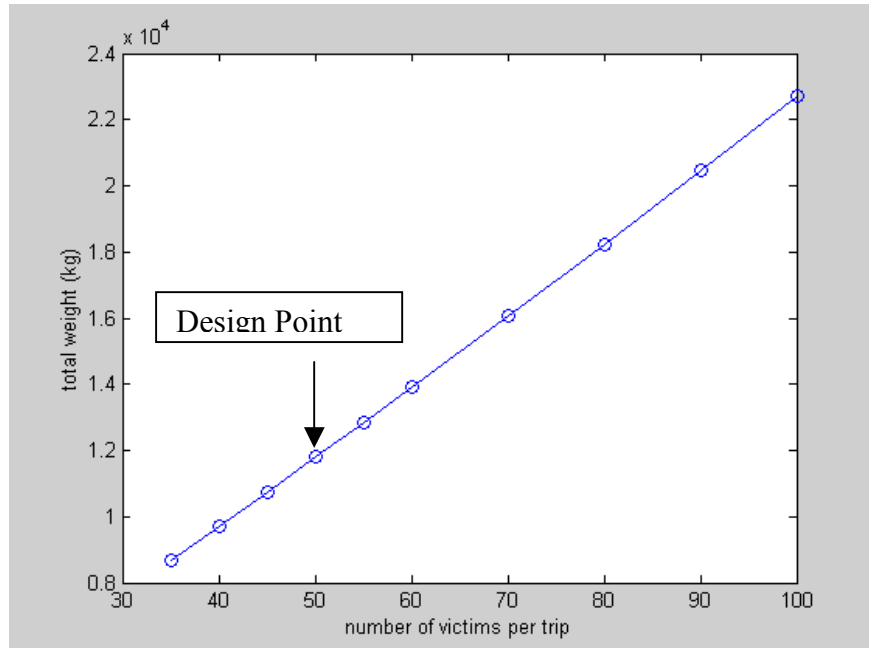


Figure 6.10: No. of victims/trip vs. total gross weight

### 6.5.2 Case 2: Rooftop Extraction (from rooftop to adjacent rooftop)

For the passenger extraction from one rooftop to adjacent rooftop, a distance between the high rise buildings of 100 meters was assumed for the helicopter to travel; the loading and unloading time for passengers remain the same that is 1.5 seconds per passenger; the landing time on the rooftop of 10 seconds was assumed due to limited spaces on the congested rooftop. In order to achieve the goal of extracting 1200 people per hour, the necessary forward speed was calculated for each payload, which consists of the number of people per trip and the weight of the necessary subsystem. Based on an unloading and loading time of 1.5 seconds per passenger and additional 10 seconds of landing time, it was found that it does not appear feasible to extract 1200 people per hour from the rooftop to the adjacent rooftop. This extraction rate would result in a negative number for travel time between the buildings (see Table 6.2).

# of Passengers per trip	Payload (kg)	loading time (sec)	unloading time (sec)	total time each trip (sec)	travel time (sec)
20	2500	30	30	60	-10
30	3500	45	45	90	-10
35	4000	52.5	52.5	105	-10
40	4500	60	60	120	-10
45	5000	67.5	67.5	135	-10
50	5500	75	75	150	-10
55	6000	82.5	82.5	165	-10
60	6500	90	90	180	-10
65	7000	97.5	97.5	195	-10
70	7500	105	105	210	-10

Table 6.2: rooftop-rooftop extraction @1200 people/hour

Since it is not feasible to achieve the goal of 1200 people/hour from rooftop to adjacent rooftop, a more realistic extraction rate of 1100 people/hour is examined as follows (Table 6.3):

# of Passengers per trip	Payload (kg)	loading time (sec)	unloading time (sec)	total time each trip (sec)	travel time (sec)	dash speed for travel between buildings (m/s)	dash speed for travel between buildings (km/hour)
20	2500	30	30	65.454545	-4.5454545	-44	-158.399956
30	3500	45	45	98.181818	-1.8181818	-110	-395.99989
35	4000	52.5	52.5	114.54545	-0.4545455	-440	-1583.99956
40	4500	60	60	130.90909	0.90909091	220	791.99978
45	5000	67.5	67.5	147.27273	2.27272727	88	316.799912
<b>50</b>	<b>5500</b>	<b>75</b>	<b>75</b>	<b>163.63636</b>	<b>3.63636364</b>	<b>55</b>	<b>197.999945</b>
55	6000	82.5	82.5	180	5	40	143.99996
60	6500	90	90	196.36364	6.36363636	31.42857143	113.1428257
65	7000	97.5	97.5	212.72727	7.72727273	25.88235294	93.17644471
70	7500	105	105	229.09091	9.09090909	22	79.199978

Table 6.3: Rooftop-rooftop @ 1100people/hour

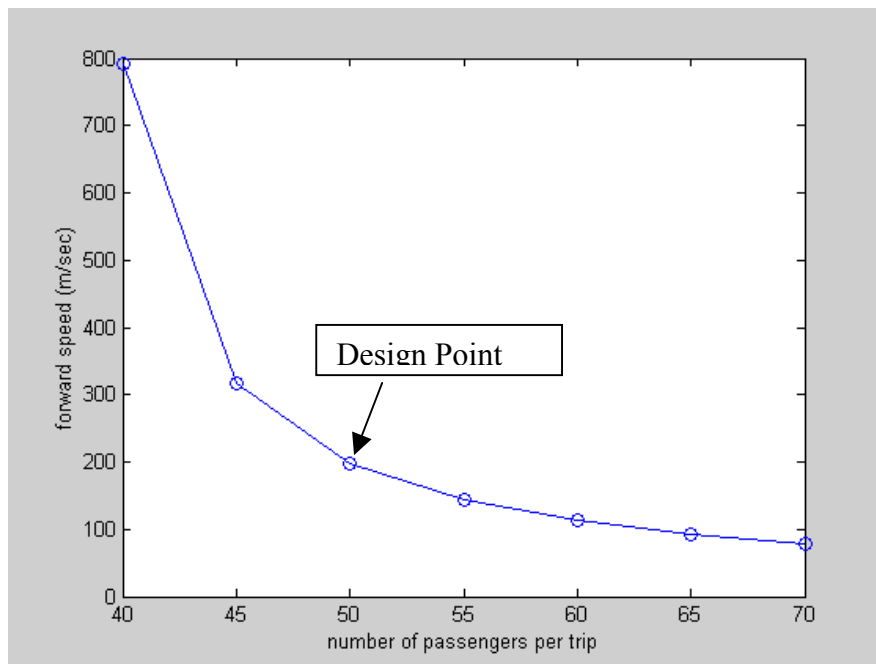


Figure 6.11: No. of passengers/trip vs. dash speed

From Table 6.3 and Figure 6.11 shown above, extracting 1100 people/hour from one rooftop to adjacent Rooftop is feasible if the number of passenger for each trip is 50 or higher. However, higher than 50 passengers per trip will result in a higher payload which will in turn increase the total weight, power and also the size of the helicopter. Therefore, an extraction rate of 50 passengers per trip is chosen for rooftop to rooftop extraction mission. The helicopter is required to dash at a speed of 198 km/hr or 106 knots between the buildings in order to cover the 100 meters distance in 3.63 seconds. The engine power requirements, total weight, and also the main rotor diameter will be the same as the rooftop to ground extraction since the amount of payload is the same.

## **6.6 Face Extraction**

For face extraction requirements, the feasibility of extracting 800 people per hour is examined.

The three case studies are:

1. Extract people from the middle- 50% of a 1500 feet tall building.
2. Extract people from near the roof at 85% of building height.
3. Extract people from the floor at 15% of building height.

Air density used in the calculations is  $0.9555 \text{ kg/m}^3$  and the loading and unloading time is equal to the number of people times four seconds. The reason for setting this loading/unloading time per passenger is that the time it takes for victims to get into the extraction basket from the face of the building will be greater due to longer distance and situational panic. We are assuming the same climb and descent rates as in rooftop

extraction. A disk loading of  $35 \text{ kg/m}^2$ , two engines, and four blades per rotor were used in the calculation. Below (Table 6.4) are the results for these three cases.

# of Passenger Per trip	Payload (kg)	loading time (sec)	total time each trip (sec)	climb time (sec)
20	2500	80	90	-35
25	3000	100	112.5	-43.75
30	3500	120	135	-52.5
35	4000	140	157.5	-61.25
40	4500	160	180	-70
45	5000	180	202.5	-78.75
50	5500	200	225	-87.5

Table 6.4: Face extraction rate of 800 people/hour @ 50% building height

From the above initial calculation, it is clear that it is impossible to achieve the goal of 800 people per hour because the time needed to climb is computed to be a negative number (Table 6.4). This means that there is not enough time to complete the mission with a rate of 800 people per hour. Lowering the rate of face extraction further to 600 people per hour is more reasonable, and below a study is conducted to see if this is feasible.

# of Passenger Per trip	Payload (kg)	loading time (sec)	total time each trip (sec)	climb time (sec)
20	2500	80	120	-20
25	3000	100	150	-25
30	3500	120	180	-30
35	4000	140	210	-35
40	4500	160	240	-40
45	5000	180	270	-45
50	5500	200	300	-50

Table 6.5: Face extraction rate of 600 people per hour, 50% building height

As seen from Table 6.5, the time for climb is still negative numbers, indicating that there is still not enough time to complete the mission. Decreasing the rate further yet to 400 people per hour (Table 6.6) indicates that, this time there is enough time to complete the mission, and other figures of interest are also shown in the study.

# of Passenger Per trip	Payload (kg)	loading time (sec)	total time each trip (sec)	climb time (sec)	Climb rate (m/sec)
20	2500	80	180	10	22.86
25	3000	100	225	12.5	18.288
30	3500	120	270	15	15.24
35	4000	140	315	17.5	13.063
40	4500	160	360	20	11.43
45	5000	180	405	22.5	10.16
50	5500	200	450	25	9.144

Table 6.6: Face extraction 400 people/hr @ 50% building height (case 1)

Now let us move on to the second and third case studies, which involve face extractions from 85% and 15% building heights respectively. A face extraction rate of 400 people per hour will be maintained, as it was concluded that this rate is feasible for 50% building height.

# of Passenger Per trip	Payload (kg)	loading time (sec)	total time each trip (sec)	climb time (sec)	climb rate (m/sec)
20	2500	80	180	10	38.862
25	3000	100	225	12.5	31.09
30	3500	120	270	15	25.908
35	4000	140	315	17.5	22.207
40	4500	160	360	20	19.431
45	5000	180	405	22.5	17.272
<b>50</b>	<b>5500</b>	<b>200</b>	<b>450</b>	<b>25</b>	<b>15.545</b>

hover power (hp)	climb power (hp)	rotor diameter (m)	total weight (kg)	induced velocity (m/sec)
1806.4	4424.941537	10.17	5686.6	13.404469
2076.3	4484.378917	11.02	6675.5	13.403077
2351.1	4623.854251	11.82	7677	13.400547
2630	4808.168738	12.57	8690.1	13.406683
2912.5	5023.133368	13.29	9714	13.406589
3198.2	5258.428322	13.98	10748.1	13.406114
<b>3487</b>	<b>5509.593465</b>	<b>14.65</b>	<b>11791.9</b>	<b>13.399805</b>

Table 6.7: Extracting 400people/hr @ 85% building height (case 2)

Notice that the climb rate and total power in climb for case 2 (Table 7) are significantly larger because the helicopter has to climb an additional 35% of the building height in the same amount of time as in the 50% building height case. Finally, case 3 (Table 8) provides the results for face extraction from 15% of building height. As expected the values for the climb rate and total power in climb are the lowest, at only 2.74 m/s and 3843.92 hp respectively for 50 passengers per trip, since for this case the victims must be transported over only 15% of the building height.

# of Passenger Per trip	Payload (kg)	loading time (sec)	total time each trip (sec)	climb time (sec)	climb rate (m/sec)
20	2500	80	180	10	6.858
25	3000	100	225	12.5	5.4864
30	3500	120	270	15	4.572
35	4000	140	315	17.5	3.91886
40	4500	160	360	20	3.429
45	5000	180	405	22.5	3.048
50	5500	200	450	25	2.7432

hover power (hp)	climb power (hp)	rotor diameter (m)	total weight (kg)	Induced velocity (m/sec)
1806.4	2268.495565	10.17	5686.6	13.40446883
2076.3	2501.255103	11.02	6675.5	13.40307745
2351.1	2752.17428	11.82	7677	13.40054666
2630	3014.382718	12.57	8690.1	13.4066827
2912.5	3284.964712	13.29	9714	13.40658884
3198.2	3561.769704	13.98	10748.1	13.40611373
3487	3843.928259	14.65	11791.9	13.39980538

Table 6.8: Extract 400 people/hr @15% building height (case3)

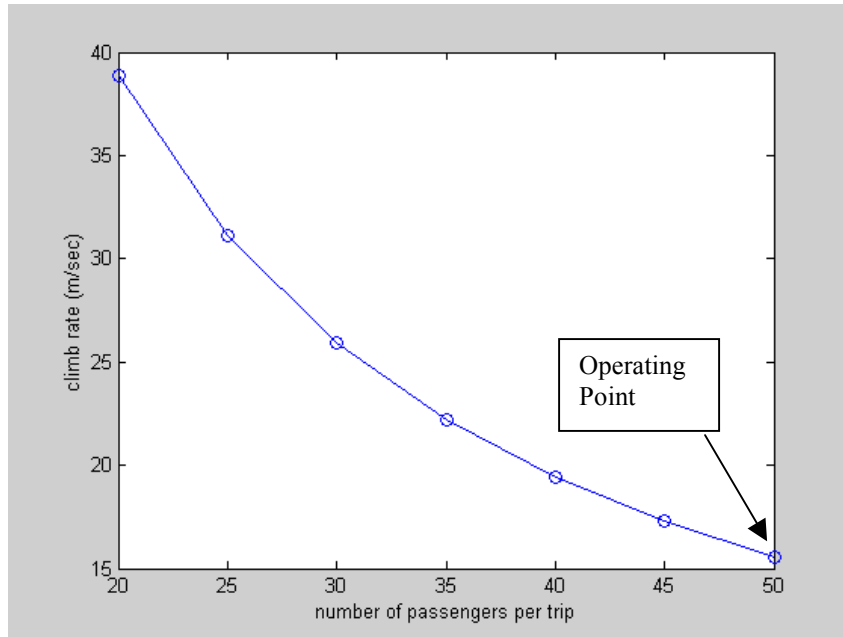


Figure 6.12: No. of passengers/trip vs. climb rate (case 2)

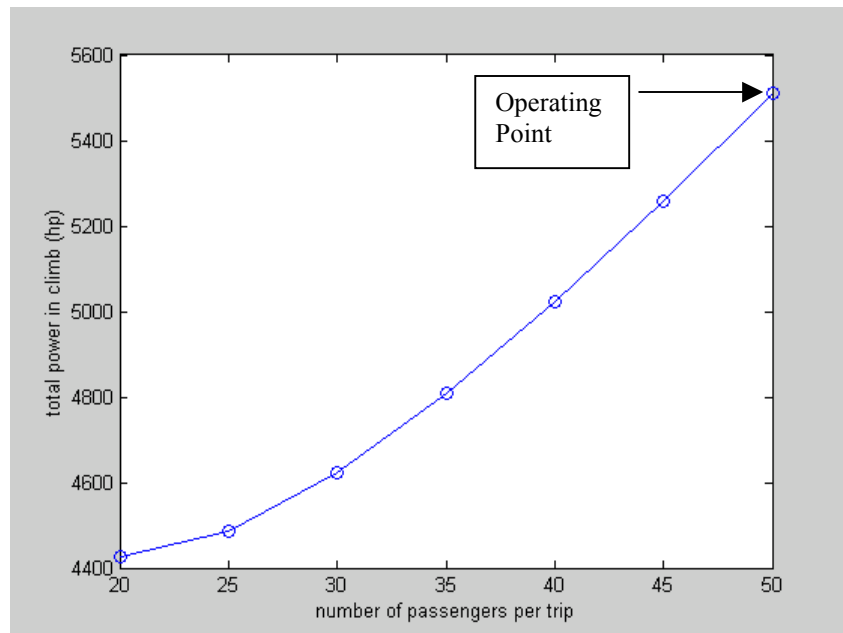


Figure 6.13: No. of passengers/trip vs. total power (case 2)

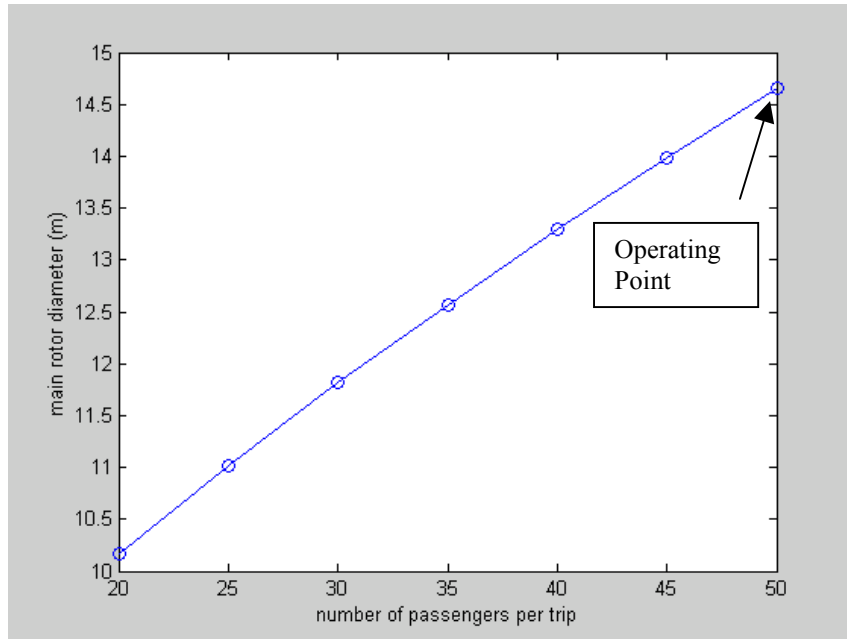


Figure 6.14: No. of passengers/trip vs. main rotor diameter (case 2)

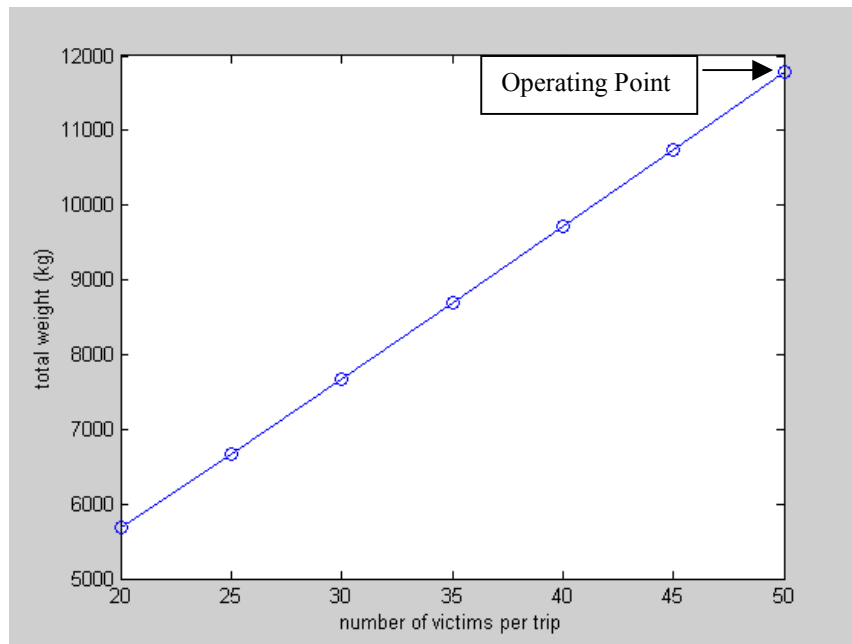


Figure 15.No. of Victims/trip vs. total weight (case 2)

In conclusion, from the three face extraction cases at 50%, 85% and 15% building height at a constant extraction rate 400 people per hour, the worst case scenario which translates into the highest total power in climb and highest climb rate was found to be case 2: face extraction at 85% building height, rescuing 50 people per trip. The corresponding plots for extraction rate of 400 people per hour at 85% building height were shown in Figures 6.12 to 6.15. These results indicate that the weight and power requirements for face extraction of 400 people per hour from 85% building height, can be met by the Extricator. This is because the roof-top extraction mission (for 900 people per hour) requires marginally higher power and maximum climb rate requirements as compared to the face extraction mission from 85% building height. Therefore the Extricator (which is designed for roof-top extraction of 900 people per hour) can also extract up to 400 people/hour from the building face.

## **6.7 Firefighting and Firefighter Deployment Mission**

The helicopter system must be able to deliver teams of 15 to 20 firefighters weighing 300 pounds each with gear to rooftops up to 1500 feet in no more than 2 minute cycles. The following calculation incorporates 20 firefighters which weigh about 300 pounds (136 kg) each with equipment. For the firefighting mission, an internal water tank of 500 gallons (1900 kg) must be carried along with the ability to lift 5 inch diameter water hoses which weigh about 75 lbs. (34 kg) per 50 feet. 1500 feet are necessary to reach the top floor of the high rise buildings. This amounts to a weight of 1700 kg. Assuming there is water uniformly along the entire length of the hose. The total weight required to accomplish these missions are 2800 kg for deployment of 20 firefighters and

3600 kg for the firefighting mission with internal water tank and hoses. The unloading/loading time for the firefighter deployment mission is 1.25 sec. for each of firefighters. Below are the results (Table 6.9) for these two missions. Of importance to note is that the firefighting mission requires more power and weight as firefighter deployment mission because the associated payload is larger. Consequently, the helicopter must be designed for the firefighting mission, thereby being able to accomplish both missions.

	Payload (kg)	loading time (sec)	total time each trip (sec)	climb time (sec)
fire fighter deployment mission	2800	25	120	35
fire fighting mission	3600			

climb rate (m/sec)	hover power (hp)	climb power (hp)	rotor diameter (m)	total weight (kg)	induced velocity (m/sec)
13.06	1967.7	2946.237	10.69	6278.4	13.13091
13.06	2406.5	3602.739	11.97	7878.7	13.136545

Table 6.9: Firefighting and firefighter deployment missions

## **6.8 Removal of Debris and Command and Control**

The helicopter system must have the ability to carry external cargoes of at least 5000 lbs. To supply disaster relief materials or aid in the emergency removal of debris, we propose an external bay concept to support a basket that would carry debris and other external loads. Another mission requirement is to provide a command and control platform to disaster response decision makers to coordinate all aspects of disaster response. A minimum of four personnel is required with capability for simultaneous multiplexed communication on six different communication frequencies. The removal of debris payload study and command and control was similarly calculated just as the firefighting and firefighter deployment missions. However, in terms of performance requirements and payload, these two missions were not the most demanding and the helicopter designed to meet firefighting mission, was also able to accomplish the command and control and debris removal tasks.

## Chapter 7 Cost Analysis

The cost of a helicopter is based on factors such as weights of individual components, materials used, production rate and production quantity. For instance, the cost of the rotor systems group was based on the yoke material factor, number of blades, blade material factor, main rotor system application, as well as the production rate and production quantity. A similar analysis was used for the other major helicopter components. The equations used to calculate the component costs [Koratkar-1999] are listed in Appendix B of this report.

The production quantity (see Chapter 9 of this report) was determined, based on the populations of major cities in the United States, to be approximately 126 helicopters in total. The production rate is 42 helicopters per year for a three-year period.

<b>Component</b>	<b>Cost</b>
Rotor System	\$3,665
Vertical Stabilizer	\$1090
Horizontal Stabilizer	\$778
Fuselage	\$1071,668
Landing Gear	\$46,473
Nacelle Group	\$2463,887
Air Induction Group	\$4336,533
Engine and Installation	\$1183,379
Drive System	\$573,161
Flight Controls	\$197,380
Instrumentation	\$448,592
Hydraulics	\$329,412
Electrical Systems	\$25,755
Avionics Systems	\$69,293
Furnishings & Equipment	\$428
Air Conditioning	\$251,387
Load & Handling	\$71,490
Final Assembly	\$455,294
<b>TOTAL</b>	<b>\$11.5 Million</b>

The estimated unit price of the Extricator (take-off gross weight: 11,791 Kg) using our preliminary analysis is about \$11.5 Million. This compares well with data for other helicopters in the same weight class [Koratkar-1999]. For example- the Aerospatiale, AS-332L-2 (take-off gross weight: 8,600 Kg) has unit cost of \$10 Million, similarly the Sikorsky, S-92 (take-off gross weight: 10,082 Kg) is priced at \$13.9 Million). The EH-101 is considerably heavier at 14,292 Kg and is priced at \$18 Million.

## Chapter 8 Risk identification and Risk Reduction plan

Upon investigation, several possible risks were identified. These are summarized below:

1. The possibility of main rotor striking the face of the building during face extraction mission or maneuvering between buildings.
2. Vehicle instability results from the moment created by the passengers rushing into the extraction basket from building face.
3. Vehicle instability results from large cg travel.
4. The possibility of engine failure.
5. The possibility of structure failure due to high payload (tethered basket assembly)
6. The danger of passengers falling off during face extraction.

The corresponding risk reduction plans for each of the possible risk described above were developed, and they are summarized below:

1. To prevent the possibility of rotor striking the building face, specially designed stoppers, which are longer than the main rotor radius will be added to all four sides of the helicopter (front, back, left and right). Also, additional sensors will be mounted on the tip of the rotor to warn the pilot if the rotor is too close to the building.
2. The moment created from passenger rushing through the basket can be counter balanced using an auto-stabilizer device at the bottom of the basket. This auto-stabilizer consists of a gyroscope, a linear actuator, weight on a track that is

- driven by the actuator. As the gyroscope sees an imbalance of the basket, it sends a signal to the linear actuator that moves the weight to counteract the moment created by passengers rushing into the basket.
3. The cg travel problem can also be solved by the linear actuator with weight as described above.
  4. In the case of one engine failure (OEI) condition, the descent rate can be reduced by quick release of the water (500 gallons) that is stored onboard. A quick release valve can be used to achieve this. Note that the transmission system is designed such that in the event of a one engine failure, the other engine can drive both of the main rotors, albeit at a reduced collective pitch setting.
  5. The problem may be solved by increase the factor of safety associated with the design of the primary and secondary bulkheads that support the fuselage and the external basket system.
  6. The extended channel (walkway) from the extraction basket will be anchored to the building by the firefighter before the passengers rush into the basket, and also the depth of the channel was carefully designed taking into consideration passenger height.

## Chapter 9 Fleet Size and Development Schedule

Skyscrapers.com defines a high-rise as a building 35 meters or greater in height, which is divided at regular intervals into occupiable levels. This height was chosen based on an original 12-floor cutoff, which is normally, the minimum height needed to achieve the physical presence, which earns the name "high-rise." The twelve-floor limit also represents a compromise between ambition and manageability for a worldwide database.

The following is data gathered from skyscrapers.com sighting the total number of high-rise buildings per major US city and city population.

<b>US City</b>	<b># High-Rises</b>	<b>City Population</b>	<b>Avg # Ppl/Highrise</b>
New York City	5,145	8,008,278	1,557
Los Angeles	387	3,807,400	9,838
Chicago	1,366	2,896,016	2,120
Houston	346	1,953,631	5,646
Philadelphia	309	1,517,550	4,911
San Diego	128	1,255,700	9,810
Dallas	268	1,188,580	4,435
Detroit	158	951,270	6,021
Indianapolis	103	791,926	7,689
San Francisco	283	776,733	2,745
Columbus	77	711,470	9,240
Austin	90	656,562	7,295
Baltimore	106	651,154	6,143
Milwaukee	76	596,974	7,855
Washington D.C.	218	572,059	2,624
<b>AVG</b>	<b>431</b>	<b>1,254,062</b>	<b>4,187</b>

As one can see, New York City hosts the greatest number of high-rise buildings for the greatest population concentration in the United States. On a rough average, there are approximately 4,000 people who work per city high-rise in this country. Although this number may seem high, one must remember that there were approximately 50,000

employees of the World Trade Center and almost 25,000 rescues on September 11<sup>th</sup>, 2001 [abc-news-2001]. Therefore, 4,000 occupants in need of rescue is a safe number with which to work. Albeit not every major U.S. city has a top ranked skyscraper, one must provide Search and Rescue Helicopters for a worst-case scenario, or be prepared to seek help from neighboring cities.

The Extricator is designed to rescue 900 people per hour from a rooftop and as much as 400 occupants per hour by building face extraction. Therefore, it is a necessity for a larger populated city to provide more than one system of rescue.

Vincent Dunn, Deputy Chief F.D.N.Y. (ret) states, that unlike a low-rise fire which can easily be extinguished in 30-40 minutes, a high-rise fire, if not controlled in that amount of time, will require firefighters for the next 2-3 hours to firefight inside the building. One also has to take into account the response time for the Helicopters to arrive, which typically will take around 15 minutes, allowing the fire to spread in that time. Therefore one hopes to rescue as many people in the first hour as possible and that the fire doesn't spread rapidly beyond that time.

In order to rescue 4000 people with one helicopter from the roof using the project goal of 900 people per hour, it will take over 4.4 hours, and rescuing that many people using building face extraction of 400 people per hour will take up to 10 hours. Thus, it seems probable based on that information to have 4 systems on average ready for rescue in a major city. This would enable rescue of all occupants in approximately one hour's time, providing that some occupants will not require rescuing and not all occupants will need building face extraction.

Due to maintenance, crew, storage space, and overhaul and repair, it may prove be costly to purchase and upkeep 4 rescue helicopters. Since high-rise fires are not an everyday occurrence, it seems practical to provide 2-3 rescue helicopters per 1,000,000-person city population.

### **Day in the life of the system description**

- **911 how can I help you?**

We live in a complex society that requires us to consider the interrelationship of many things as we deal with emergencies and routine operational matters. Understanding these interrelationships is frequently accomplished by acquiring and carefully analyzing accurate information in a spatial context. The first thing that people do when there is an emergency, is calling 911. You might ask, How does 911 works? 911 is more than just a number. The term "9-1-1" has become synonymous with the agencies that provide your public safety services. Dialing 911 is actually a quick and efficient way to access your public safety provider. Once a person has accessed the 911 system, employees of the local police, fire and emergency medical services are called into action. If you dial 911 from your home or business phone, the address will generally be provided electronically to the call receiver.

In case of fire on the high rise building desaster, several phone calls are going to be to made to 911 from the site. These calls will be routed to the command and control platform on the helicopter. After the dispatchers pick up the calls, they need to identify

the type of the emergency. The extricator will be equipped with the following facilities in order to efficiently process this information;

*Automatic Number Identification*

A feature, which displays, at the Public Safety Answering Point where the call is answered, and the number of the telephone from which the 911 call was placed

*Automatic Location Identification*

A feature which displays the service address of the telephone from which the call was placed along with the law enforcement, fire/rescue and emergency medical service agencies that serve the displayed address.

*Selective Routing*

A feature that routes all 911 calls to the Public Safety Answering Point dispatching center that serves the area from which the call originated.

*Circuit Diversity*

This feature is the configuration of the 911 call delivery network using completely separate facilities so as to provide at least two paths (primary and secondary route) over which 911 calls can be transmitted.

*Emergency Transport Backup*

Where no diversity exists, this feature automatically reroutes 911 calls to a Public Safety Answering Point via the cellular network whenever normal 911 services fail

## 911 Tandem Backup with Advanced Route Selection

A feature which utilizes two 5ESS digital switches to perform 911 call processing.

Advanced Route Selection is the ability to continue to process 911 calls in the event of a failure of the primary route without human intervention.

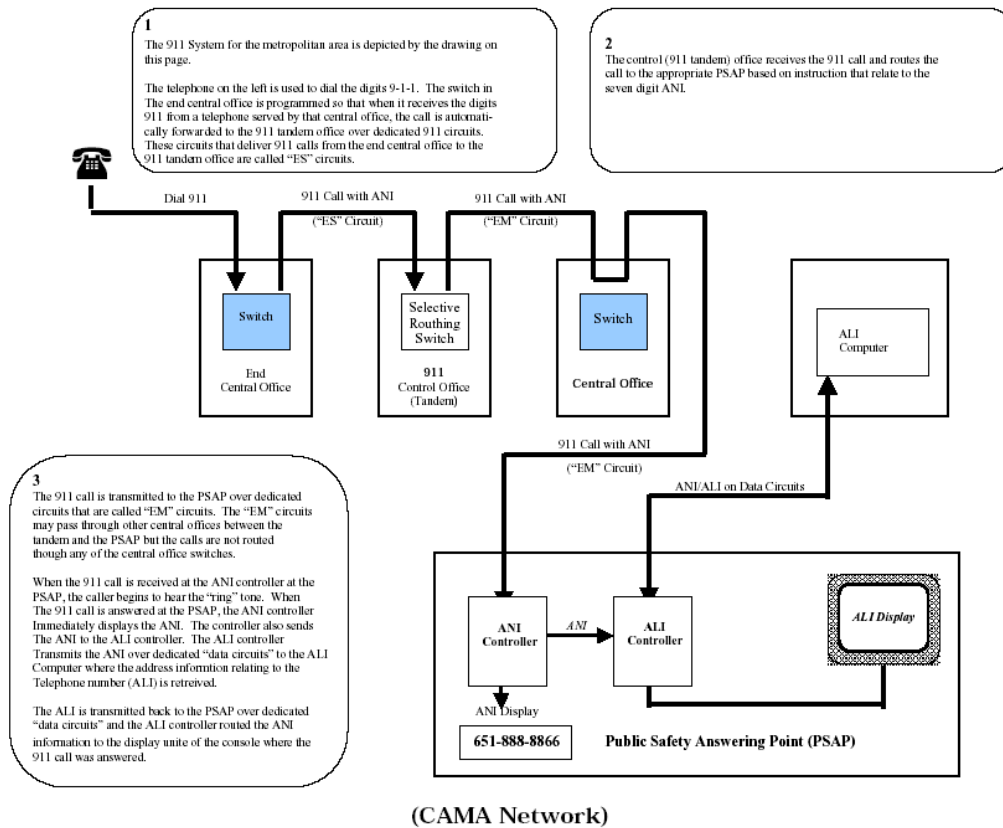


Figure 9.1: Proposed 911 response system

## Plan Development

In order to develop appropriate plans for combating high-rise incidents, there needs to be an understanding of buildings construction. Figure 9.1 gives an overview of the 911 response system proposed for the Extricator.

A growing area of concern for 911 operations is the use of cellular or wireless technology. The concern comes in the number of call that may come in to 911 related to an incident. It used to be that police/fire would get 1 or 2 calls and a particular incident. Now that number has grown rapidly. One can imagine the burden that this places on 911 system. It is also important for people to know where they are when they call 911 on a cellular phone. The current technology to track phones is still somewhat limited, so people should know where they are so help can get to them quickly.

## **Development of Schedule**

The development schedule for the Extricator is provided in Table 9.1. We envision a 6 stage process as shown below. This will span a total of 7 years from designing the RFP to delivery in the field

Stages	Tasks	Start	End
1	<b>Design Requirements (Define Needs)</b> <ul style="list-style-type: none"> <li>○ · High rise Firefighter deployment</li> <li>○ · Rooftop Occupant extraction</li> <li>○ · Building face penetration and occupant recovery</li> <li>○ · Ground pump water cannon fire fighting</li> <li>○ · Self contained tank water cannon fire fighting</li> <li>○ · Disaster command and control</li> </ul>	01/03	06/03
2	<b>Concept Down-selection Process</b> <ul style="list-style-type: none"> <li>○ Comparison matrix</li> <li>○ Performance analysis</li> <li>○ Detailed trade-off studies</li> </ul>	06/03	06/04
3	<b>Preliminary design</b> <ul style="list-style-type: none"> <li>○ Analysis</li> <li>○ Weights, sizing, performance and cost estimation</li> </ul>	06/04	06/05
4	<b>Design and Manufacturing</b> <ul style="list-style-type: none"> <li>○ Material Selection</li> <li>○ Frame</li> <li>○ Rotor blades</li> <li>○ Molds</li> <li>○ Landing edge</li> <li>○ Jigs</li> <li>○ Assembly</li> </ul>	06/05	06/07
5	<b>Implementation</b> <ul style="list-style-type: none"> <li>○ Model testing and validation studies</li> <li>○ Manufacturing processes</li> <li>○ Meeting the schedule</li> <li>○ Cost effectiveness</li> </ul>	06/07	06/09
6	<b>Final delivery</b> <ul style="list-style-type: none"> <li>○ Flight Testing</li> <li>○ Training of operators</li> </ul>	06/09	06/10

Table 9.1: Development schedule for the Extricator

## **Chapter 10 Manufacturing**

The primary focus of the design of The Extricator is the maximization of overall value to the customer. Manufacturing is one of the most important steps in the process of delivering a high value product. Designing, from conceptual through detailed design, with the goal of reducing manufacturing and total life cycle costs will produce the most cost effective product. In addition, safety is a very important part of value. Hence, crashworthiness, lightning protection, and structural safety have not been compromised in the manufacturing of the helicopter.

### **Technology**

The information age has made it possible to use technology for manufacturing. The design process has made and will continue to make full use of CAE, CADAM, electronic document tracking and optimizers. These tools have been proven to pay for themselves, primarily by reducing costs associated with reworking.

### **Lean manufacturing**

Lean Manufacturing is a systematic approach to perform the minimum work necessary in production. Continual quality improvement, small production runs and the ability to reconfigure the production line for different products are the major benefits of this manufacturing philosophy. There are many elements of lean manufacturing: the basic ones being (i) elimination of waste (ii) continuous flow and (iii) quality control. For the

small production run stipulated by the RFP, continuous flow is of primary importance. Continuous flow manifests itself as the ability to easily convert the production line from one product to another at the conclusion of a production run or between production runs so that manufacturing down-time is minimized. Additionally, facility overhead costs are spread over more products. Optimizing the manufacturing process for low rate production will keep production costs low.

## **Manufacturing details**

### **Primary structure**

Material options: Four construction techniques were examined for the primary structure:

- Metal.
- Composite with autoclave curing.
- Composite wet layup with room temperature/vacuum bag cure.
- Mixed metal and composite.

These techniques were evaluated for their ability to yield low initial production costs and low life cycle costs. All-metal construction is a tried and true construction technique with many advantages including low cost, available facilities, excellent crashworthiness and lightning protection, and easy structural reparability. The corrosion issues associated with metals can be mitigated by modern coatings applied during manufacture and an aggressive corrosion tracking and inspection regime. However, the cost of airframe monitoring programs, continual corrosion inspections and the replacement of affected parts decreases the initial cost savings and increases life cycle costs.

Composite structures are light and strong and offer a reduction in part count. However, they suffer from lightning, crashworthiness, water absorption and impact damage issues. The typical aerospace industry approach is to use high technology elevated temperature cured resins with graphite fibers, this technique requires molds, bonding, and autoclaves and yields light but expensive components with all the attendant issues relevant to composite structures as outlined above. Another composite manufacturing option is wet layup with room temperature cure. This technique has its own set of advantages and disadvantages. While they are inexpensive and have good finish quality, weight savings are sacrificed thereby partially offsetting the price advantage. In addition, manufacturing consistency can be difficult to achieve.

An all-composite design could face difficulties during FAA certification since only one composite design, namely the Beach Starship has been FAA certified. The FAA has little experience with composite airframe certification and this lack of experience will manifest itself as requirements for additional testing, lower allowable for material properties and increased certification time and expense.

The final construction technique examined was a hybrid method: composite skin over a metal frame. In this technique, a metal frame is constructed, onto which composite panels are fastened. Both the skin and frame serve as load bearing structures. The design will maintain crashworthiness, lightning protection, and have a more predictable fatigue life while reducing part count.

## **Material selection**

Of the many choices, the hybrid composite-metal frame emerged as the obvious choice. With proper design, it is possible to have the advantages of both construction techniques: the lightning protection, crashworthiness, reparability of metal construction and the reduced parts count, corrosion protection and simplified construction of composite construction. In addition, there is synergistic benefit in the combination of construction methods. Reduction in the number of jigs, simple panel removal for airframe access and molding in multiple parts will combine to reduce the total life cycle cost of the helicopter. There are potential disadvantages also arising out of a hybrid construction. Two of the most significant are different coefficients of thermal expansion and the possibility of galvanic material corrosion. Care in the detail design stage will ensure that no undue stresses will occur with dissimilar material expansion due to temperature changes. The greatest potential for galvanic corrosion in this design is between aluminum and the carbon/graphite fibers. Every location where these two materials are joined will be doubly insulated. Carbon fiber will be insulated by a fiberglass cloth layer. Aluminum will be coated with primer followed by several layers of paint. Each coat will be a different color so that the depth and severity of any scratch can be easily determined. This technique has been used successfully on underwater submersibles.

## 11 Summary and Conclusions

The design of the Extricator- a novel urban disaster response vehicle has been presented. The Extricator uses the co-axial rotor configuration with 4 blades on each rotor, it eliminates the need for a tail rotor and allows a compact design (main rotor diameter: 14.65 m) while still generating the required amount of thrust (aircraft weight: 11,792 Kg) at a reasonable disk loading ( $35 \text{ Kg/m}^2$ ). Specially designed airfoil meets the requirements of high lift. Three different types of airfoil were used on different sections of the blades. The RAE9648 airfoil was used from the root to 50% of the blade span, the OA312 airfoil was used from 50% to 77.5% of blade span, and the remainder of the blade all the way to the tip utilizes the OA309 airfoil.

The fuselage houses the pilot cabin, the command and control module and on-board water tank. Passengers from the disaster site are rapidly extracted into a basket system. This enables a relatively short fuselage to minimize the overall size of the helicopter (compactness). The basket is tethered from a bulkhead located close to the vehicle center of gravity to minimize cg travel issues. Retractable bridge on the passenger basket enables safe extraction from the building face. A stabilizer device underneath the basket is used to counteract the moment created by the victims rushing into the helicopter during face extraction. A fixed tricycle landing gear system is used in this aircraft. Since the design cruise speed is only 60 kts, drag due to the wheels will not be significant enough to warrant a retractable system.

We performed extensive parametric studies to arrive at the various performance figures for the different missions. The helicopter offers a 5,500 kg payload capability (that includes 50 people in the external basket) and has a gross take-off weight of about

11,792 Kg. Rooftop extraction of 900 people per hour (50 people per trip) and face extraction of 400 people per hour (50 people per trip) was deemed feasible. Higher extraction rates resulted in excessive climb rates (that were considered hazardous) with associated high climb power requirements. The helicopter was designed for 60 knots cruise (at 3000 ft) for one hour and sustained hover for one hour at a density that corresponds to a 95<sup>th</sup> percentile day in Denver. Note that the Extricator features a common design that can cater to multiple mission profiles such as roof top extraction, face extraction, fire fighting, command and control and removal of debris. A subsystem attachment bay enables quick configuration of the helicopter from one mission to another. Subsystems such as external water tank, passenger basket, cargo-bay can be conveniently attached so that the same basic design fulfils all the missions.

The helicopter control system relies on current proven technology, this includes dual interconnected swashplates as well as a specially designed yaw control mechanism. Bearingless rotor hubs with elastomeric lag dampers are used to minimize part count and maintenance costs. The Extricator is driven by two 2950 HP engines. The transmission is designed to harness the power of both engines simultaneously into a common shaft and is later split equally between the inner and outer rotor drive shafts. This was done to ensure safety, since if an engine is lost, there is still an equal reduced amount of power going to each rotor. The structural design of the blades and bearingless hubs rely on state of the art composite material and the distribution of multiple airfoils were chosen for their ability to provide good performance throughout the blade span. We believe that this helicopter design is feasible, safe, reliable and will provide a vastly superior solution to existing urban high-rise fire-fighting capabilities.

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## Appendix (A): Preliminary Design Code

Adopted from- M. Tishchenko, V. T. Nagaraj and I. Chopra, “Preliminary Design of Transport Helicopters”, Journal of the American Helicopter Society”, Vol. 48, No. 2, April 2003, pp. 71-79.

### List of Symbols

$C_{E1}$	Engine specific fuel consumption (kg/hp/h)	$t_{TR}$	tail rotor thrust losses
$C_{E2}$	Engine specific fuel consumption (kg/hp/h)	$V_{CR}$	Cruise speed (Km/h)
$(CT / \sigma)_{MR0}$	Main rotor thrust coefficient	$Z_{MRBL}$	Number of main rotor blades
$(CT / \sigma)_{TR0}$	Tail rotor thrust coefficient	$Z_{TRBL}$	Numer of tail rotor blades
$C_{POW}$	Nominal engine power factor	$Z_{ENG}$	Number of engines
Cruis	FM of main rotor	$\eta_{PR}$	Main rotor propulsive efficiency
$F_{MTR}$	FM of tail rotor	$\rho_0$	air density at sea level at standard temp.
$f_{SH}$	Overloading factor	$\rho_{HOGE}$	air density at 8000 ft and standard temp.
K	Lift-to-Drag ratio	$(\omega R)_{MR}$	Main rotor tip speed (m/sec)
L	Given Range (Km)	$(\omega R)_{TR}$	Tail rotor tip speed (m/sec)
$n_{MTR}$	Ratio of main rotor to tail rotor diameter	$\xi_{CR}$ (1rotor)	Cruise power conversion efficiency
$n_{SH}$	Tail rotor shaft RPM	$\xi_{CR}$ (2rotors)	Cruise power conversion efficiency
p	Disk loading	$\xi_{MR}$ (1rotor)	Main rotor power conversion efficiency
$P_{DC}$	Power consumption of pump and other (hp)	$\xi_{MR}$ (2rotors)	Main rotor power conversion efficiency
$T_{RES}$	Given time reserve (h)	$\xi_{TR}$	Tail rotor power conversion efficiency
$t_{MR}$	main rotor thrust losses		

#### Main parameters

$W_{PL}$	Payload weight (Kg)
$W_{FURN}$	Weight of additional furnishing (Kg)
p	Disk loading

#### Temporary initial date

$k_{WE}$	Weight efficiency coefficient	$\lambda_{MRBL\_MIN}$	Minimum of main rotor aspect ratio
$C_{E_{CR}}$	Engine specific fuel consumption (kg/hp/h)	$\lambda_{TRBL\_MIN}$	Minimum of tail rotor aspect ratio

Main performance and geometrical dimensions calculation

$p$	Disk loading	$P_{ENG} Z_{ENG}$ adjusted	Adjusted engine power required (hp)
$W_{TO\ initial}$	Take off weight, initial (Kg)	$P_{ENG.NOM}$	Nominal Power (hp)
$W_{TO\ calculated}$	Take off weight, calculated (Kg)	$P_{CR}$	Cruise rotor power (hp)
$D_{MR}$	Main rotor diameter (m)	$P_{CR}/$ $P_{ENG.NOM}$	
$\sigma_{MR}$	Main rotor solidity	$C_{eKR}$	Engine specific fuel consumption (kg/hp/h)
$Z_{MRBL}$	Number of main rotor blades	$W_{TO\ calculated}$ 1	Take off weight, calculated 1(Kg)
$\lambda_{MRBL}$	Main rotor aspect ratio	$q_{CR}$	fuel required per kilometer (kg/km)
$b_{07MR}$	Main rotor chord (m)	$W_{FUEL}$	Fuel weight (kg)
$P_{ENG} Z_{ENG}$ preliminary	Engine power required (hp)	$M_{TTR}$	Tail rotor shaft torque moment (kgm)
$M_{MRT}$	Main rotor shaft torque moment (kgm)	$M_{TSH}$	Shaft torque moment (kgm)
$D_{TR}$	Tail rotor diameter (m)	$\sigma_{TR}$	Tail rotor solidity
$T_{TR}$	Tail rotor thrust (kg)	$Z_{TRBL}$	Numer of tail rotor blades
$P_{TR}$	Tail rotor power (hp)	$\lambda_{TRBL}$	Tail rotor Inflow ratio
$\xi_{HOV}$	Hover power conversion efficiency	$b_{07TR}$	Tail rotor chord (m)

Weight Prediction Auxiliary coefficients

$R_{rMRBLCG}$	
$R_{rTRBLCG}$	
$C_{SHbrea}$	
$K_{anti-ice}$	
$K_{fuz}$	

Main weight coefficients and some part weights

$k_{MRBL}^*$	main rotor blade weight coefficient, kg / m <sup>2.7</sup>	$FC_{MRBL}$	
$k_{TRBL}^*$	tail rotor blade weight coefficient, kg / m <sup>2.7</sup>	$f_{ZMRBL}$	
$k_{1APU}$	first APU weight coefficient, kg/hp	$FC_{TRBL}$	
$k_{2APU}$	second APU weight coefficient, kg	$f_{ZTRBL}$	
$k_{1BCS}$	first booster system weight coefficient, kg	<b>part weight</b>	
$k_{2BCS}$	second booster system weight coefficient, kg.		
$k_{1ENG}$	first engine weight coefficient, kg/hp		
$k_{2ENG}$	second engine weight coefficient, kg		
$k_{1FUS}$	first fuselage weight coefficient	$W_{MRBL}$	main rotor blade weight
$k_{2FUS}$	second fuselage weight coefficient	$W_{MRH}$	main rotor hub weight
$k_{3FUS}$	third fuselage weight coefficient, kg / m	$W_{SP}$	swash plate weight
$k_{1SP}$	first swash plate weight coefficient, kg / m <sup>3</sup>	$W_{BCS}$	booster system weight
$k_{2SP}$	second swash plate weight coefficient, kg	$W_{TRBL}$	tail rotor blade weight
$k_{ELSYS}$	electrical system weight coefficient, kg / kW	$W_{TRH}$	tail rotor hub weight
$k_{EMP}$	empennage weight coefficient, kg/m <sup>2</sup>	$W_{MGB}$	main gearbox weight

$k_{FS}$	fuel system weight coefficient	$W_{TRGB}$	tail gearbox weight
$k_{IGB}$	intermediate gearbox weight coefficient, kg / kg m	$W_{IGB}$	intermediate gearbox weight
$k_{LG}$	landing gear weight coefficient	$W_{SH}$	transmission shaft weight
$k_{MGB}$	main gearbox weight coefficient, kg / kg m	$W_{ENG}$	engine weight
$k_{MRHUB}$	main rotor hub weight coefficient, kg / mt1.35	$W_{PIS}$	power plant installation weight
$k_{PIS}$	power plant installation weight coefficient	$W_{APU}$	APU weight
$k_{SH}$	transmission shaft weight coefficient, kg / kg m <sup>2</sup>	$W_{FS}$	fuel system weight
$k_{SLE}$	special load equipment weight coefficient	$W_{LG}$	landing gear weight
$k_{TGB}$	tail gearbox weight coefficient, kg / kg m	$W_{FUS}$	fuselage weight
$k_{TRHUB}$	tail rotor hub weight coefficient, kg / mt1.35	$W_{EMPEN}$	empennage weight
$W_{AVSYS}$	avionics system weight, kg	$W_{ELSYS}$	electrical system weight
$W_{PBC}$	pre-booster electronic system weight coefficient.	$W_{SLE}$	special load equipment weight

$W_{EMPT}$	empty weight
<i>Reserv</i> 5%	empty weight 5% reserved
TOW new	total weight
$k_{WE}$	weight efficiency coefficient

## Sequence of Performance Calculations

$$W_{TO,initial} = \left[ k_{WE} - \left\{ \frac{(L + T_{RES} V_{CR}) C e_{CR}}{270 K \eta_{PR} \xi_{CR}} \right\} - 0.005 \right]$$

$$W_{TO,calculated} \begin{cases} = W_{TO,initial} & (IF \ TOW_{new} = 0) \\ = TOW_{new} & (IF \ TOW_{new} \neq 0) \end{cases}$$

$$D_{MR} = \sqrt{\frac{4W_{TO,calculated}}{\pi P}}$$

$$\sigma_{MR} = \frac{W_{TO,calculated}}{(C_T / \sigma)_{MR0} \rho_0 \pi (D_{MR} / 2)^2 (\omega R)_{MR}^2}$$

$$b_{07MR} = \frac{D_{MR}}{2 \lambda_{MRBL}}$$

$$P_{ENG} Z_{ENG,pre} = \frac{(W_{TO,calculated} t_{MR})^{3/2}}{33.25 FM_{MR} \xi_{MR} \sqrt{(\rho_{HOGE} / \rho_0)} D_{MR}}$$

$$M_{MRT} = \frac{716.2 P_{ENG} Z_{ENG,pre} \pi (D_{MR} / 2) \xi_{MR}}{30 (\omega R)_{MR}}$$

$$D_{TR} = \frac{D_{MR}}{n_{MTR}}$$

$$T_{TR} = \frac{2M_{MRT}}{(D_{MR} + D_{TR} + 0.3)}$$

$$P_{TR} = \frac{(T_{TR} t_{TR})^{3/2}}{33.25 FM_{TR} \xi_{TR} \sqrt{(\rho_{HOGE} / \rho_0)} D_{TR}}$$

$$\xi_{HOV} = \frac{P_{ENG} Z_{ENG,pre} - P_{TR} - P_{DC}}{P_{ENG} Z_{ENG,pre}}$$

$$P_{ENG} Z_{ENG,adj} = \frac{(W_{TO,calculated} t_{MR})^{3/2}}{33.25 FM_{MR} \xi_{HOV} \sqrt{(\rho_{HOGE} / \rho_0)} D_{MR}}$$

$$P_{ENG,NOM} = P_{ENG} Z_{ENG,adj} C_{POW}$$

$$P_{CR} = \frac{W_{TO,cal} V_{CR}}{270 K \xi_{CR} \eta_{PR}}$$

$$C e_{KR} = \frac{C e_1 P_{ENG,NOM}}{P_{CR}} + C e_2$$

$$W_{TO,calculated1} = \left[ k_{WE} - \left\{ \frac{(L + T_{RES} V_{CR}) C e_{KR}}{270 K \eta_{PR} \xi_{CR}} \right\} - 0.005 \right]$$

$$q_{CR} = \frac{W_{TO,cal1} C e_{KR}}{270 K \xi_{CR} \eta_{PR}}$$

$$W_{FUEL} = W_{TO,cal} \left[ \left\{ \frac{(L + T_{RES} V_{CR}) C e_{KR}}{270 K \eta_{PR} \xi_{CR}} \right\} + 0.005 \right]$$

$$M_{TR} = \frac{716.2 P_{TR} \pi (D_{TR} / 2) \xi_{TR}}{30 (\omega R)_{TR}}$$

$$M_{TSH} = \frac{716.2 P_{TR} f_{SH}}{\eta_{SH}}$$

$$\sigma_{TR} = \frac{T_{TR}}{(C_T / \sigma)_{TR0} \rho_0 \pi (D_{TR} / 2)^2 (\omega R)_{TR}^2}$$

$$\lambda_{TRBL} = \frac{Z_{TRBL}}{\pi \sigma_{TR}}$$

$$b_{07TR} = \frac{D_{TR}}{2 \lambda_{TRBL}}$$

$$FC_{MRBL} = \frac{W_{MRBL}}{z_{MRBL} \cdot g} \left( \frac{2 \cdot (\omega R)_{MR}}{D_{MR}} \right)^2 \frac{D_{MR}}{2 \cdot 1000} Rr_{MRBLCG}$$

$$f_{ZMRBL} = \begin{cases} 1 & (\text{if } z_{MRBL} \leq 4) \\ 1 + (z_{MRBL} - 4) \cdot 0.05 & (\text{if } z_{MRBL} > 4) \end{cases}$$

$$FC_{TRBL} = \frac{W_{TRBL}}{z_{TRBL} \cdot g} \left( \frac{2 \cdot (\omega R)_{TR}}{D_{TR}} \right)^2 \frac{D_{TR}}{2 \cdot 1000} Rr_{TRBLCG}$$

$$f_{ZTRBL} = \begin{cases} 1 & (\text{if } z_{TRBL} \leq 4) \\ 1 + (z_{TRBL} - 4) \cdot 0.05 & (\text{if } z_{TRBL} > 4) \end{cases}$$

$$W_{MRBL} = \frac{k_{MRBL}^* \sigma_{MR} (D_{MR} / 2)^{2.7}}{(\lambda_{MRBL} / 18)^{0.7}}$$

$$W_{MRH} = k_{MRHUB} f_{ZMRBL} FC_{MRBL}^{1.35} z_{MRBL}$$

$$W_{SP} = k_{1SP} \left( \frac{D_{MR}}{2} \right) b_{07MR}^2 \left( \frac{V_{CR}}{3.6 \cdot (\omega R)_{MR}} \right) + k_{2SP}$$

$$W_{BCS} = k_{1BCS} \left( \frac{D_{MR}}{2} \right) b_{07MR}^2 \left( \frac{V_{CR}}{3.6 \cdot (\omega R)_{MR}} \right) + k_{2BCS}$$

$$W_{TRBL} = \frac{k_{TRBL}^* \sigma_{TR} (D_{TR} / 2)^{2.7}}{(\lambda_{TRBL} / 18)^{0.7}}$$

$$W_{TRH} = k_{TRHUB} f_{ZTRBL} FC_{TRBL}^{1.35} z_{TRBL}$$

$$W_{MGB} = k_{MGB} M_{MRT}^{0.8}$$

$$W_{TRGB} = k_{TGB} M_{TTR}^{0.8}$$

$$W_{IGB} = k_{IGB} M_{TSH}^{0.8}$$

$$W_{SH} = k_{SH} M_{TSH}^{0.8} \cdot 0.5 \cdot \left( D_{MR} + \frac{D_{TR}}{0.7} + 0.3 \right)$$

$$W_{ENG} = k_{1ENG} P_{ENG.NOM} + k_{2ENG}$$

$$W_{PIS} = k_{PIS} W_{ENG}$$

$$W_{APU} = k_{1APU} P_{ENG.NOM} + k_{2APU}$$

$$W_{FS} = k_{FS} W_{FUEL}$$

$$W_{LG} = k_{LG} W_{TO.cal}$$

$$W_{FUS} = k_{1FUS} W_{TO.cal} + k_{2FUS} W_{PL} + k_{31FUS} W_{TO.cal} \left( \frac{D_{MR}}{20} - 1 \right)$$

$$W_{EMPEN} = 0.01571 \cdot k_{EMP} \cdot D_{MR}^2$$

$$W_{ELSYS} = k_{ELSYS} \left( 15 + 0.6 \cdot \left( \frac{D_{MR}}{2} z_{MRBL} b_{07MR} + \frac{D_{TR}}{2} z_{TRBL} b_{07TR} \right) \right)$$

$$W_{SLE} = k_{SLE} W_{PL}$$

$$W_{EMPT} = W_{MRBL} + W_{MRH} + W_{SP} + W_{BCS} + W_{PBC} + W_{TRBL} + W_{TRH} + W_{MGB} + W_{TRGB} + W_{IGB} + W_{SH} + W_{ENG} \\ + W_{PIS} + W_{APU} + W_{FS} + W_{LG} + W_{FUS} + W_{EMPEN} + W_{ELSYS} + W_{AVSYS} + W_{SLE}$$

$$Reserve(5\%) = W_{EMPT} \cdot 1.05$$

$$TOW_{NEW} = Reserve(5\%) + W_{FUEL} + W_{PL} + W_{FURN}$$

$$k_{WE} = \frac{TOW_{NEW} - Reserve(5\%)}{TOW_{NEW}}$$

Preliminary design code (PDC) with full weights, sizing and performance calculations

Preliminary and initial data

$Ce_1$	0.09	$n_{MTR}$	5.50	$\eta_{PR}$	0.98
$Ce_2$	0.10	$n_{SH}$	4000.00	$\rho_0$	0.104893
$(CT / \sigma)_{MRO}$	0.080	$\rho$	35 - 55	$\rho_{HOGE}$	0.097401
$(CT / \sigma)_{TRO}$	0.08	$P_{DC}$	150.00	$(\omega R)_{MR}$	240
$C_{POW}$	1.10	$T_{RES}$	1.00	$(\omega R)_{TR}$	220
$F_{MMR}$	0.85	$t_{MR}$	1.01	$\zeta_{CR}$ (1rotor)	0.94
$F_{MTR}$	0.67	$t_{TR}$	1.06	$\zeta_{CR}$ (2rotors)	0.94
$f_{SH}$	1.80	$V_{CR}$	115.00	$\zeta_{MR}$ (1rotor)	0.94
$K$	4.20	$Z_{MRBL}$	3.00	$\zeta_{MR}$ (2rotors)	0.94
$L$	220.00	$Z_{TRBL}$	6.00	$\zeta_{TR}$	0.975
		$Z_{ENG}$	2		

Main parameters

$W_{PL}$	5500						
$W_{FURN}$	0						
$\rho$	30	40	50	20	15	10	35
initial date	Temporary	<b>Temporary Initial data</b>			<b>I data</b>		
$k_{WE}$	0.46			$\lambda_{MRBL,MIN}$	10		
$Ce_{CR}$	0.22			$\lambda_{TRBL,MIN}$	10		

Main performance and geometrical dimensions calculation

$\rho$ (disk loading)	30	40	50	20	15	10	35
$W_{TO}$ initial	14306.2	14306.2	14306.2	14306.2	14306.2	14306.2	16206.2
$W_{TO}$ calculated	10965.9	10930.6	11407.7	10147.4	10013.0	9960.8	11791.9
$D_{MR}$	21.57	18.65	17.04	25.42	29.15	35.61	14.65
$\sigma_{MR}$	0.0621	0.0828	0.1034	0.0414	0.0310	0.0207	0.0724
$Z_{MRBL}$	5	5	5	5	5	5	4
$\lambda_{MRBL}$	16.50	19.23	15.39	38.46	51.28	76.93	17.58
$b_{07MR}$	0.6537	0.4850	0.5539	0.3304	0.2842	0.2315	0.4165
$P_{ENG}$ $Z_{ENG}$ preliminary	2110.51	2429.15	2834.43	1594.59	1362.67	1106.81	2769.98
$M_{MRT}$	6687.36	6655.02	7095.55	5952.74	5834.86	5789.29	5958.32
$D_{TR}$	3.92	3.39	3.10	4.62	5.30	6.47	2.66
$T_{TR}$	518.49	595.68	694.19	392.43	335.78	273.16	676.77
$P_{TR}$	156.94	223.52	307.74	87.71	60.52	36.36	344.76
$\zeta_{HOV}$	0.855	0.846	0.839	0.851	0.846	0.832	0.821
$P_{ENG}$ $Z_{ENG}$ adjusted	2321.5	2698.3	3177.5	1761.5	1515.0	1251.0	3170.0
$P_{ENG,NOM}$	2553.7	2968.1	3495.3	1937.7	1666.5	1376.1	3487.0
$P_{CR}$	1207.2	1203.3	1255.8	1117.1	1102.3	1096.5	1298.1
$P_{CR} / P_{ENG,NOM}$	0.4727	0.4054	0.3593	0.5765	0.6615	0.7968	0.3723
$Ce_{KR}$	0.2798	0.3097	0.3366	0.2474	0.2285	0.2067	0.3283
$W_{TO}$ calculated 1	15057.3	15462.7	15847.1	14641.3	14408.4	14148.9	15727.3

Q <sub>CR</sub>	4.033	4.584	5.106	3.468	3.152	2.799	4.943
W <sub>FUEL</sub>	1038.80	1140.11	1288.33	855.93	783.79	709.98	1300.51
M <sub>TTR</sub>	102.31	125.98	158.49	67.37	53.32	39.12	152.57
M <sub>TSH</sub>	50.58	72.04	99.18	28.27	19.51	11.72	111.11
σ <sub>TR</sub>	0.1056	0.1624	0.2266	0.0576	0.0375	0.0204	0.2992
Z <sub>TRBL</sub>	6	6	6	6	6	6	6
λ <sub>TRBL</sub>	18.078	11.763	8.428	33.153	50.977	93.504	6.383
b <sub>07TR</sub>	0.108	0.144	0.184	0.070	0.052	0.035	0.209

## Weight Prediction

### Auxiliary coefficients

Rr <sub>MRblCG</sub> =	0.48	Rr <sub>TRBLCG</sub> =	0.47				
C <sub>SHbrea</sub> =	2.3						
				K <sub>anti-ice</sub> =	0.18	K <sub>fuz</sub> =	0.12

### Main weight coefficients and some part weights

K <sup>*</sup> <sub>MRBL</sub>	10.5	main rotor blade weight coefficient, kg / m <sup>2.7</sup>						
K <sup>*</sup> <sub>TRBL</sub>	14	tail rotor blade weight coefficient, kg / m <sup>2.7</sup>						
K <sub>1APU</sub>	0.006	first APU weight coefficient, kg/hp						
K <sub>2APU</sub>	40	second APU weight coefficient, kg						
K <sub>1BCS</sub>	25	first booster system weight coefficient, kg						
K <sub>2BCS</sub>	30	second booster system weight coefficient, kg.						
K <sub>1ENG</sub>	0.1	first engine weight coefficient, kg/hp						
K <sub>2ENG</sub>	80	second engine weight coefficient, kg						
K <sub>1FUS</sub>	0.095	first fuselage weight coefficient						
K <sub>2FUS</sub>	0.06	second fuselage weight coefficient						
K <sub>3FUS</sub>	0.02	third fuselage weight coefficient, kg / m						
K <sub>1SP</sub>	46	first swash plate weight coefficient, kg / m <sup>3</sup>						
K <sub>2SP</sub>	54	second swash plate weight coefficient, kg						
K <sub>ELSYS</sub>	1.9	electrical system weight coefficient, kg / kW						
K <sub>EMP</sub>	12	empennage weight coefficient, kg/m <sup>2</sup>						
K <sub>FS</sub>	0.04	fuel system weight coefficient						
K <sub>IGB</sub>	0.6	intermediate gearbox weight coefficient, kg / kg m						
K <sub>LG</sub>	0.025	landing gear weight coefficient						
K <sub>MGB</sub>	0.38	main gearbox weight coefficient, kg / kg m						
K <sub>MRHUB</sub>	0.95	main rotor hub weight coefficient, kg / mt1.35 power plant installation weight						
K <sub>PIS</sub>	0.15	coefficient	swash plate weight coefficient, kg / m <sup>3</sup>					
K <sub>SH</sub>	0.05	transmission shaft weight coefficient, kg / kg m <sup>2</sup>						
K <sub>SLE</sub>	0.05	special load equipment weight coefficient						
K <sub>TGB</sub>	0.5	tail gearbox weight coefficient, kg / kg m						
K <sub>TRHUB</sub>	0.5	tail rotor hub weight coefficient, kg / mt1.35						
W <sub>AVSYS</sub>	55	avionics system weight, kg						
W <sub>PBC</sub>	150	pre-booster electronic system weight coefficient.						
FC <sub>MRBL</sub> , mt	22.26		20.82	26.10	10.84	8.39	5.92	32.14
f <sub>ZMRBL</sub>	1.05		1.05	1.05	1.05	1.05	1.05	1
FC <sub>TRBL</sub> , mt	1.79		2.97	4.48	0.86	0.52	0.26	0.00
f <sub>ZTRBL</sub>	1.1		1.1	1.1	1.1	1.1	1.1	1.1

p (disk loading)	30	40	50	20	15	10	32.63
$W_{MRBL}$ , kg	425.89	344.43	394.52	244.43	217.07	187.03	334.00
$W_{MRH}$ , kg	328.79	300.43	407.60	124.52	88.15	55.03	822.79
$W_{SP}$ , kg	82.22	67.43	70.01	62.49	61.21	59.84	123.55
$W_{BCS}$ , kg	45.34	37.30	38.70	34.62	33.92	33.17	34.23
$W_{PBC}$	150	150	150	150	150	150	150
$W_{TRBL}$ , kg	9.09	12.74	17.60	5.05	3.52	2.15	0.00
$W_{TRH}$ , kg	7.25	14.32	25.02	2.70	1.38	0.54	0.00
$W_{MGB}$ , kg	436.50	434.81	457.69	397.70	391.39	388.94	597.00
$W_{TRGB}$ , kg	20.27	23.95	28.77	14.51	12.04	9.40	0.00
$W_{IGB}$	13.85	18.37	23.73	8.69	6.46	4.30	0.00
$W_{SH}$	15.85	18.22	21.53	11.71	9.97	8.09	0.00
$W_{ENG}$	335.37	376.81	429.53	273.77	246.65	217.61	428.70
$W_{PIS}$	50.30	56.52	64.43	41.07	37.00	32.64	64.30
$W_{APU}$	55.32	57.81	60.97	51.63	50.00	48.26	50.46
$W_{FS}$	41.55	45.60	51.53	34.24	31.35	28.40	52.02
$W_{LG}$	274.15	273.26	285.19	253.68	250.32	249.02	294.80
$W_{FUS}$	1389.02	1353.68	1380.01	1348.96	1372.89	1431.78	1387.09
$W_{EMPEN}$	87.74	65.59	54.76	121.78	160.23	239.09	40.43
$W_{APU}$	47.66	48.90	50.49	45.81	45.00	44.13	0.00
$W_{ELSYS}$	70.15	55.95	57.35	53.53	53.06	52.76	44.31
$W_{AVSYS}$	55.00	55.00	55.00	55.00	55.00	55.00	55.00
$W_{SLE}$	275.00	275.00	275.00	275.00	275.00	275.00	275.00
$W_{EMPT}$	4216.31	4086.13	4399.45	3610.90	3551.59	3572.18	4753.67
Reserv 5%	4427.13	4290.44	4619.42	3791.44	3729.17	3750.79	4991.36
TOW new	10965.92	10930.55	11407.74	10147.38	10012.96	9960.76	11791.87
$k_{WE}$	0.5963	0.6075	0.5951	0.6264	0.6276	0.6234	0.5767

## Appendix (B)

## Cost Estimate Calculation

### Cost Estimate

#### Rotor System Group

$$\text{Average Rotor System Cost} = 2 * 1500 * \text{Weight}^7 * \text{Kyokmat} * \text{Bldno}^2 * \text{Kbldmat} * \text{Kappl} * (\text{Prodq} * \text{Prodr})^{-8}$$

Kyokmat = Yoke material factor

Bldno = Number of main rotor blades

Kbldmat = Blade material Factor

Kappl = Main rotor system application

Prodq = Total production quantity

Prodr = Production rate

#### Tail Group

$$\text{Average Vertical Stabilizer Cost} = 1000 * \text{Weight} * \text{Kmat} * \text{Kvstr} * (\text{Prodq} * \text{Prodr})^{-9}$$

$$\text{Average Horizontal Stabilizer Cost} = 1000 * \text{Weight} * \text{Kmat} * \text{Kvstr} * (\text{Prodq} * \text{Prodr})^{-8}$$

Kvstr = Tailrotor mounting factor

#### Body Group

$$\text{Average Fuselage Cost} = 10,000 * \text{Weight}^8 * \text{Kmat} * (\text{Prodq} * \text{Prodr})^{-13}$$

#### Landing Gear Group

$$\text{Average Landing Gear Cost} = 5,000 * \text{Weight}^5 * \text{Klgtyp} * (\text{Prodq} * \text{Prodr})^{-0.8}$$

Klgtyp = Landing gear type

#### Nacelle Group

$$\text{Average Nacelle Cost} = 5,000 * \text{Weight}^8 * \text{Kappl} * \text{Noeng}^1 * (\text{Prodq} * \text{Prodr})^{-12}$$

Noeng = Number of engines

### **Air Induction Group**

$$\text{Average Air Induct Cost} = 5,000 * \text{Weight}^{.8} * \text{Kappl} * \text{Noeng}^{.5} * (\text{Prodq} * \text{Prodr})^{-.09}$$

### **Propulsion Group**

$$\text{Average Engine Installation Cost} = (2,000 * \text{Weight}^{.7} * \text{Noeng}^{.8} * (\text{Prodq} * \text{Prodr})^{-.06}) + \text{Engine Cost}$$

$$\text{Average Drive System Cost} = (2,500 * \text{Weight}^{.9} * \text{Noeng}^{.4} * (\text{Prodq} * \text{Prodr})^{-.07}$$

### **Flight Controls Group**

$$\text{Average Flight Control System} = 300 * \text{Weight} * \text{Bldno}^{.5} * \text{Kcontyp} * \text{Kappl} * (\text{Prodq} * \text{Prodr})^{-.06}$$

Kcontyp = Flight control type factor

### **Instrument Group**

$$\text{Average Instrument System Cost} = 1,500 * \text{Weight} * \text{Ktype} * (\text{Prodq} * \text{Prodr})^{-.06}$$

Ktype = Instrument type factor

### **Hydraulics Group**

$$\text{Average Hydraulic System Cost} = 1,000 * \text{Weight} * (\text{Prodq} * \text{Prodr})^{-.07}$$

### **Electrical Group**

$$\text{Average Electrical System Cost} = 2,000 * \text{Weight}^{.9} * \text{Kappl} * (\text{Prodq} * \text{Prodr})^{-.1}$$

### **Avionics Group**

$$\text{Average Avionics System Cost} = 2,500 * \text{Weight} * (\text{Prodq} * \text{Prodr})^{-.08}$$

### **Furnishings and Equipment Group**

$$\text{Average Furnishings System Cost} = 500 * \text{Weight}^{11} * (\text{Prodq} * \text{Prodr})^{-.08}$$

### **Air Conditioning Group**

$$\text{Average Air Conditioning System Cost} = 2,000 * \text{Weight}^{.8} * \text{Kecu} * (\text{Prodq} * \text{Prodr})^{-.06}$$

Kecu = Environmental control unit factor

### **Load and Handling Group**

$$\text{Average Load and Handling System Cost} = 2,000 * \text{Weight}^{.8} * (\text{Prodq} * \text{Prodr})^{-1}$$

### **Final Assembly**

$$\text{Average Final Assembly Cost} = 30,000 * \text{Weight}^4 * \text{Engno}^{-9} * \text{Kfusmat} * (\text{Prodq} * \text{Prodr})^{-.15}$$

Kfusmat = Fuselage material factor