

**Waterspout - Advanced Deployable  
Compact Rotorcraft in Support of Special  
Operation Forces**



**Penn-State Student Design Team**



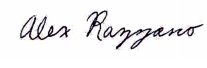


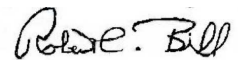
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## Abbreviations

AFCS	Automatic Flight Control System
AHS	American helicopter society
AoA	Angle of attack
ARV	Approach and Recovery Vehicle
BEMT	Blade Element Momentum Theory
C.G.	Center of Gravity
FLIR	Forward Looking Infrared
FM	Figure of Merit
GPS	Global Positioning System
GW	Gross Weight
H/D	Height/Diameter
HOGE	Hover Out of Ground Effect
HUMS	Health and Usage Management System
IEEE	Institute of Electrical and Electronics Engineers
INS	Inertial Navigation System
INS	Inertial Navigation System
IR	Infrared
JTIDS	Joint Tactical Information Distribution System
JTRS	Joint Tactical Radio System
L/D	Lift/Drag
MR	Main Rotor
NACA	National Advisory Committee for Aeronautics
PhLASH	Photographic Landing Augmentation System
RADAR	Radio Detection And Ranging
RF	Radio Frequency
RFP	Request For Proposal
RPM	Rounds per minute
SAR	Search And Rescue
SLS3	Sea Level State 3
SOF	Special Operation Forces
SSCN	Submersible Ship Aircraft Carrier
VTOL	Vertical TakeOff and Landing

## Nomenclature

$\alpha$	Aircraft pitching angle
$\phi$	Aircraft roll angle
$\theta$	Tilt angle of the helicopter relative to the water surface
$Cd$	Blase's section drag coefficient
$Cl$	Blase's section lift coefficient
$R$	Distance between C.G. and a certain reference point in the vehicle
$\rho_w$	Water density [ $Kg/m^3$ ]
$A_{cable}$	Surface area of the retrieval mechanism's cable
$Cp$	Specific heat [ $J/(Kg \cdot K)$ ]
$E_{heat}$	Energy required for hub heating [J]
$E_{steel}$	Young's Modulus for steel
$I_{heat}$	Electric current used for heating methods [ <i>Ampere</i> ]
$P_{heat}$	Electric power required for heating and de-icing [ $W$ ]
$T$	Absolute temperature [ $K$ ]
$V_{heat}$	Heating batteries voltage [ $V$ ]
$W$	Total weight of hub components [ $Kg$ ]
$k$	Thermal conductivity coefficient [ $W/(m^{\circ}C)$ ]
$F$	The ARV's drag created when swaying in the water
$I$	The ARV's moment of inertia
$P$	Dynamic oscillation period
$S$	Surface area of an equivalent cylinder used for under-water drag calculations
$\omega_n$	Fuselage dynamic oscillation frequency
$V_w$	Sea-wave velocity [ $m/s$ ]

# Chapter 1

## Helicopter Design Objective and Mission Description

### 1.1 Introduction

This report presents a second year running successful international collaboration of undergraduate students from two institutes: The Vertical Lift Research Center at the Pennsylvania State University, and the Faculty of Aerospace Engineering at the Technion Israel Institute of Technology. The *Waterspout* helicopter, presented here, is an advanced submarine deployable compact rotorcraft in support of special operation forces, as a response to the 2007 annual American Helicopter Society student design competition. The participating students have benefited from this joint venture by acquiring some experience in both rotorcraft design and international coordinated teamwork as customary in our contemporary industry.

Among the design requirements for this Approach and Recovery Vehicle design challenge are: vertical takeoff and landing, 30 minute floating capabilities at Sea Level State 3 (detailed conditions in Sub-Section 3.1.2) and the capability of this vehicle to transport the 2 crew members from the submerged submarine through water on to dry land and back, healthy or injured, without being detected. Due to necessary transfer through water and the unique operational environments special attention was devoted to keeping the vehicle well sealed and able to function even in extreme weather.

The profile and blade design was assigned to the Penn State team, along with the avionics suites, trim analysis, performance and crashworthy fuel system design. The Technion Team was in charge of stability analysis, mechanical deck design, crew cabin layout, de-icing analysis for extreme weather conditions, water proofed design, and submarine launch/retrieval method and mechanism. The general airframe design, internal layout, entrance/egress path and landing gear were continuously discussed between the 2 teams, achieving progressive solutions until finalizing the design of the vehicle.

This combined effort produced an innovative compact co-axial helicopter, designed to exit and enter the submarine launch compartment vertically and float to the water surface already in take off position, requiring only the deployment of the rotor blades for mission take off. The main requirements for this challenge as derived from the request for proposal [1] for the 24th AHS student design competition and the *Waterspout's* design capability to meet them are summarized in Table 1.1 for convenience.

## 1.2 Helicopter Design Objective and General Description

### 1.2.1 Background

#### Special Forces

Due to the clandestine and covert quality of the U.S. Special Operation Forces work, a requirement has been raised for a new undetectable submersible aircraft providing fast approach and recovery in operations from maritime environments. Even though submersible watercraft already exist they provide transportation from the submerged base to land through water only and then need to be concealed, while different means of transportation are sometimes necessary for land deployment. Designing such an automatic aircraft would offer the advantages of stealth and transportation both above water and land, and would enable the team to approach and return from their mission without the constraints of the vehicles' whereabouts. Since most of the world's population (and most capitals) live within close proximity to the coastline, the advantage of stealth and flexible mobile capability give an important advantage. This is coupled with the position of sea lines of communications which are identified as high-priority targets that must be defended against terrorist acts.

#### Submersible Ship Aircraft Carrier

The Approach and Recovery Vehicle designed for the mission is intended to be carried on an upgraded Ohio class SSCN submarines (Figure 1.1), which will launch these vehicles while in periscope depth. The vehicle will then float to the water surface and takeoff on it's own toward the objective. The Ohio class submarine missile silos are currently sized to house a single trident D-5 missile (dimension can be found in the RFP [1], therefore two options are possible:

- Designing our aircraft for an optimal fit to the external hatch diameter, thus altering only the submarine interior launch/retrieval.
- Modifying the existing structure inside and out, including new launch hatches on the submarine exterior.

In addition to the submersible carrier requirements, the ARV should be fit to carry on board a C-130J aircraft. Cargo bay area dimensions are: Length of 12.1[m], Width of 3.1[m], and Height of

<b>Design Requirement</b>	<b><i>WaterSpout</i> Capability</b>	<b>section</b>
Two-seat ARV	Two-seat compact ARV	Throughout
Storage and operation capability from a SSCN	Folding blades, launch capability from SSCN	Sub-Section 1.3.1, Section 3.3
Efficient use of submarine space	Small ARV, various storage options	Sub-Section 3.3.3
Must be impervious to effects of water	Waterproof ARV, designed using smart material selection and innovative sealing solutions	Sub-Section 2.2.3, through Chapter 2
30 min flotation at SLS-3	Stability analysis at SLS3	Sub-Section 3.1.2
All-weather capability: maritime, arctic, desert etc.	The ARV is equipped with de-icing and sealing systems	Sub-Section 2.3.1
Stealth operation	Lower heat signature, radar-absorbent coatings	Sub-Section 2.2.4 & Section 2.6
Must be capable of VTOL	Coaxial helicopter configuration VTOL capable	Sub-Section 1.2.2
Specific mission launch/retrieval timing	The <i>Waterspout</i> meets all timing limitations specified	Section 1.3, Figures 1.5-1.7
Hover out of ground effect capability @6[kft]/95°[F]	Engine/rotor design are based on required conditions	Sub-Section 2.1.1
Completely automatic operation: takeoff, landing, etc.	Autonomous ARV, including launch/retrieval mechanism	Section 2.6 & Sub-Section 3.2.1
Should enable takeoff aborts and/or recovery wave-offs	The <i>Waterspout</i> allows non-pilot mission aborts	Section 2.6, Sub-Section 2.7.2
Crashworthy fuel system	Blanket covered fuel system separated from crew cabin	Sub-Section 2.5.6
Allow transport of one/both of the crew as injured	Equipped with specially designed seats and hoist system	Sub-Sections 2.7.4 & 2.7.1
Landing capabilities on water and land	Cone shaped bottom, flotation devices, landing gear	Sub-Sections 2.2.1 & 3.1.2, Section 2.8
800[lbs] Payload	Gross Weight/power/structure fitting for required payload	Table A.1, Section 2.2
High degree of availability and reliability	Accessible mechanics, easy storage, elastomeric hinges	Section 2.5, Section 3.3
5% contingency on empty weight	ARV's estimated empty weight was increased by 5%	Table A.1

Table 1.1: Proposal Requirements Matrix

2.7[m]. This requirement comes in order to allow for rapid deployment of the ARVs to any location via the air.

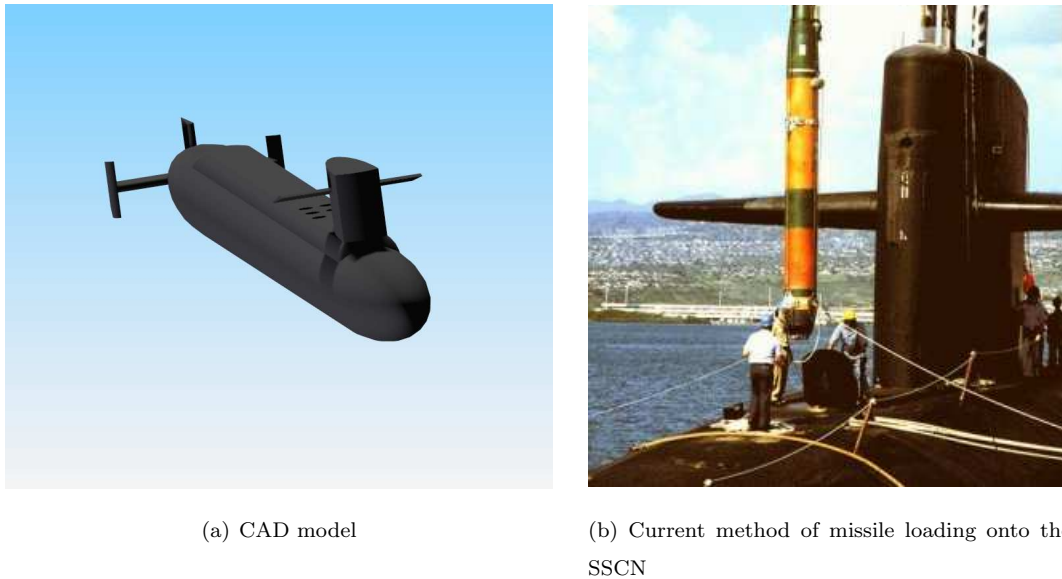


Figure 1.1: Ohio class SSCN submarine

Aspiring to keep the submarine modifications at a minimum, the *Waterspout* team decided to design an ARV in accordance with the silo size: Diameter of 2.11[m] and Height of 13.4[m], keeping the original launch hatch and subsequently the external submarine body intact, thus altering only the inner submarine design which is a non-primary structure. This decision has a major effect on our design, but allows a compactness advantage in storage (on board the SSCN and the C-130J), also minimizing the complicated and more expensive submarine external modifications. The helicopter-submarine interface was identified by the team as one of the main design issues in this RFP.

## 1.2.2 Preliminary Vehicle Trend Analysis

### Initial Sizing

Prior to choosing a design configuration for this challenge, initial sizing took place, derived from the main RFP requirements, and a trade study focusing on relatively lightweight helicopters made by a prior project team [2]. The initial sizing process utilized a set of basic trend figures such as GW vs. payload so that if the payload is given (as in the present case), an estimation for the GW can be found based on existing helicopters trendline. A payload requirement of 800[lbs] including 2 crew members (270[lbs] each), and mission equipment (260[lbs]) was used as a starting point, and the results are presented in Table 1.2. Note that this trend analysis is for conventional tail-rotor configurations.

Payload	800[lbs]	360[kg]
Gross Weight	3000[lbs]	1300[kg]
Empty Weight	1500[lbs]	680[kg]
Main Rotor Diameter	26[ft]	8[m]
Power	300[HP]	230[kW]

Table 1.2: Initial Sizing

### Capsule Concept

The RFP states that the ARV must travel through water from the release in periscope depth ( 50[ft]), up to the water surface. Understanding this issue as the major unsolved part of aircraft design to date, the issue was addressed before choosing a helicopter configuration. One solution was placing the vehicle in a capsule-type structure (an example shown in Figure 1.2), thus preventing most contact with the water. Such a strong sealed structure would offer the advantages of sparing the need for complicated sealing of the vehicle and strengthening the main structure for withstanding the pressure in periscope depth, thus lowering it's G.W.. Moreover all requirements for flotation would be transferred to the capsule including any retrieval mechanisms. However, it would force the vehicle to become even smaller (silo size limitation of 2.11[m] see Sub-Section 1.2.1), would not spare basic waterproofing on the maritime fitted aircraft, and it would also significantly limit the ARV's operation autonomy by requiring an extremely precise landing in order to correctly close the capsule over the vehicle. Due to these disadvantages it was decided that the *Waterspout* would be completely autonomous, without the need for a capsule.

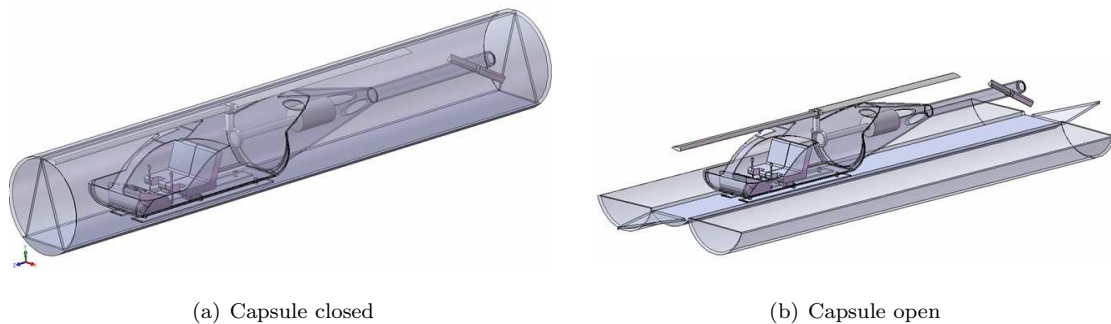


Figure 1.2: Capsule concept

### Configuration Choice

Once the decision on the ARV's autonomy (no-capsule) was made and the capsule concept dropped, the helicopter configuration choice had to be addressed. Out of the wide variety in the aviation VTOL world a number of configurations were examined for suitability. Below is a short summary:

- **Conventional Tail Rotor Helicopter:** The most common configuration to date, and therefore might be the easiest to design (abundance of references). However, the tail unit is an unnecessary excess usage of volume, the tail rotor dangerously close to the water when floating (safety hazard in SLS3). In addition, the vehicles horizontal float would require modification to the SSCN hatches, and the hatch diameter sets a serious height limitation on the design. Due to these disadvantages, this configuration was eliminated.
- **Tip-Jet Driven Helicopter:** Considered for it's innovative qualities, might offer forward speed advantages and lower fuel consumption. However, the tip-jets produce great noise which greatly reduce stealth qualities, and the configuration lacks references (only few such configurations exist). Forward speed was found secondary to stealth, so this concept was eliminated as well.
- **Tandem Helicopter:** This configuration, more common in large G.W. categories, was considered for it's relative higher stability in flight and float, fairly easy folding and storage options, and in the current case - smaller disk areas (thus keeping the blades away from the waves). However, this configuration would also require a 90° rotation after leaving the sub. It would also be limited in height according to the silo diameter.
- **Co-Axial Configuration:** Considered for it's height rather than length, it was found to offer advantages of keeping the blades far from the water as the hatch diameter would not affect the rotocraft height, straight vertical navigation through the water, and natural vertical take-off with a cone-shaped bottom. Disadvantages may include stability in forward flight, some challenges in design of rotorhead (and appropriate sealing), and blade folding. However the vehicle was expected to be smaller than the others, and easy to store in the sub.

After a considerable discussion, it was pointed out that the aspect of helicopter-submarine interface and travel through water is the most demanding design parameter. Once determined that the external hatch diameter is kept intact - it was decided to proceed with the coaxial helicopter configuration (vertically launched and stored). All other options require a 90° rotation in the water (both when exiting and returning to the submarine) which is difficult and highly complicated in both aspects of vehicle mechanics and crew layout. No significant advantage was found to compensate for these downfalls.

### **Final Configuration: General Description**

As said above, our design concept for this challenge as seen in Figure 1.3 is a co-axial, tailless, cylindrical with a cone shaped bottom, vertically stored and launched aircraft. Limited in it's diameter to the 2.11[m] of the missile silo and carrying 2 sets of 2.6[m] double bladed rotors. We believe this design to be the most fit to offer solutions for the main requirements of this project.

Measurements are in [cm]

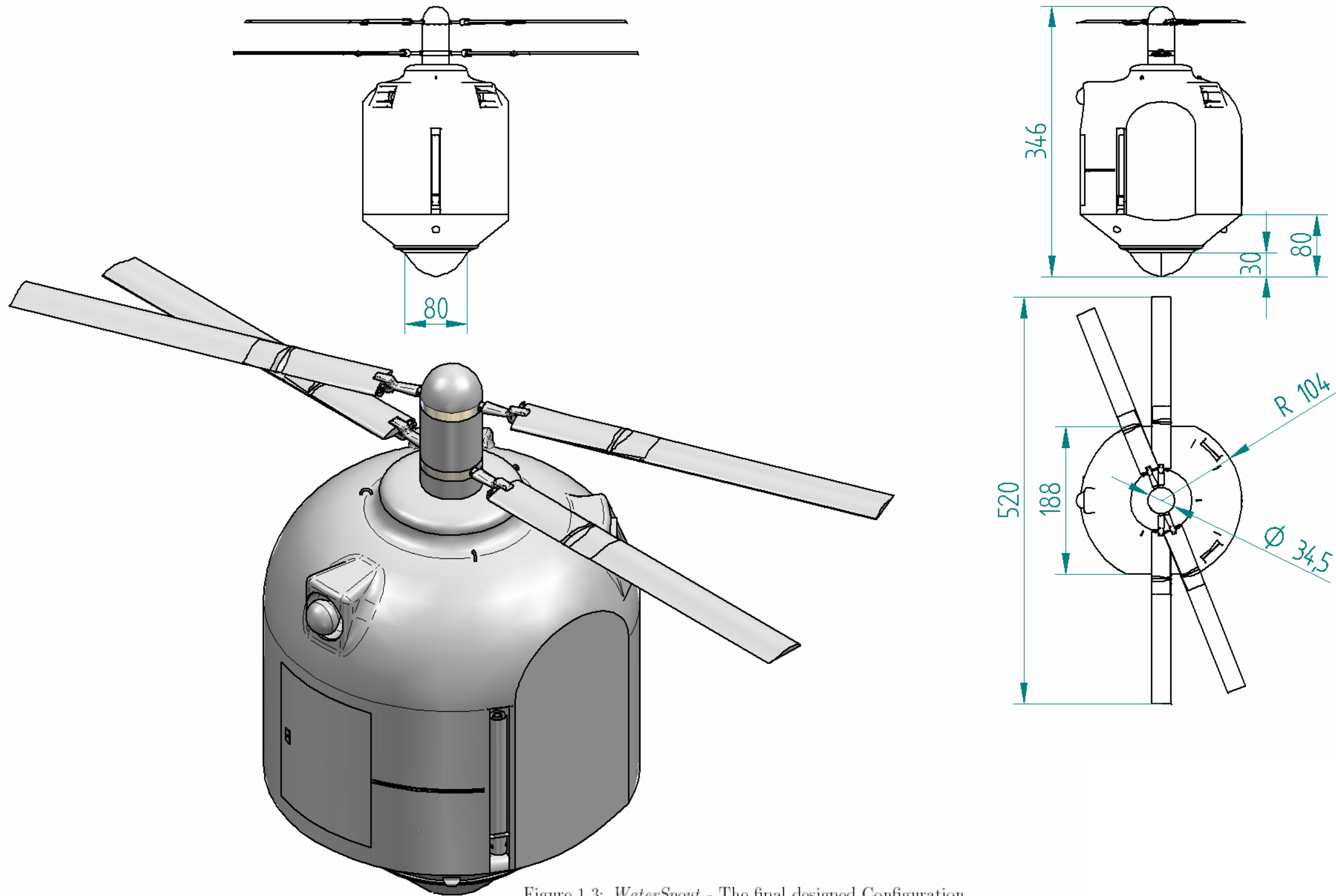


Figure 1.3: *WaterSpout* - The final designed Configuration

## 1.3 Mission

Using the ARV, SOF teams would move directly from a submerged submarine to the objective as swiftly as possible and recover back to the submarine without being detected. The different stages for completing this mission, partly specified in the RFP [1] and derived from our design are described below:

### 1.3.1 Pre-launching preparations

#### Loading and Unloading

The *WaterSpout* ARV will operate from a sea based platform - an Ohio class SSCN submarine (Figure 1.1). When loading or unloading the vehicle, it is connected by a cable to a crane. The cable is attached to the vehicle at 3 points on the perimeter of the upper fuselage, grasping the vehicle in such a way that enables easy inserting of the vehicle through the launch hatch. The process of the vehicle entry is very similar to the process of the Trident missiles entry to the sub in current operations (Figure 1.1(b)).

**Submarine Dock:** The loading and un-loading of the ARV from the SSCN will be done through the launching hatches. In a way similar to the current loading of the Trident missiles, using a crane. The vehicle would be carried by the crane, positioned directly over the launch hatch, and placed on the retrieval mechanism (see Section 3.2) that will lower the ARV into the submarine. There it can be stored in special storage compartments (as described in Section 3.3), or in the launching silo ready for mission.

**C130:** The ability of SOF aviation assets to be rapidly deployed in theater is essential, therefore our ARV should be transportable via a C-130J aircraft. Designed to fit in it's internal cabin, the vehicle would be rolled on and off the C-130J, blades folded or detached, via the back door and transported to the SSCN location.( Figure 1.3.1 shows *WaterSpout* ARVs stored in the C-130).

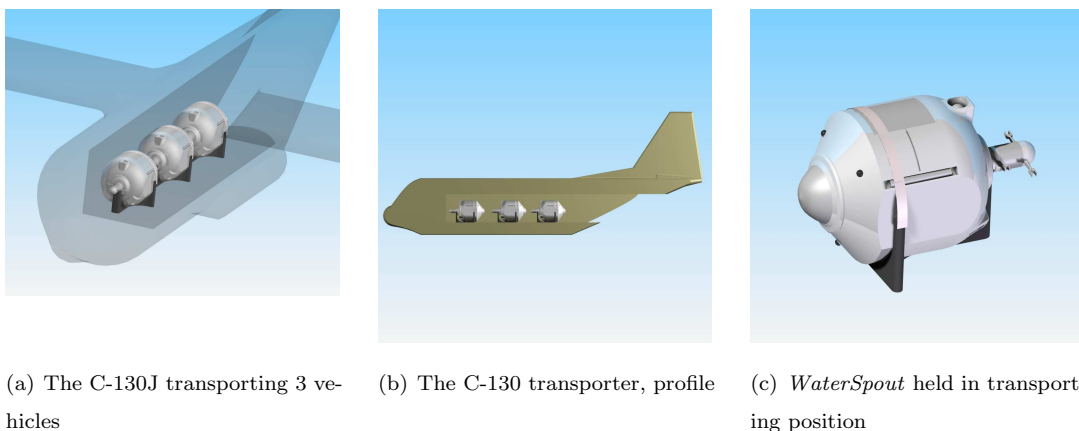


Figure 1.4: The C-130J transporting the ARVs

## **Transport in Sub**

Inside the SSCN the rotorcraft can be moved between the storage space, hangar, and launch/retrieval station, using a specially designed wheeled carrier. This mobile structure was designed for vehicle transportation, easy maintenance, and easy storage. In case a mission is received and the ARV is in storage it can be easily moved to the launching pad on such a structure.

## **Crew Entrance**

When called for mission, the vehicle is designed to be capable of launching within 30 minutes. The 2 SOF crew members carrying the task appropriate equipment enter the ARV located below the launching compartment through the vehicles' sliding door located on its side, placing the equipment in their compartments and taking place in their seats (see Section 2.7). Once ready for launch, the rotorcraft doors are closed and sealed, and the ARV is then elevated into the launch compartment, which is finally locked and sealed as well.

## **Launch Compartment Flooding**

With the rotorcraft held tightly in place, doors locked and safely sealed, the launch compartment flooding system is turned on allowing water to moderately flood the compartment, while the vehicle is raised by platform to the silo exit on the top of the launching tube (see detailed design in Sub-Section 3.2.1). In such a way, once the launching hatch is opened and the vehicle is placed in the right position preventing it from bumping into the openings edges, it is free to float toward the water surface.

## **From Hatch to Surface**

Using only its positive buoyancy the ARV begins to float to the surface while connected to the submarine by cable for restraint (see Sub-Section 3.2.1). When the vehicle reaches the water surface the flotation devices (Figure 3.3) deploy allowing float stability even in harsh sea conditions. The cable disconnects once the vehicle is safely floating on the water surface.

As seen in Figure 1.5 the whole process of preparing the vehicle for launch starting with the crew entering, up to the point the ARV is released should take a maximum of 10 minutes. Thus leaving approximately 17 out of the 30 allotted minutes for any other preparations that may be required (for example: setting the vehicle mission on the computer or additional equipment loading). Note that the time frames in Figure 1.5 are thoughtful estimates for each stage, made after some group discussions.

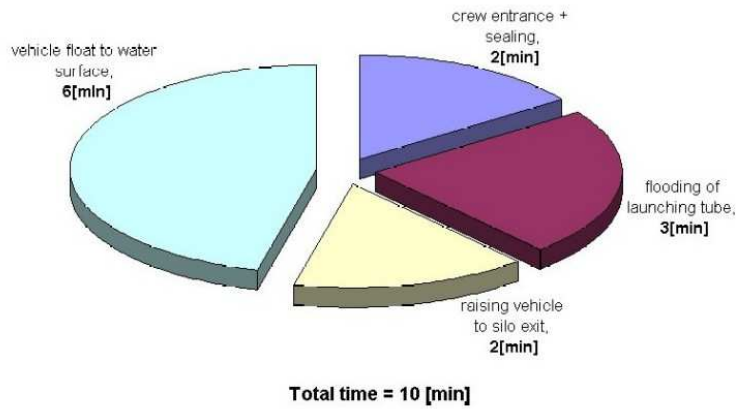


Figure 1.5: Time division from task receipt to launch

### 1.3.2 Task Execution

#### Vehicle Takeoff

The Vehicle is designed to be capable of take-off within 10 minutes after being positioned on the water surface. Once floating, the vehicle's intake and exhaust are un-sealed, the rotor blades unfolded upwards, and the engine is started and warmed up. In case if arctic weather, the intake, exhaust, blade folding joints, and landing gear joints are de-iced first (described in detail in Sub-Section 2.3.1). Once obtaining the required RPM the vehicle can take off. As seen in Figure 1.5 this process should take a maximum of 5 minutes. Thus leaving 5 of the 10 minutes stated above for any other preparations that may be in need (for example - de-icing larger ice accumulations).

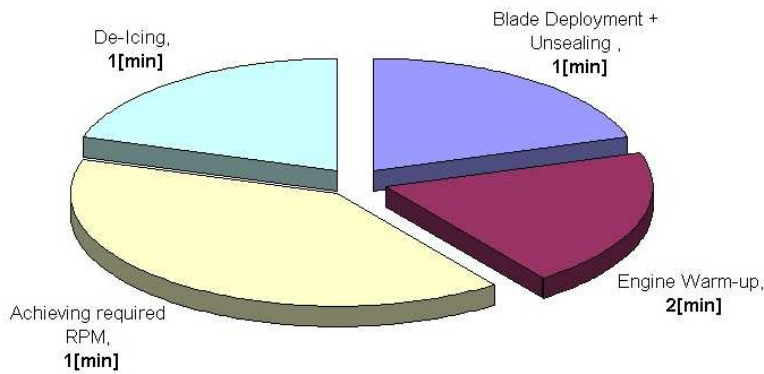


Figure 1.6: Time division prior to take-off

## Vehicle Cruise

The RFP [1] states the vehicle's flight objective is 140[nm], undetected low altitude cruise to the pre-designated location. Once there, a mid-mission HOGÉ is performed in order to pick up or deploy the troops. The last part is a similar flight back to the submarine.

## Deployment and Pick-up of Troops

Deployment of SOF personnel from the rotorcraft as well as the picking up can be performed via one of 2 doors: the outward opening door placed at the bottom of the ARV, or the sliding door on the vehicles' side (door design specified in Sub-Section 2.7.3)

**When in Mid-Air:** Deployment of the crew members at the objective when the rotorcraft is hovering in air is via a winch connected to the top of the crew cabin, dropping the crew members one at a time through the bottom door. The crew members shall be fitted with a special harness over their torso and will control the hoist system themselves (see Sub-Section 2.7.4). The very same method is used to pick-up the crew returning to the SSCN, as well as picking up injured personnel.

**When Landing:** Deployment of the crew when landing will be made through the side sliding door placed 1.30[m] above ground, (Sub-Section 2.7.3) activated automatically or manually by the crew. The SOF will slide from their seats out to the ground using a bar placed above the door. Due to the doors height, they can also easily enter the ARV when they are picked up.

## Mission Abort

In case of emergency the ARV is fitted with a manual interface enabling takeoff aborts and/or recovery wave-offs for any mission plan. In this case the vehicle will either retrieve to the submarine, or land on the ground using the landing gears folded on the side of the body (Sub-Section 2.8), according to the emergency that is in place, and a pre-designated location and flight plan that are programmed on the automatic flight computer.

### 1.3.3 Retrieval

Once the crew members have safely entered the ARV, the vehicle can perform the flight back to the submarine location in order to land on the water surface (stabilizing itself using the flotation buoys, Sub-Section 3.1.2). Once it has landed on the water surface the vehicle is designed to be capable of receding beneath the water surface to the submarines entrance hatch in 10 minutes. The deviation of these allotted 10 minutes is shown in Figure 1.7, this time frame is easily met in our design for this challenge (note that two catching trials of the vehicle were considered, and that the time it takes the vehicle to reach the submarine may be shorter since it depends on the pulley on the submarines side, and thus can be shortened considerably).

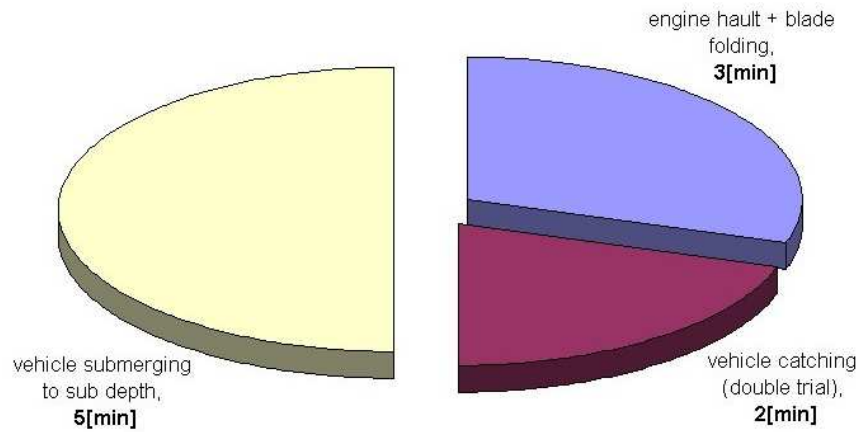


Figure 1.7: Time division from landing on water until fully descended

### Attachment to Retrieval Mechanism and Descent

As the vehicle lands on the water, the retrieval mechanism homes on a light-beacon at the bottom of the ARV (a simple led that may be infra-red to avoid detection), and floats toward it until a connection is established (detailed in Sub-Section 3.2.1 and visually presented in Figures 3.8 and 3.9). Then it is pulled down through the water by a cable ,descending moderately until reaching the platform which is positioned on the top of the launching compartment (see platform design in Section 3.2, specifically in Figure 3.8(a) and.

### Slide down the Tube

Once the vehicle is safely secured on the platform (guided by the cable), the platform is lowered down the tube until reaching the tubes sealed bottom door(Sub-Section 3.2.1). Then the tube is emptied from water, and the bottom door opens. The vehicle, still sat on the platform, is lowered to the carrier based beneath the launching tube (for additional details the reader is referred to Section 3.2).

A detailed, self explanatory, section-view of the different *Waterspout* compartments can be seen in Figure 1.8.

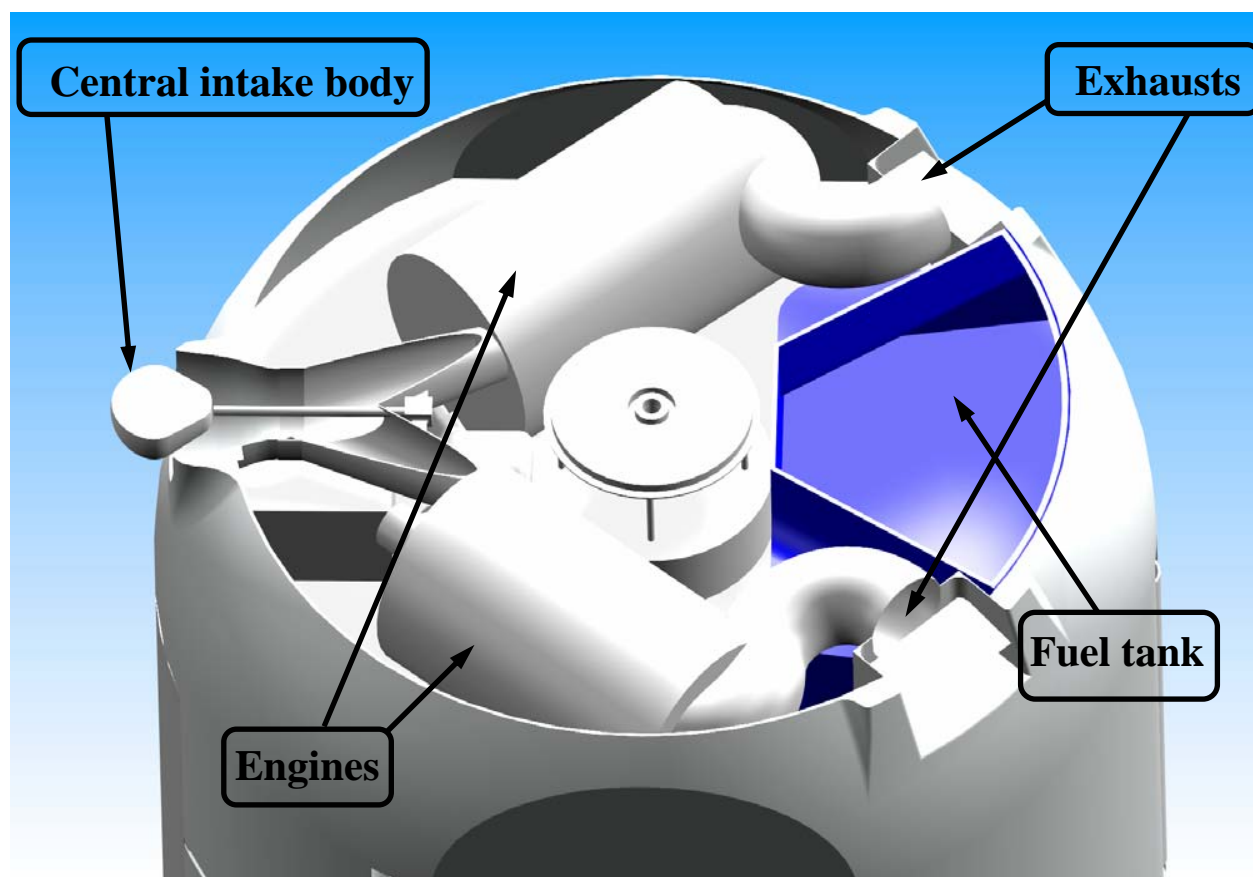
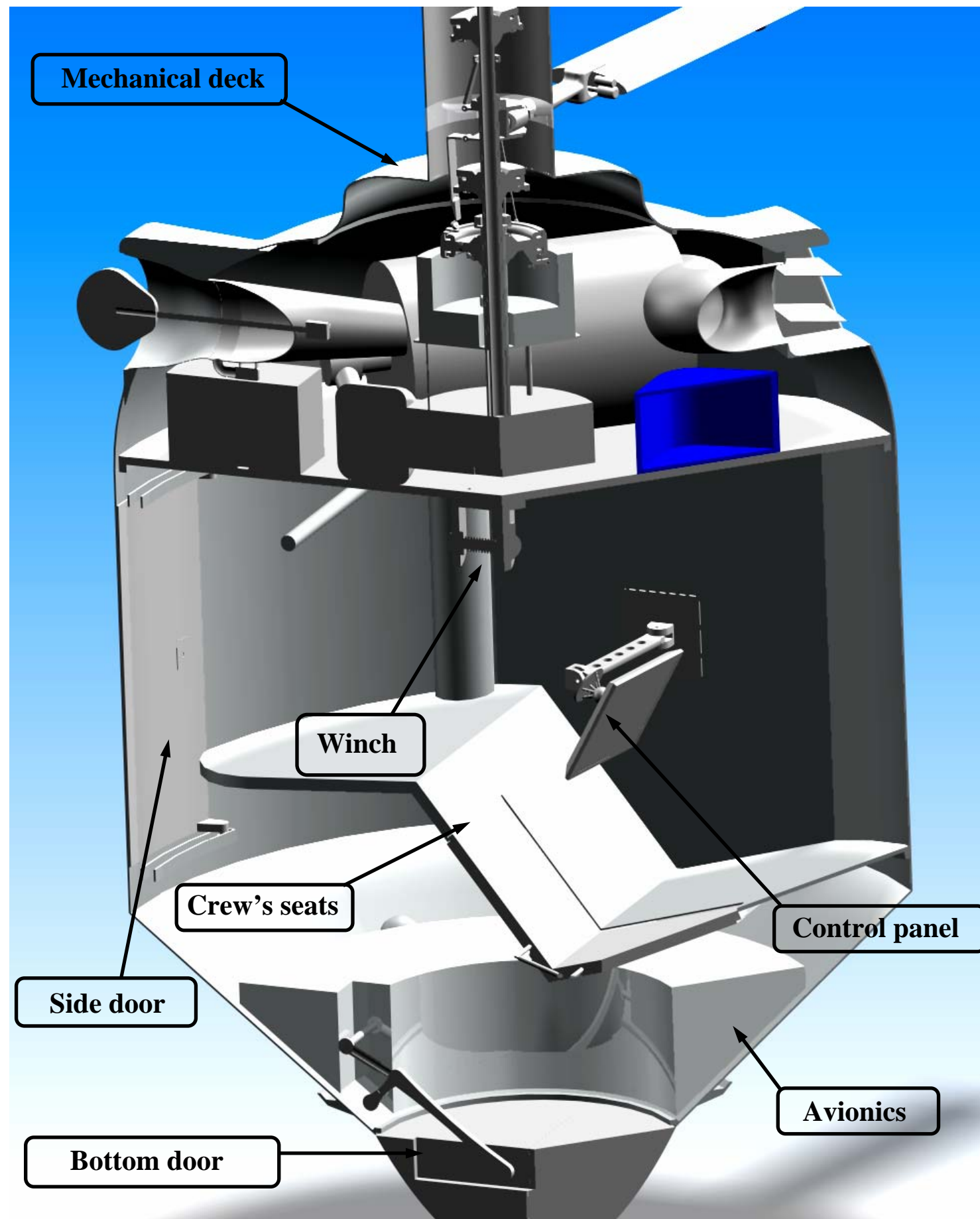
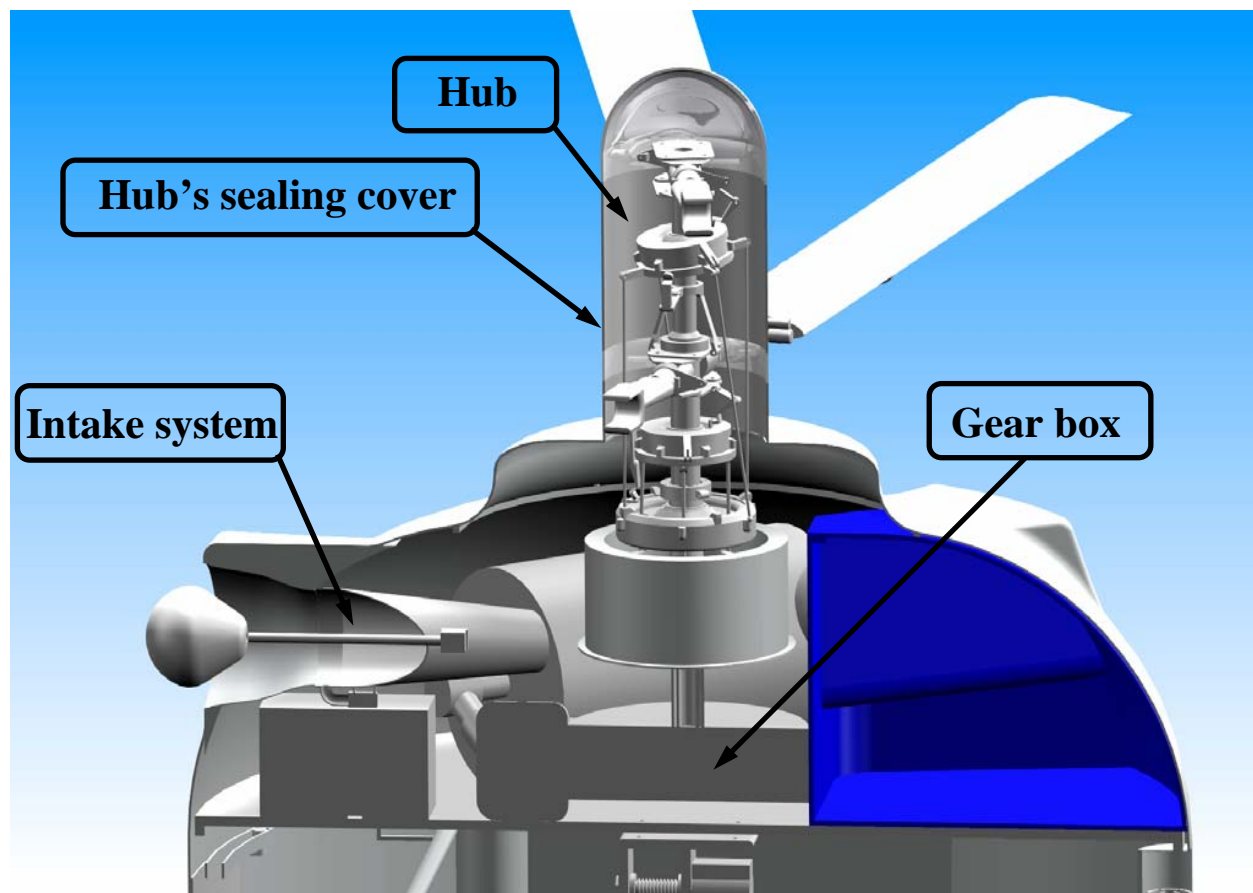


Figure 1.8: *WaterSpout* - sectioned view of the different compartments.

## Chapter 2

# Waterspout Design Characteristics

## 2.1 Aerodynamics

### 2.1.1 Preliminary Rotor and Performance Specifications

The computational tool used for this analysis was based on momentum theory, adjusted for coaxial rotor configurations. The three major topics emphasized when designing the *Waterspout's* rotor were: low noise signature (stealth), reasonable cruise velocity, and good maneuverability. Maneuverability was considered a major focus point due to the fact that a military helicopter must be able to maneuver well while in vulnerable situations. A high cruise velocity is always a leading design point for all helicopters, especially military ones (mission timing, and fuel efficiency).

For acoustic considerations, it was decided that the rotor tip speed would be  $183[m/s]$  or  $600[ft/s]$  [3] (compared to  $700[ft/s]$  for the Robinson R22, or  $680[ft/s]$  for the Hughes 500E [4]). Lower tip speed produce weaker tip-vortices and thus reduces blade vortex interaction, and subsequently vehicle's noise (in addition, the tip Mach number is lower, thus reducing the noise caused by compressibility effects). Maximum climb velocity was used as the main parameter to determine the *Waterspout's* maneuverability mainly because it relies on available excess power: higher max climb velocity means higher excess power available which means that the helicopter will also have more power to maneuver (this approach was also mentioned by Prouty [4]).

Figure 2.1 shows that the G.W. of the *Waterspout* is at a minimum when the rotor radius is at  $9.5[ft]$ . Decreasing the rotor radius below  $7[ft]$  resulted in the inability of the helicopter to fly the specified mission. From Figure 2.1 it can also be seen that increasing the radius above  $10[ft]$ , results in a large drop in cruise velocity along with the exponential increase in G.W.. Although the  $7[ft]$  radius can obtain the highest velocities, the vehicles fuel weight, engine/transmission weight, and thus G.W. becomes very large. The  $7[ft]$  rotor is also much too close to the boundaries of the mission to hold true to the conservative approach to the design. Figure 2.2 illustrates the fact that the excess power available is the greatest for the smallest rotor radius. From this information, it

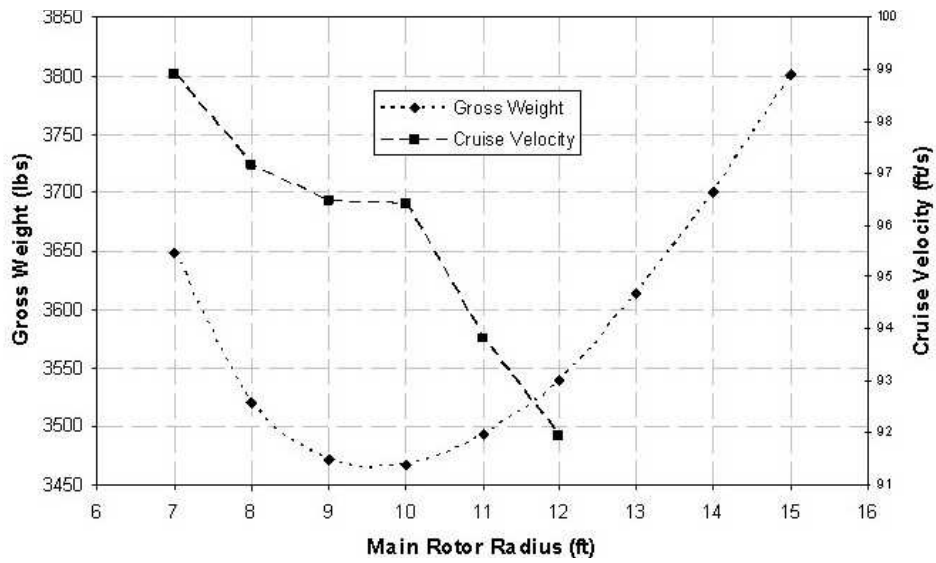


Figure 2.1: Gross Weight and Cruise Velocity variation with increasing rotor radius

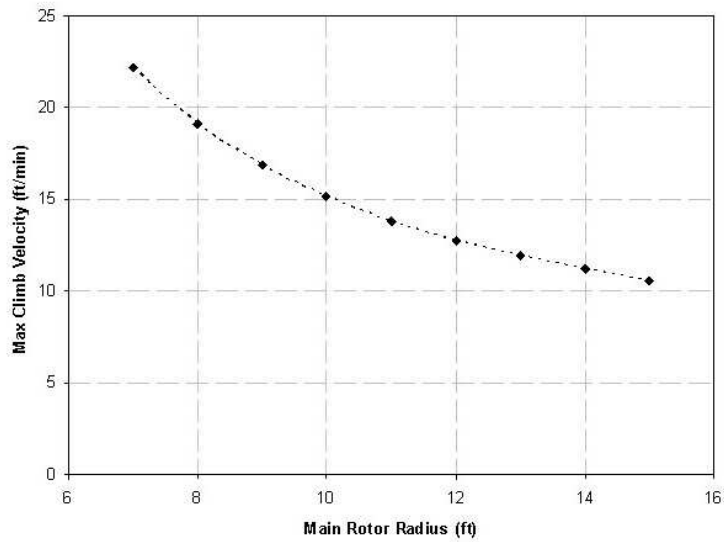


Figure 2.2: Max Climb Velocity variation with increasing rotor radius

was decided to focus on the radii between 8[ft] and 10[ft]. In this region, the rotor size with a good cruise velocity, low G.W., and good maneuverability could be determined.

These plots show that if the radius is reduced to 8.5[ft] then a small increase in cruise velocity and excess power can be obtained for only a small increase in G.W.. Any further decrease in radius causes an increasingly larger G.W.. Therefore, due to the main focus points of the rotor design, it was decided to take the small increase in G.W. to increase the cruise velocity and maneuverability of the *Waterspout*, and a rotor radius of 8.5[ft] was decided upon. The major characteristics of the *Waterspout* are shown in Table 2.1. Detailed vehicle weights are summarized in Table A.1 in Chapter A.

Main Rotor Radius	8.5[ft]
H/D	0.11
Number of Blades (for each rotor)	2
Tip Speed	600[ft/s]
Gross Weight	3570[lbs]
Cruise Velocity	100[Knots]
Max Climb Velocity	1100[ft/min]
Fuel Weight	595[lbs]
Disk Loading (upper rotor)	7[lbs/ft <sup>2</sup> ]
Engine Power	MRP : 660[HP], MCP : 504[HP]

Table 2.1: *Waterspout* Characteristics with conservative FM=0.75

For the design of the mechanical deck, the *Waterspout* will make use of two engines due to several considerations such as better space utilization, reducing heat signature (separate emission exhausts and enhanced mixing with downwash). This part is explained and illustrated in detail in Sub-Section 2.5.1 and Sub-Section 2.2.4. In addition, the final rotor distance design parameter was changed and is  $H/D = 0.077$  which is slightly lower than initially designed. This came from the desire to keep the helicopter as short as possible, hence the rotors were made closer. However, this should not harm the performance significantly [5].

Moreover, the final design weight of the *Waterspout* is estimated as / 1200[Kg], taking into account the final weights of all parts and mechanics, in addition to the weights that are stated as mandatory by the RFP [1]. Any excess power available as a result of this estimation can be easily attributed to an additional maneuverability of the final rotorcraft design only attributed to an additional maneuverability of the final rotorcraft design.

Maximum mission time (according to the RFP specifications), includes: 4 minute idle engine warm-up, take-off and 2 minutes HOGE, 1 hour and 40 minutes cruise to destination, 4 minutes HOGE, 1 hour and 40 minutes cruise back to submarine location, and 2 minutes HOGE including landing. The total time for the *Waterspout* is therefore: 3 hours and 32 minutes, with an additional

20 minutes worth of fuel to spare (also required by the RFP).

### 2.1.2 Airfoil Selection

Most previous coaxial helicopters in the United States used symmetric airfoils such as the NACA 0012 used on the Gyrodyne QH-50 drones [6]. The Russian company, Kamov, have been using NACA 23015 for the root and NACA 23012 for the tip airfoil sections on their line of coaxial helicopters [7]. These were not symmetric airfoils and offered improved lift and L/D ratios while at a cost of higher pitching moment. Single main rotor helicopters of our weight class have also mainly been using NACA symmetric or 5 digit variants to allow for a simple and low cost rotor design and predictable performance [8].

For the *Waterspout* the airfoils listed below were selected for their relatively low pitching moment, low thickness and high drag divergence Mach number. For all these airfoils the aerodynamic coefficients and characteristics were calculated using JavaFoil [9]:

- NACA 23012, 23015, 23018
- OA 206, 209, 212, 213
- Clark Y H, Y Smooth
- FX 05-H-126, 66-H-60, 66-H-80, 68-H-120, 69-H-083, 69-H-098
- NLR 1T, 7223-62, 7223-43
- SSCA09
- VR12

The airfoils were compared against each other for the minimum drag coefficient, maximum lift coefficient, pitching moment at maximum lift, thickness and lift-to-drag ratio. The final airfoil selection was based on a low thickness ratio for the tip airfoil for acoustic considerations and an inboard airfoil with a high L/D ratio. The tip airfoil selected was the NLR-7223-62 with a thickness ratio of 8.6% and the inboard airfoil selected was the FX 05-H-126 with a predicted max L/D ratio of 72. Both airfoils' data are presented in Figure 2.3.

### 2.1.3 Blade Design

Based on the performance evaluation code (Sub-Section 2.1.1), the recommended blade radius was 2.6[m] with a tip velocity of 183[m/s]. These numbers were used throughout the blade's aerodynamic design. The number of blades per rotor was set to two; this result was a product of space constraints (external hatch diameter), folding mechanics, and stowage ease (Sub-Section 1.2.1). The blades were to be comprised of two different airfoil sections, the inboard being the FX 05-H-126 airfoil for its relatively high maximum lift and also L/D ratio (Figure 2.3) and the tip being the NLR-7223-62

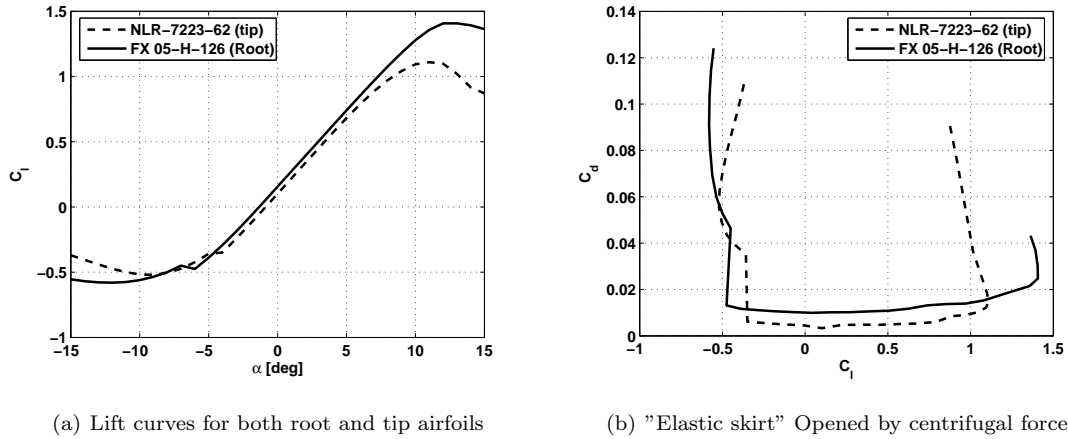


Figure 2.3: Drag polar plots for both root and tip airfoils

for its low thickness ratio (Sub-Section 2.1.2). This section completes the blade design parameters: twist rate (assuming linear twist), effective solidity, taper ratio, and airfoil transition location. The entire blade design was intended for the  $6[Kft]/95^\circ F$  conditions as a conservative estimate.

The developed blade element momentum theory based code already included tip loss effects using the Prandtl tip loss factor equation [10]. It also included a provision for a root cut-out which was set at  $1.3[ft]$ . This was mainly done to account for fuselage blocking. Aside from the BEMT code another code was developed to determine the various sectional Reynolds number for varying effective  $3/4$  span solidity and taper ratios. This was done to ensure that the chord length of the blades would operate at Reynolds numbers within the regime of the lift curves and drag curves generated through JavaFoil (Sub-Section 2.1.2).

Radial Reynolds number variation for varying taper ratios for effective  $3/4$  span solidities of 0.01, 0.05, 0.1 and 0.15 respectively were calculated. The Reynolds number range across the blade for the different effective solidities is only valid for effective solidity values of 0.1 and 0.15. However for these particular effective solidities the chord length varies significantly for various taper ratios. For taper ratios above 1.5 in the case of an effective solidity of 0.1 the chord lengths are too big to be realistic. The same applies for a effective solidity ratio of 0.15 wherein the chord lengths are too big for a two bladed rotor set. Therefore based on this observation it was determined that the optimal  $3/4$  effective solidity was 0.1 and the optimal taper ratio was 1.5. The average Reynolds number is 3.3 million (based on average blade chord) which is quite typical. The root and tip chords are  $1.6[ft]$  and  $1.3$  respectively (note that taper is calculated from the rotor center point, and the blade's root is  $1.3[ft]$  outboard of the center point thus the geometric taper ration is 1.23).

In order to allow for a conservative estimate, each rotor set was set to produce a lift of about  $790[Kg]$  which is approximately 50% of the aircraft initial weight estimate (as stated in Table 2.1, final weight is much lower, about  $1200[Kg]$ , as stated in Sub-Section 2.1.1). As seen in Figure 2.4, FM generally rises for any particular value of twist rate but then at a transition location of approximately

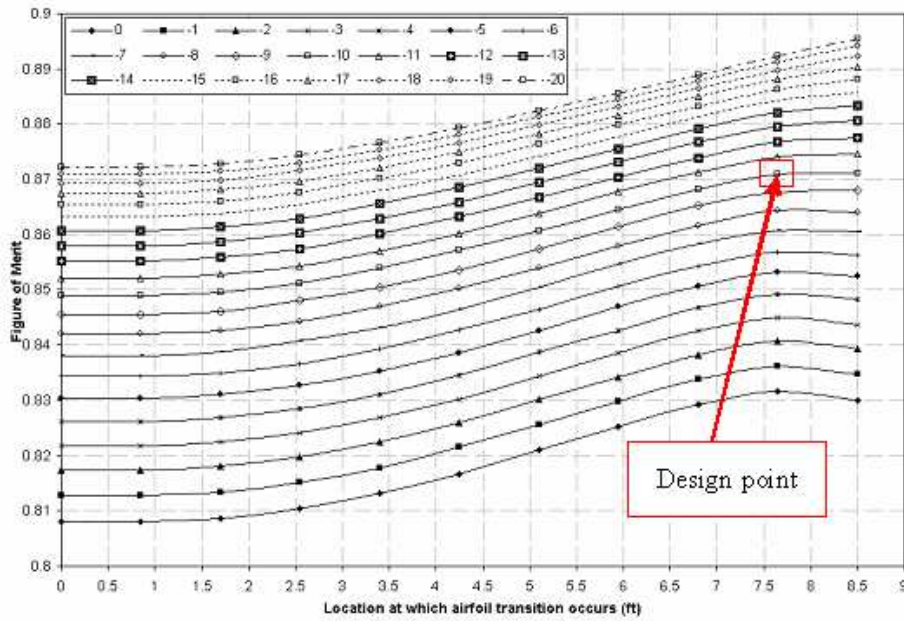


Figure 2.4: Figure of Merit variation as a function of airfoil transition location for various twist rate values.

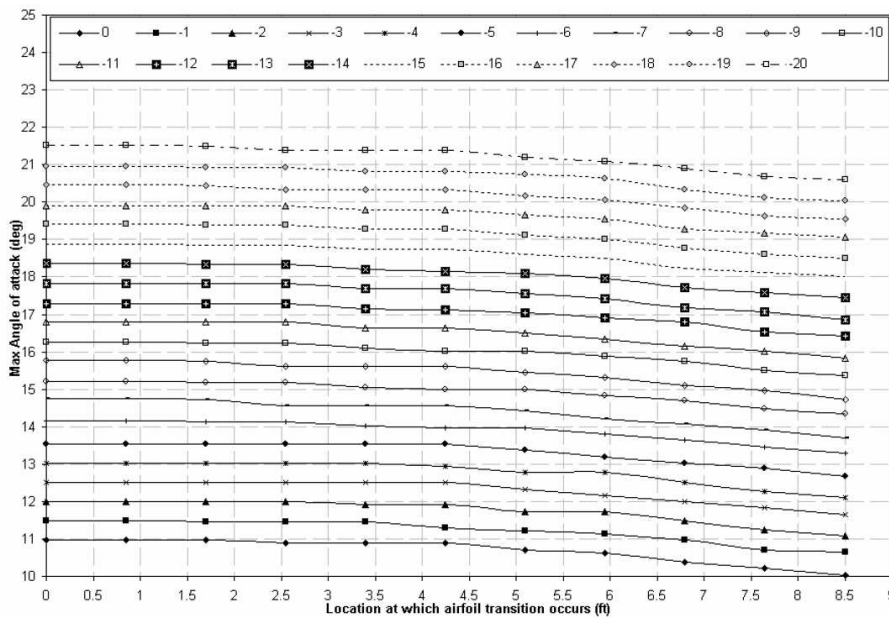


Figure 2.5: Maximum sectional  $\alpha$  variation as a function of airfoil transition location for various twist rates values

2.33[ft] it begins to drop down for lower values of twist rate, therefore this would be an optimal location for the airfoil transition (Figure 2.5). Although the FM values are significantly higher for larger twist rate values, the higher values of twist rate reduce the margin between the local AoA of attack and the stall AoA (Figure 2.5) hereby reducing maneuvering capabilities. Therefore taking this into consideration a twist rate  $-10^\circ$  was picked as its max local AoA for the various airfoil transition locations was between the ranges of  $6.5^\circ$  and  $6^\circ$ .

### 2.1.4 Flight Stability Characteristics

Despite known qualities like improved stability and handling qualities, due to the constraints of fitting the *Waterspout* inside the external hatch dimensions, the decision was not to fit the vehicle with a horizontal stabilizer or a vertical fin. The addition of these surfaces would require complex folding mechanisms that would reduce design simplicity.



(a) Bell 47B



(b) Gyrodyne QH-50 coaxial helicopter

Figure 2.6: Existing helicopter without stability surfaces

Examples of popular helicopters, without horizontal or vertical stabilizers include the Bell Model 47 "Sioux" from the 1950's and 1960's (Figure 2.6(a)), used by over 30 mil

To determine the hover stability a simple mass-spring-damper system was considered. Rotor stability derivatives were solved for obtaining a characteristic equation. The full equation is a fourth order polynomial, simplified by Prouty [4] to a second order polynomial with very little effect on accuracy. First, the helicopter is assumed to be constrained vertically so all of the Z-Force equations can be eliminated. Next, the equation can be further simplified by assuming the helicopter operates like a pendulum and has a single degree of freedom (mass + spring). This gives the second order characteristic equation:  $-\frac{\partial M}{\partial q} s^2 + g \frac{\partial M}{\partial \dot{x}} = 0$

Where the natural frequency is:  $\omega_n = \sqrt{\frac{-g \frac{\partial M}{\partial \dot{x}}}{\frac{\partial M}{\partial q}}}$ , and the period of oscillation is:  $P = \frac{2\pi}{\omega_n}$

Moreover, using a Routh's discriminant analysis stability/instability of the helicopter may be found: stable for  $\frac{\partial M}{\partial \dot{x}} < 0$  and unstable for  $\frac{\partial M}{\partial \dot{x}} > 0$ . The stability analysis has been completed



-0.5[ft] to 0.5[ft] in the x-direction and 0[ft] to -8 in the z-direction. Above these values the code could not converge on a solution. The collective pitch input as well as the aircraft orientation ( $\alpha$  and  $\phi$ ) were then observed for non-physical results. It was generally found that the variation in the required collective pitch input and the  $\phi$  values were in the feasibility range. However for some cases it was found that the  $\alpha$  values were non-physical.

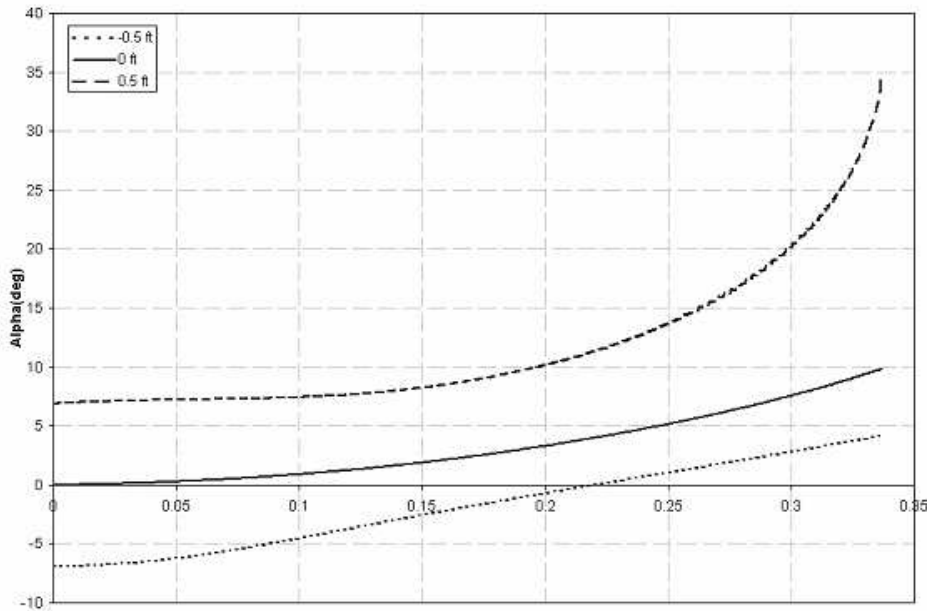


Figure 2.8: CG location variation in the x-direction

As seen from Figure 2.8 there is a large variation in the  $\alpha$  angle of the aircraft for larger values of forward velocity. However, this angle jumps up to non-physical values for the case of 0.5[ft] C.G. offset in the x-direction. Therefore it can be concluded that the trim characteristics of the aircraft become very poor for large C.G. offsets in the x-direction especially if it is forward of the rotor shaft. According to the trim calculation results, the x-direction C.G. offset limits are 0.5[ft] in the aft direction and 0.4[ft] in the forward direction. With the variance of the C.G. location in the y-direction it was found that the  $\alpha$  and  $\phi$  ranges were feasible and therefore the bounds were set to be -1[ft] to 1[ft], although this range could be set to be larger it would require trim  $\phi$  values that were larger than  $3^\circ$  or less than  $-3^\circ$ . Lastly C.G. variance in the z-direction did not produce a significant change in trim  $\alpha$  or  $\phi$  values for a large range of forward speed. This led to the conclusion that the limits on the z-direction C.G. location are bounded only by the physical dimensions of the aircraft.

## 2.2 Structural Design

### 2.2.1 Exterior Shape

As mentioned before (Sub-Section 1.2.2), our vehicle is a counter rotating coaxial helicopter in a shape of cylinder with a cone-shaped bottom. The outer shape of the vehicle was chosen inspired by the Canadian CL-227 UAV [11] Figure 2.9. After deciding that the outer sub hatch would not be altered, this shape allows our concept to be launched vertically, thus eliminating the 90° turn on the way to the surface. The bottom of the vehicle is cone shaped in order to provide easier takeoff from the water and would pierce the water skin tension on landing (spearing the water surface). Furthermore, the symmetrical shape means that the vehicle can fit into the launching tubes in any azimuthal angle relative to the sub. This eliminates the need to navigate through water in more than two degrees of freedom: vertical and vertical relative tilting angle. No azimuthal control is required.



Figure 2.9: Canadian CL-227 UAV

### 2.2.2 Interior Structure

The interior structure is comprised of 8 reinforcement vertical beams, and 4 beams on the circumference, on which the vehicle's skin is assembled. The circumference also serve as the baseline for the mechanical deck floor, crew cabin floor, and bottom doors assembly. The skin of the vehicle is about 10 [mm] thick, made up of 3 layers:

1. A layer that is against Radar signal, specified in Sub-Section 2.2.4.
2. A layer of composite material, the actual coating of the vehicle, specified in Sub-Section 2.2.3.
3. A layer of isolation material, specified in Sub-Section 2.3.1

### 2.2.3 Skin and Materials

In order to minimize the vehicles body weight, composite materials were chosen for the *Waterspout* skin. Using Kevlar was considered due to it's potential invisibility to RADAR radiation, good weight to strength ratio, and high crashworthy qualities. On the other hand, Kevlar has a disadvantage in water absorbance, and is also very expensive. Thus, graphite epoxy was examined. Graphite epoxy has a better weight to strength ratio and it is commonly used. The vehicle has to withstand under 25[m] water pressure, causing a uniform pressure of 0.15[MPa] (considering an existence pressure of 1[atm] in the vehicle). In order to assure durability of the body to sudden impacts and to ease insertion of rivets, it was decided on no less than 2[mm] of the vehicle skin. Once proven that the buckling load of a 2[mm] vehicle skin is about 21[MPa] and no buckling scenarios is assured( [12] and refering [13]), the 2[mm] graphite epoxy skin was set.

### 2.2.4 Stealth

Stealth was pointed out as a major requirement in the RFP [1] since the ARV is in support of covert operations performed by SOF personnel. Stealth can be achieved by passive or active methods. In this section, only passive methods are discussed and the reader is referred to active methods using avionics components in Section 2.6.

In order to remain undetected from radar radiation a special honeycomb radar-absorbing skin coating was selected: C-RAM HC. This coating is highly absorbent in a wide range of wavelengths and is also light-weight (nominal density of 4.5[lbs/ft<sup>3</sup>], for additional details the reader is referred to Ref. [14]). The required thickness of this material was also considered as part of the heat analysis in Sub-Section 2.3.1 (see also Fig. 2.11). In addition this material is waterproof [15] which means that the outer coating can also withstand the contact with the water.

Another important stealth-related issue is the heat signature, due to the use of infra-red guided missiles. Most of the heat generated by the helicopter originates from the engine emission. In order to reduce the heat signature, the emission is mixed with fresh (and much colder) air that flows from the rotor downwash with a relatively high velocity (also with the freestream in case of forward flight). The mechanical deck (Sub-Section 2.5.2) was designed so that the two engines will have separate exhaust outputs, thus already dividing the heat signature that would be generated by an equivalent single engine. In addition the exhaust pipes are directed at the maximum possible angle relative to the freestream (Figure 2.14) in order to enhance the mixing between the hot exhaust fumes and the outside air, and also in order to achieve the maximum separation between the two exhaust streams.

For visual stealth, the *Waterspout* is colored in gray which should supply camouflage for the ARV while at sea, in the air, or around desert scenarios (see Figure 2.27 for example). However, it is recommended to use other camouflage schemes for tropical environments where the dominant color is green. Note that the flotation devices in Figure 3.3 are colored in orange only for clarification. The inspiring design for the *Waterspout*, the CL-227, was also known for it's visual stealth characteristics.

Pilots were sent to look out for it but could not spot the helicopter until it was at a range of less than 100[m] from them [11].

Noise signature is expected to be rather low, mainly due to relatively low tip speed of 183[m/s] (see Sub-Section 2.1.1), but also due to the use of two engines, minimizing intakes/exhaust hatches, and the overall shape of the *Waterspout* which should not create much noise due to interaction with the rotors' downwash.

## 2.3 Weather endurance

The RFP requires the *Waterspout* to be operable in all global conditions. This includes arctic, maritime (naturally), tropical, and typical desert conditions. This section describes the solution that were integrated to the *Waterspout* design in order to fulfill these requirements. The most critical conditions that were identified were the arctic ones due to the possibility of ice accumulating on mechanical joints, moving parts or the fuselage. For this reason, these extreme weather conditions were specifically targeted, especially after a “no-capsule” concept was decided upon.

### 2.3.1 Heat Transfer Analysis

One of the design requirements is that the ARV must be mission capable in all global environments including maritime, arctic, tropical, and desert. This part specifically deals with the arctic environment which was pointed out as the most extreme conditions for the *Waterspout* mainly since it will come in contact with water at the critical stages of take-off. Anti-icing refers to the prevention of any ice buildup on any surface during flight while De-icing denotes removing ice that has already formed on a surface. Ice might block mechanical parts, change airfoil shape and balance, or simply add weight, therefore an anti-icing/De-icing system should be implemented, preventing ice accumulation on the blades, fuselage and mechanical systems. The components analyzed ahead are (sorted by importance): blade folding mechanism, hub, engine air intake/exhaust, landing gear (flotation devices), blades, fuselage and low internal temperature.

The power required for heating the folding mechanism, hub, engine air intake/exhaust was estimated and listed below (a calculation example is given for the hub heating):

- electrothermal pads engine air intake/exhaust sealing 1300[W]
- electrothermal pads installed in the folding area requiring 1200[W]
- electrothermal pads installed in landing gear joints requiring 900[W]
- fan installed inside the rotorhead space requiring 202[KJ] calculated by the formula:

$$E_{heat} = [Cp_{air}W_{air} + Cp_{graphite}W_{graphite} + Cp_{steel}W_{steel}]\Delta T \text{ using the constants: } Cp_{air} = 1005[J/(Kg \cdot K)], Cp_{graphite} = 935[J/(Kg \cdot K)], Cp_{steel} = 455[J/(Kg \cdot K)] \text{ (Ref. [16]) under}$$

the assumption of  $\Delta T = 10^{\circ}C$ . Dividing the result by 60 seconds of operation the fan requires 3400Watts.

A common blade heating method was employed using an array of electric heating pads along the blade. Other methods like, the Pneumatic Boot, similar to that found on some fixed-wing aircraft (see [17]). Fluid Anti-icing system is limited by the amount of fluid carried by the rotorcraft, resulting in very short operational time. Moreover, other non-electrothermal solutions are still under development but lack information and validity. Heating the blades is achieved by using an array of electrothermal pads installed fragmentally along the blades, covering 50% of the blade's surface area, and requires 21[KWatts]( [18]). Similar heating elements are shown as an example in Figure 2.10

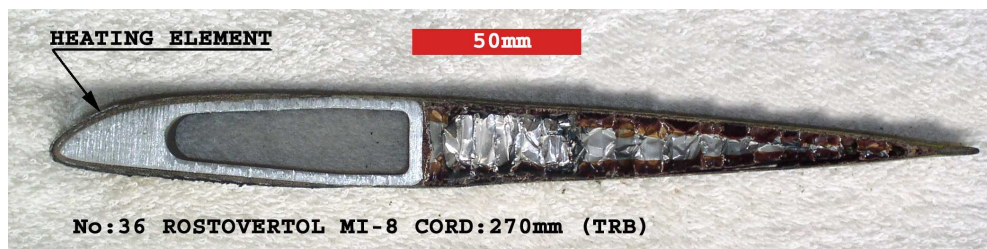


Figure 2.10: Heating element on a MI-8 airfoil section

When flying in extreme arctic weather the interior of the vehicle should be heated to  $15^{\circ}$  in favor of the crew. An analysis was carried out, modeling the fuselage as two concentric cylinders, a one dimensional heat transfer analysis was conducted along the radial coordinate, for the most extreme situation with an outside temperature of  $-20^{\circ}C$ . Skin material is graphite-epoxy (Sub-Section 2.2.3) which has a relatively low thermal conductivity coefficient of  $0.87[W/(m^{\circ}C)]$  compared to  $160[W/(m^{\circ}C)]$  for aluminum. An internal layer for insulation was added, made of Polyurethane foam (as found in FAO-Corporate Document Repository [19]) which is a very light insulator with a low thermal conductivity of  $0.026[W/(m^{\circ}C)]$ . The external anti-radar coating effect was neglected (Figure 2.11). The thickness of the insulation was chosen after some iterations to be  $6[mm]$  and weighs  $3Kg$ . This yields a required power of  $2.5[KW]$ .

During the launch we need to rely on battery power for heating, until the engine starts and powers the generator. Once the ARV is at the water surface we must use the battery for de-icing of the engine intake/exhaust (approx one minute, using the heaters mentioned above). Battery capacity was estimated using the formula  $P_{heat} = V_{heat} \cdot I_{heat} \Rightarrow I_{heat} = P_{heat}/V_{heat}$  which yields  $80[A]$  and  $241[A]$  for both heaters, assuming a regular 28 volts power line. Therefore, batteries should supply  $24[A \cdot Hr]$  which should weigh no more than  $10[Kg]$  (compared to current automobile batteries).

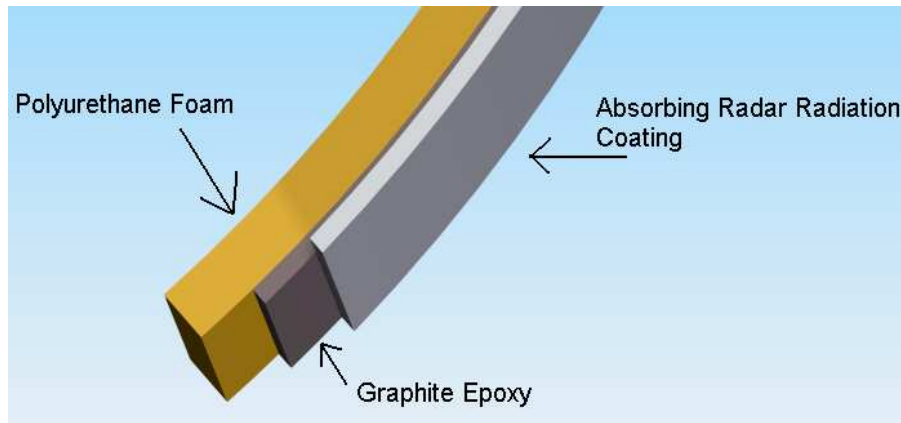


Figure 2.11: Isolation layers integrated into the vehicles skin.

## 2.4 Additional Weather Conditions

The *Waterspout* is designed to operate in all weather extreme conditions.

In case of tropic weather conditions, characterized by high humidity and rain, the ARV is sealed for maritime protection (as detailed in Sub-Section 2.5.2 and Sub-Section 2.5.4 throughout, and in Sub-Section 2.7.3) and equipped with an inner intake water pump (Sub-Section 2.5.2) extracting fluid condensing and accumulation in the engines and mechanical deck. For tasking in desert conditions, where extreme heat and sandstorms are expected, the *Waterspout* crew cabin temperature is kept fairly comfortable by the skin isolation layer, characterized by low thermal conductivity (Sub-Section 2.3.1), and an internal intake filter (not drawn) is installed to prevent dust and sand particles from interfering with the engine and Mechanics.

## 2.5 Mechanical Layout

### 2.5.1 Mechanical Deck Design

Most mechanical systems are placed on the mechanical deck (Figure 2.13), which contributes to shorter shafts and easy access for maintenance using a minimum number of access doors. The engines are installed with a  $60^\circ$  angle between them, in front of the gearbox, thus shortening the shafts, use a common intake for easier sealing, and separate the exhaust in order to reduce infra red signature by enhanced exhaust mixing from both sides of the helicopter (also the relative pressure on the cylinder sides will help the exhaust fumes to leave the pipes).

As mentioned in the performances analysis (Table 2.1), The *Waterspout* requires  $230[Kg]$  (approximately  $500[lbs]$ ) of fuel in order to carry out its missions. The *Waterspout* is equipped with a crashworthy fuel system for minimum damage in emergency situations (Sub-Section 2.5.6). The 290 liter fuel tank is located between the two exhausts of our vehicle, also on the mechanical deck,

in such a shape that maximizes use of the unoccupied volume as seen in Figure 2.14.

## 2.5.2 Engine

During the design process, 2 engines types were considered: turbo-shafts and aviation diesel engines. Diesel engines will have a lower heat signature but their main disadvantage is the power-to-weight ratio. It was estimated that almost 200[*Kg*] will be added to the G.W.. In addition, air cooling for the diesel engines was quite complicated due to the sealing requirements. This would require the use of water cooling which results in another G.W. increase. Therefore the *Waterspout* was designed with two turbo shaft engines of the type offered by the RFP [1]. Engine properties: Power - 330[*HP*], Length - 740[*mm*] Diameter - 460[*mm*] (each engine, according to the formula given in the RFP [1]).

The two engines are installed as shown in Figure 2.14. Both drive shafts connect to the gearbox (Sub-Section 2.5.3). The 90° shaft-turn is achieved using conical sprockets. Each engine also has a overrunning clutch, so that if one engine malfunctions, it would enable the other to work alone. This also enables simple autorotation in the event of losing both engines.

### Engine Intake

The intake is designed with a central body working as an air regulator and sealing method (Figure 2.13). While the intake is open, the central body filters small particles such as sand and dust, preventing them from reaching the engine. The intake has a water separating mechanism which includes a bore with a centrifugal pump in its bottom, pumping the water outside, and a controllable plate which tilts down preventing water from flowing into the engine when the helicopter is at low altitude or even floating (not drawn). Intake sealing is achieved when the central body is pulled back by a servo engine to a tight fit (seen in Figure 2.12).

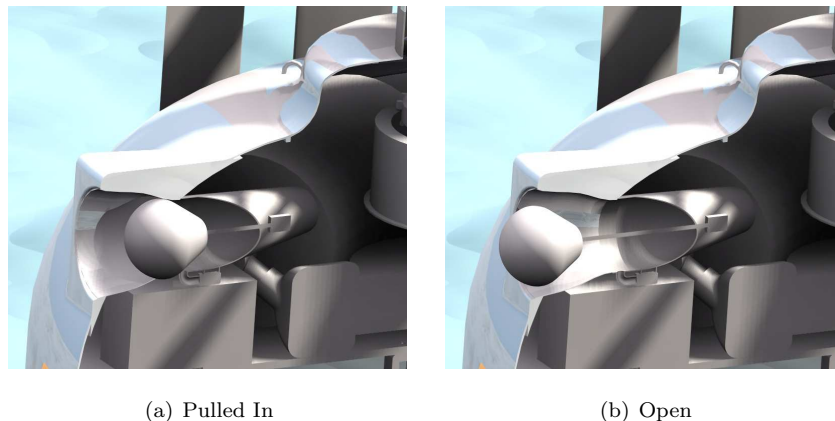


Figure 2.12: The engine intake

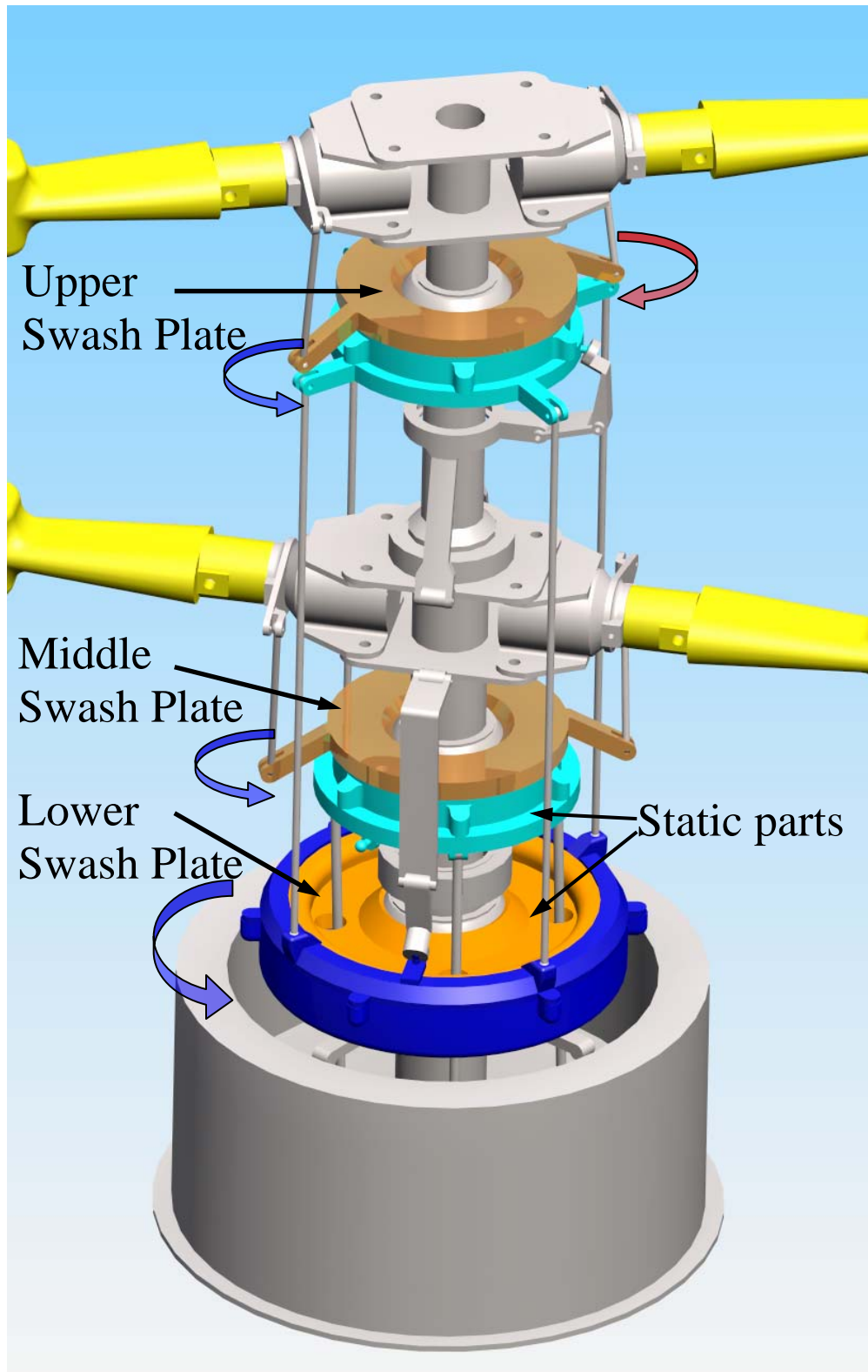


Figure 2.15: Rotor head design



Figure 2.16: Rotor head, sealed

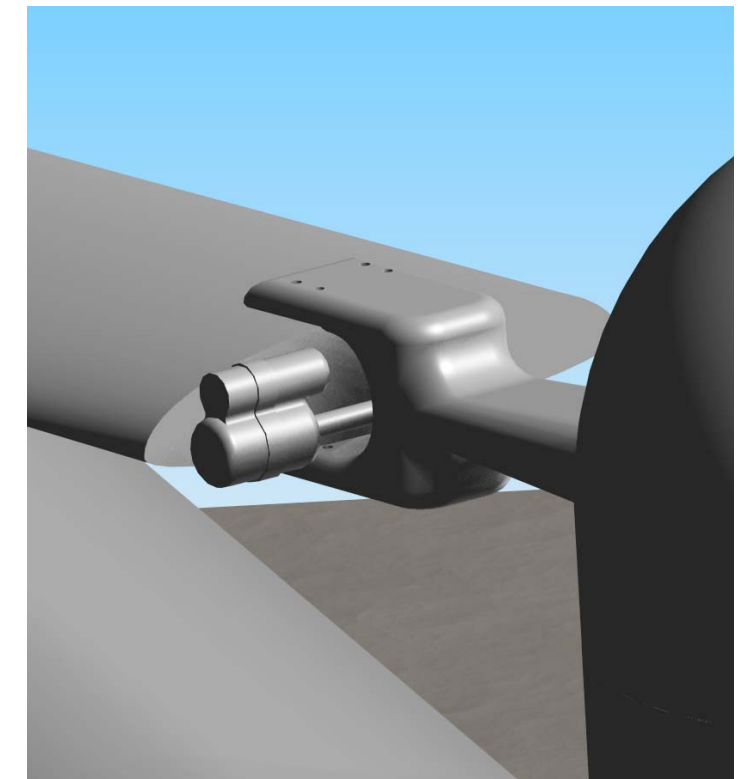


Figure 2.17: The elastic hinge, enlarged

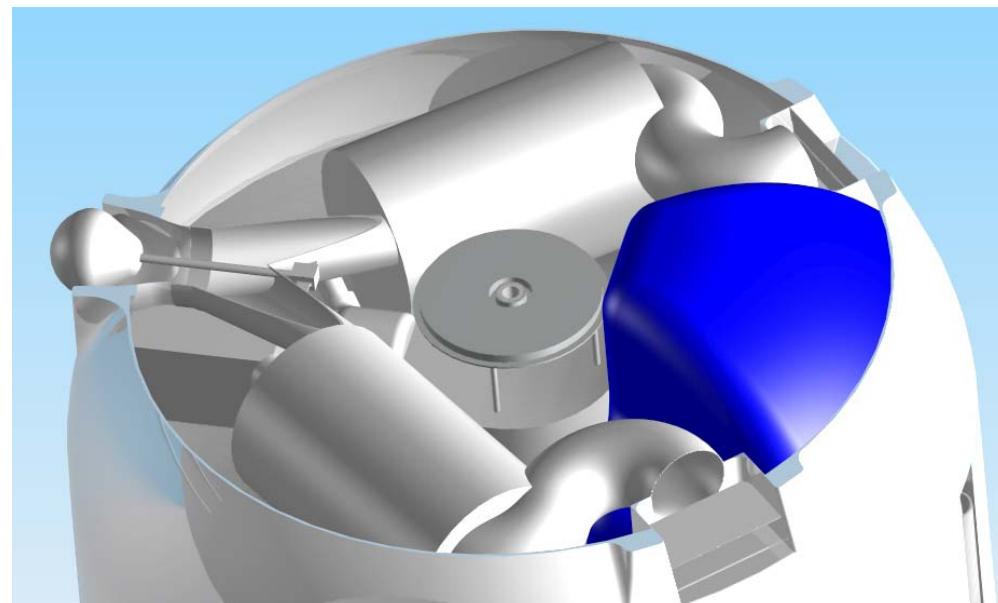


Figure 2.13: A general view of the mechanical deck

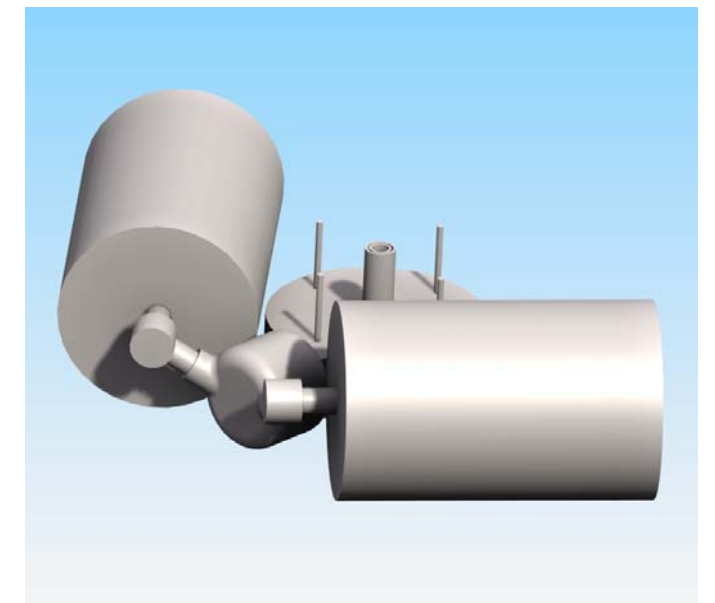


Figure 2.14: A view of the engine layout

## Engine Exhaust

Each engine has its own exhaust with a hot air disperser. It works by mixing outboard cold air from some additional intake and with hot air from the engine. In non flight mode, all exhaust systems are sealed by heat durable shutters that are built at the exhaust ends. In flight mode these shutters open by servo engines to allow the air flow. The engines exhaust can be seen in Figure 2.18.

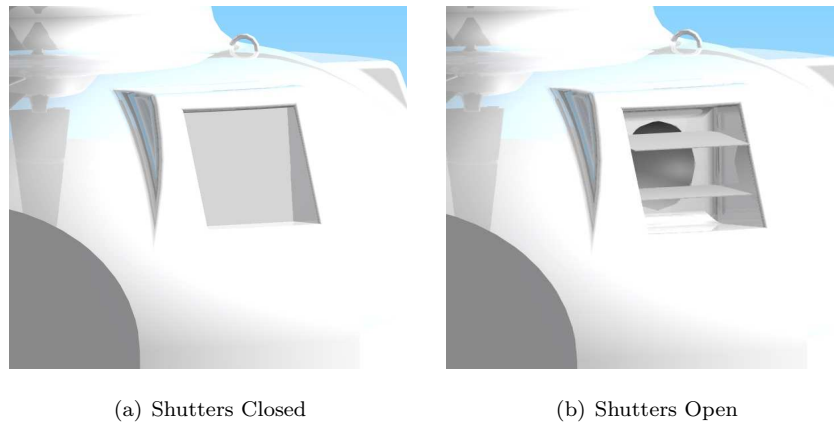


Figure 2.18: The engine exhaust

### 2.5.3 Transmission

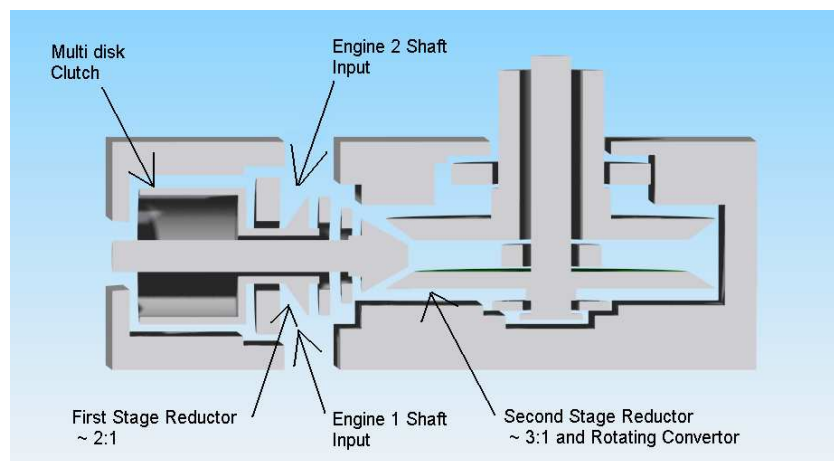


Figure 2.19: The ARVs transmission

Generally the gearbox, clutch and rotation converter work together and have many shared parts, and therefore they are also placed together. The transmission design can be seen in Figure 2.19. The gearbox in our design has a total reduction ratio of 6:1, achieved in two stages. The first stage has a reduction ratio of 2:1 and is placed where the engine shafts enter the gearbox case. It has a set of conical sprockets, providing the reduction ratio, engines coupling, and rotation direction

shifting. Finer engine coupling is done electronically by measuring the torque on both engine shafts. The second stage has a reduction ratio of 3:1 and is placed in the rotation converter. Note that we assumed that the engines have an integrated reduction gear inside, thus the output engine shaft RPM should be 4030 RPM.

Integrating the clutch into our transmission enables easy starting and heating of the engines without external loads. It is a dry, multi-disk clutch with coaxial shafts. Since the clutch disks have finite lifetimes and require periodic maintenance, this configuration keeps the clutch outside the entire mechanical assembly making both accessing and maintenance easier. Despite the high torque that passes through the clutch we believe its dimensions would be not that big because it works in transition mode only twice per mission in relatively low RPM.

The rotation converter in our design has two coaxial shafts, both are driven by conical sprockets coming out from the clutch. This enables clockwise and counter-clockwise rotation of the coaxial rotors. The rotation converter also provides a reduction ratio of (3:1) and serves as the second stage of the gearbox. Around and between the Rotor shafts are tapered roller bearings that pass the loads from the shafts to the rotation converter body which is connected to the helicopter structure with shock absorbers.

## 2.5.4 Rotor Head Design

### mechanical Design

The design of the rotor head for this vehicle is based on 3 main ideas:

1. Rotor cyclic commands are controlled by an autopilot system, therefore no need for a human interface. This provides simple rotor head mechanics and control-authority over each rotor separately, by an original swash plate design allowing each rotor to receive different commands. The lower rotor controls (Figure 2.15) are similar to those of single rotor helicopters, its swash plate push-rods (middle swash plate in cyan, static) pass through the lower non-rotating swash plate (in orange), that is connected straight to the hydraulic actuators (below, not seen in figure). The upper rotor is controlled by the lower swashplate (in blue, rotating counter-clockwise) that moves the upper one (upper swashplate in cyan, also rotating counter-clockwise), which provides control for the upper rotor itself through the upper brown swashplate (rotating clockwise).
2. To achieve mechanical sealing simplicity, a waterproof volume containing the mechanics of the differential pitch control only was designed (Figure 2.16), leaving only the elastomeric flapping and lead-lag hinge outside. When using this design, only two simple types of sealing solutions are required: O-rings around each pitch shaft and an original solution along the cowling perimeter (see below), due to higher rotation. The elastomeric hinges are designed to allow for a relatively low flapping angle of no more than  $8^\circ$  total. That way the two rotors

would not have a chance of collision (assuming that the rotors do not work against each other with opposite flapping angles). Rotor separating distance is  $40[cm]$  which allows for  $10^\circ$  flap angle, thus leaving a safe margin of  $2^\circ$ .

3. Using advanced elastic hinges for flapping and lead-lag motions (Figure 2.17), which are becoming more and more popular in modern helicopters (such as the RNLN Lynx [20]), will simplify the mechanics and maintainability of the rotorhead system. Specifically for the *waterspout*, substituting the more common mechanical hinges with elastic hinges allows for much simpler mechanics that is easily left outside the rotorhead sealed volume. Using elastomeric hinges also eliminates the mechanical complexity of hinges order

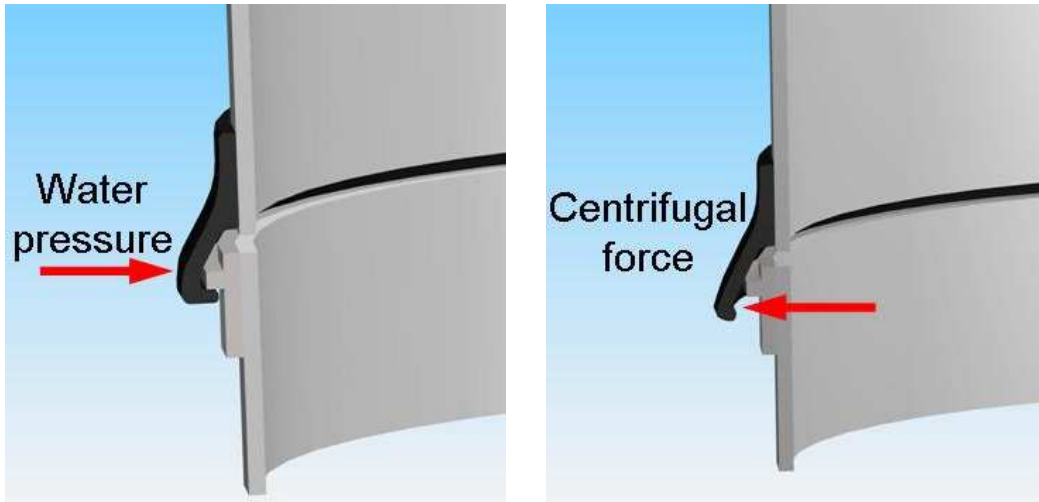
#### **Sealing between the rotors:**

In order to seal the hub, keeping the internal mechanical systems safe from water, a simple but original sealing mechanism was designed to be placed around both interfaces between the three different hub sections (Figure 2.20). On the top section of each interface an 'L' shaped "elastic skirt" is placed, while on the bottom sections an inflexible material was placed, with a relatively low friction coefficient, shaped in a complimentary manner as a fitting reversed 'L'. The idea behind such a design is that when the rotors are stationary (aircraft is not in flight), the "elastic skirt" fits over the inflexible material exactly, creating a perfectly fitted seal around the entire circumference. Furthermore, the 'L' shape allows the "rubber skirt" to use outside water pressure when the vehicle is submerged, to tighten the sealing, further blocking water from entering the hub. When the vehicle is in flight mode (or even when the rotors are started), the centrifugal force of the rotor rotation, makes the "elastic skirt" lower circumference stretch just enough to disconnect it from the inflexible material, allowing for smooth rotation motion.

### **2.5.5 Blade Folding Mechanism**

The blades folding mechanism is made of 3 components: an electric actuator, a pushrod, and a hinge (see Figure 2.21(a)). The actuator is responsible for pushing and pulling the push rod which is located along the blade's base (Figure 2.21(b)). The weight of each rotor was estimated at  $4[Kg]$ , and about  $1.6[m]$  out of its span is being pulled by the actuators for folding/deploying of the blades. Considering that this part weighs about  $3.2[kg]$ , and the distance from the pushrod to the rotation axis is  $5[cm]$ , the moment that was required from the actuator is  $32[N * m]$  which was found to be a typical number for customary aircraft electric actuators [21]. The chosen actuator seen in the figures is a  $25[cm]$  long cylindrical shape with a  $7.5[cm]$  diameter.

The blade was thickened at the folding section to allow larger leverage for the pushrod. Pushing the pushrod folds the blade down. Pulling the pushrod deploys the blade and when the rotor is rotating, the lift created by the blade itself is utilized as a lock mechanism for the upright position. Prior to folding, a special mechanism rotates the rotors until the blades position coincides with the

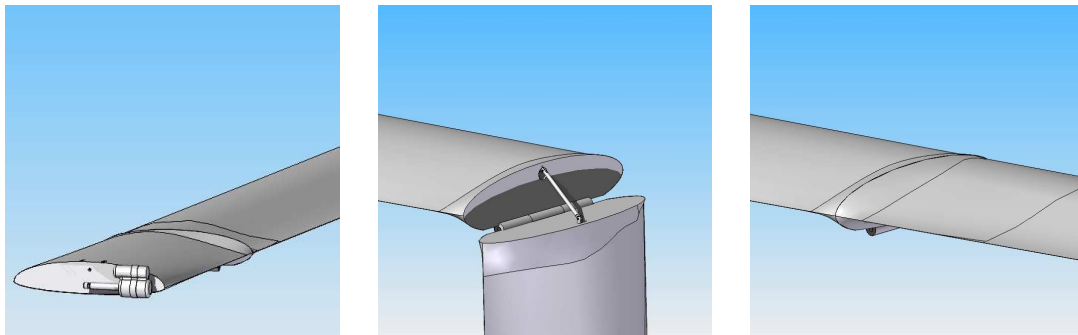


(a) "Elastic skirt" tightly fitted around the hub (engine off)

(b) "Elastic skirt" Opened by centrifugal force

Figure 2.20: Hub sealing using an "Elastic skirt"

two specially trimmed areas on the body's circumference allowing the blades to folded down in order to keep the rotorcraft major dimensions less than the external hatch dimensions.



(a) Deployed blade, actuator showing

(b) Blade folded, pushrod showing

(c) Thickened area on the blade showing

Figure 2.21: Blade folding mechanism

**The force on the folding pin:** While the blades rotate, a shear force develops on the hinge connecting the folding blade part. Considering the centrifugal force on the rotor, the calculated shear force on the pin is approximately  $30000[N]$ . Considering a high yield strength of  $500[MPa]$  ([22]) for steel, adding a safety factor of 0.6, and using the formula for a cylinder shape hinge:  $\tau = 4 * F / (\pi * d^2)$ , the hinge diameter was calculated to be  $11[mm]$ . This diameter is rather small and will not interfere with the blade folding.

## 2.5.6 Crashworthy Fuel System

The purpose of a crash worthy fuel system is mainly to minimize the chances for post crash fire by preventing fuel spillage. Fuel tank location is one of the most critical aspects for this property, and it depends on several components location like crew, ignition sources, and areas that are likely to endure impact. In addition - the C.G. location must also be considered. According to The Aircraft Crash Survival Guide [23], the main areas to avoid when installing the fuel tank are: adjacent to occupied areas, engine compartments, or electrical compartments, under heavy masses (transmissions/engines), near the fuselage bottom, or over landing gear.

Since the fuselage is rather small, some compromise is required when placing the fuel tank. Iterated with internal layout specification designs to determine optimal location of fuel system and its fortifications, and due to space constraints and the fact that any location was considered bad for crashworthiness, the tank was finally placed at the top of the aircraft with the engines. This would minimize firewalls and would not run fuel lines through the cabin.

The fuel tank will be encased in a rubber bladder which will be fitted inside a crash resistant material according to MIL-T-27422. The material around the bladder must have a smooth shape with a minimum of 25[mm] radius corners. Instead of a firewall to shroud the tank and the lines from the cabin, it is proposed that a composite flexible blanket be used, mainly to reduce weight penalties. The bladder will be encased in an aluminum alloy which has a density of 2.84[gram/cm<sup>3</sup>] and is 6[mm] thick. The volume of the fuel is 0.31[m<sup>3</sup>], and the weight of the aluminum covering is estimated at about 110[lbs]. If the blanket is used as a firewall for the engine it can also reduce noise.

## 2.6 Avionics Suite Selection

The primary challenge posed in the RFP[1] was the need for the system to be primarily autonomous and preferably flyable by a non-pilot. This is a challenge as the accuracy of GPS and inertial systems is limited and visual navigation cues can become unreliable in adverse weather/brownout conditions. Since the design was intended for the year 2020 current technologies were used as a model for what could possibly be incorporated into the aircraft.

The primary navigation of the aircraft location is accomplished via a comprehensive inertial navigation system (INS), similar to the H-764 ACE manufactured by Honeywell [24] which meets the requirements set by the military for electromagnetic interference and environmental requirements. The flight director system would be a modified version of the Chelton HeliSAS [25], which is a highly capable and compatible rotorcraft autopilot that would need to be modified for a coaxial helicopter configuration.

Terrain avoidance would be accomplished through the use of a system similar to the BAE Systems made Helicopter TERPROM [8] which employs saved terrain data in order to guide the craft around

obstacles both natural and man-made. The advantage of TERPROM over conventional terrain following RADAR is the enhanced stealth characteristics of the craft by eliminating the detectable RF emissions that an active radar system would send out.

The craft's altitude and heading would be determined using a system comparable to the Honeywell AN/APN 209(V) [24] radio altimeter and a standard electro-compass. This system is immunized to the Doppler Effect and is accurate during pitch and roll without experiencing slant. While it does require radio emissions, as they are directed straight down, their effect on detection is expected to be low, as the aircraft would be in visual range before it is detected otherwise [24]. Additionally for increased stealth, the altitude of the craft could be determined, albeit with less precision, from the GPS system. The trade off is quality of terrain following versus electromagnetic stealth.

As the *Waterspout* approaches the insertion point, the positioning of the craft will be accomplished by a system which hybridizes features of the Sikorsky made Automatic Flight Control System [AFCS] (as installed on the SAR variant of the S-92) [26], the Applied Minds developed Photographic Landing Augmentation System [PhLASH] [27], and the rest of the helicopter's navigation suite.

The preferred method for the crew to interface with the system would be the use of a touch-screen display, with moving map style interface, synchronized to the heading of the aircraft (see Sub-Section 2.7.2). The display would show the best available terrain view, be it real-time video or still images processed by the PhLASH system, with a simple user interface and any necessary navigation/terrain indicators. A "class A" filter would be employed on the display unit, as it maximizes the sensitivity of the crew's night vision goggles.

All images would be acquired via an externally mounted electro-optic system, similar to the Star SAFIRE HD electro-optic system, which is the latest offering from FLIR Systems Inc [28]. This system has a number of advantages that make it optimum for the application in question. The system has a comprehensive set of image sensors, including high definition IR, color and low light. It is an all digital system, thus image integrity is preserved whether it is being used within the digital cockpit environment, as well as when it is shared across a data-link. Lastly, the Star SAFIRE HD is already qualified to MIL-STD-810 and MIL-STD-461.

To address the requirement in the RFP for the aircraft to monitor its health and to be able to react to combat damage of critical components and systems, the aircraft is equipped with a Health and Usage Management System. This system would be an enhanced version of the Honeywell VXP HUMS [24]. The system will interpret data generated by accelerometers distributed about the aircraft, as well as temperature and pressure sensors to assess the health of various systems in the aircraft, as well as the overall airframe itself.

The communications suite of the aircraft is housed primarily within the JTRS terminal [29]. The terminal, manufactured by Rockwell Collins, is compatible with the many of the current voice and data standards employed including: HQ I/II, SATURN, DAMA, SATCOM, HF ALE, ATC HF DATA LINK, VHF AM, VHF FM, VHF AM/FM PSK LOS, ATC DATA LINK, HF SSB, HF ISB,

STANAG 5066, STANAG 4529, STANAG 4231, STANAG 4193 MODE S, SINCGARS, ATC, Link 4, Link 11, and Link 16. The multiple channel nature of the JTRS system would allow the craft to work in concert with a wide variety of battlefield partners simultaneously. Like its predecessor, the JTIDS, JTRS is secure and jam resistant, and transmits both digital voice and data [29]. For short range communications, the commercially developed IEEE 802.11 standard, or a comparable future standard would be employed. The current 802.11n standard can support data rates up to 600 Mbps, and supports the transmission of both voice and data. The digital nature also allows for complex cryptographic algorithms to keep the transmission contents secret.

## 2.7 Crew Compartment

### 2.7.1 Layout

Our primary objective is carrying 2 people in the vehicle, providing a quick and safe entrance/egress path. Crew compartment dimensions are 2 [m] in diameter, and 1.1 [m] in height. Another requirement is the ability to carry one or both of the crew as injured. The use of stretchers was considered, however, it was replaced with adjustable bed type platforms that consume less space and still provide suitable ergonomics. The platforms are placed close enough in order to allow the crew members to provide first aid to each other when needed. The gap left between the platforms allows the crew to use the bottom door (see Sub-Section 2.7.4 and Figure 2.27). The required gap size between the beds is obtained by folding part of the beds inboard (see Figure 2.25). When the vehicle is hovering, the crew rappels out through the bottom door taking the equipment from beneath the beds.

### 2.7.2 Controls

Flight data and various controls are supplied through two touch screens to both crew members (Figure 2.23). These screens will show outside conditions and will include night vision option (Section 2.6). Abort takeoff button would also be part of that control panel.

### 2.7.3 Doors

The design of the doors allows for easy and fast crew entrance/egress to the vehicle while hovering or landing. When hovering above the objective area, the entrance/egress of the crew is made through a bottom door by a winch. In case of an emergency, when landing, or if the terrain demands it, the entrance/egress will be from a side door.

Several concepts were suggested for the bottom door. A pivoting door that opens downward and then pivots around single axis, would encounter the 3 landing gears on the circumference. A cone shaped door, that opens 90° would significantly reduce the internal dimensions because of the relatively large mechanical system. Moreover, the hatch diameter will require a higher vehicle for complete opening since there was a desire to allow egress also from the bottom door while landing

(in addition to the side door). The bottom door was finally designed as a dual door that opens the same way as the second concept using two doors instead of one (Figure 2.26). This particular concept does not require a higher vehicle (hence no additional empty weight), as the doors reach full movement range while on land, and the crew exit path size is not reduced.

Two concepts were considered for the side door as well. The first was to create a door that opens downwards on the flat side of the fuselage. This is a simple idea, but it might take longer to open, and the hydraulic system is expected to be very heavy. In case of an emergency, it will be the vehicles' downfall and will endanger the crew. The second idea that was eventually chosen (seen in Figure 2.22) was to design a sliding door that will be opened by an automatic system or by the crew. Opening the door to the side is a great time saver, and in case of an emergency the manual option (not available in the previous concept due to the door's weight) increases crew safety and mission reliability. Note that manual operation cannot be expected in case both crew are injured due to the sealing force that may be required.

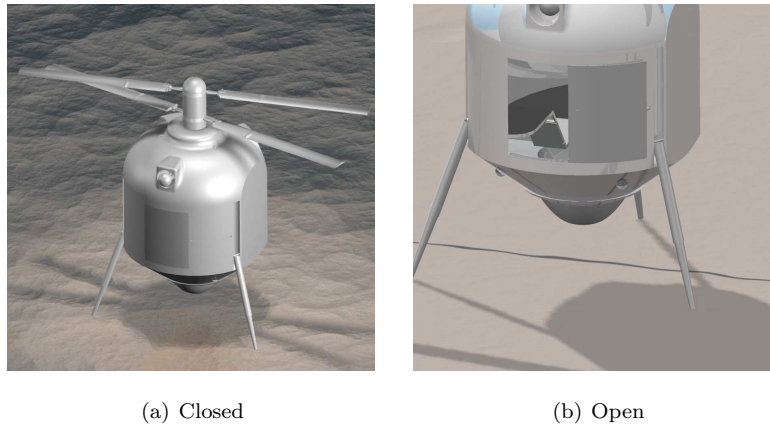


Figure 2.22: Side door design

The side and bottom door seal mechanism is identical in theory. The main idea is that around the inner door there will be rubber tubing surrounding the door's edges. A complementary rubber tubing will be placed on the inside of the vehicle around the door chamber. Once the door is closed those two rubber tubings will be pressed together, causing a sealing effect disallowing water entrance to the vehicle. The circumference of both doors are strengthened by additional carbon-fiber made beams (not shown in CAD), in order to replace the missing airframe in that area and supply resistance against typical structural cracks in that area [30].

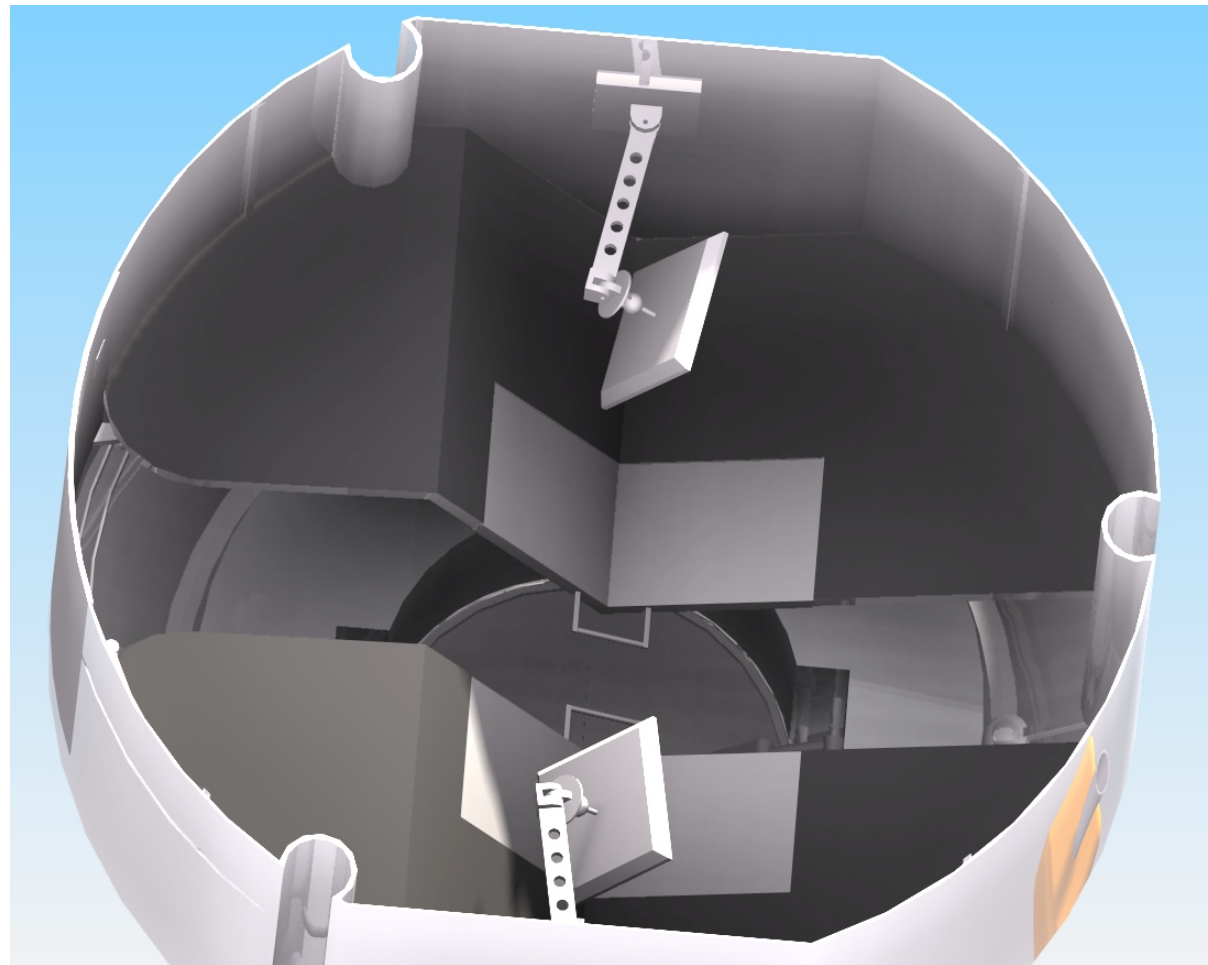


Figure 2.24: Crew cabin, general layout.

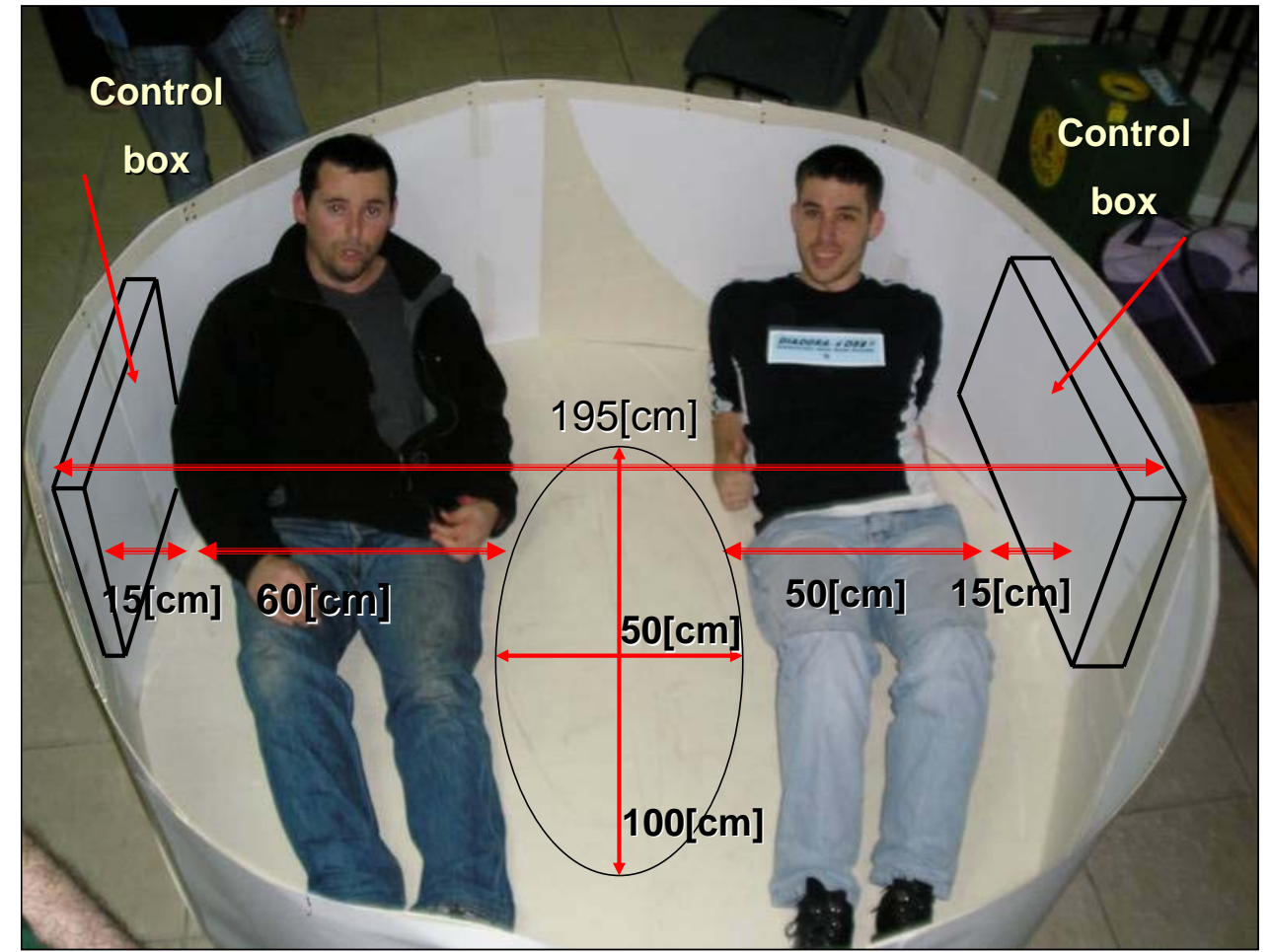
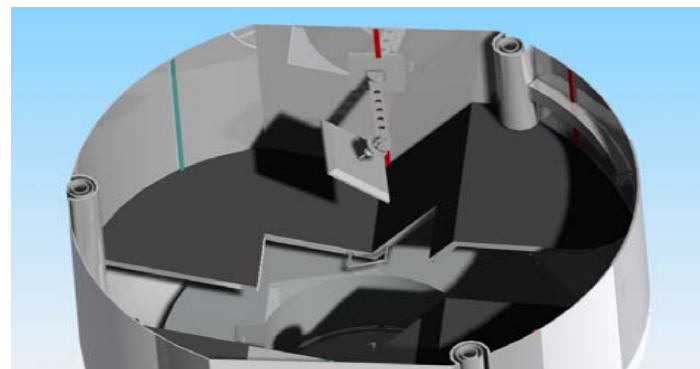
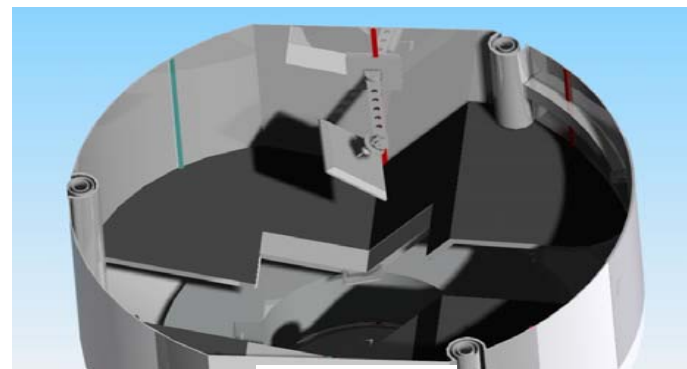


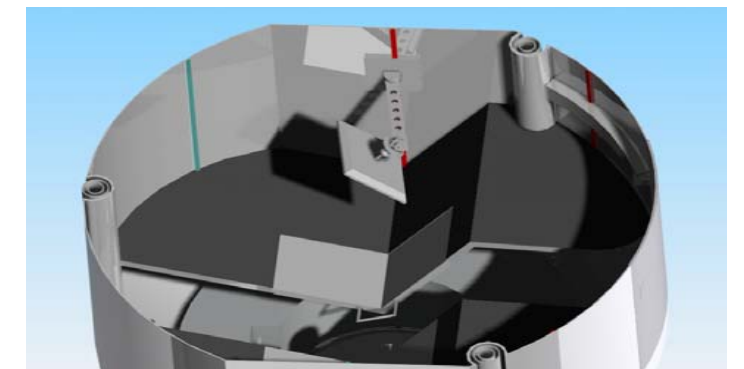
Figure 2.25: Crew cabin, fitting 2 average adults in the 1.95[m] diameter



(a) Fully pulled in



(b) Half open



(c) Fully extended

Figure 2.26: The 'seat drawer' extending out for comfort

Figure 2.18: The seat drawer, extending out for comfort

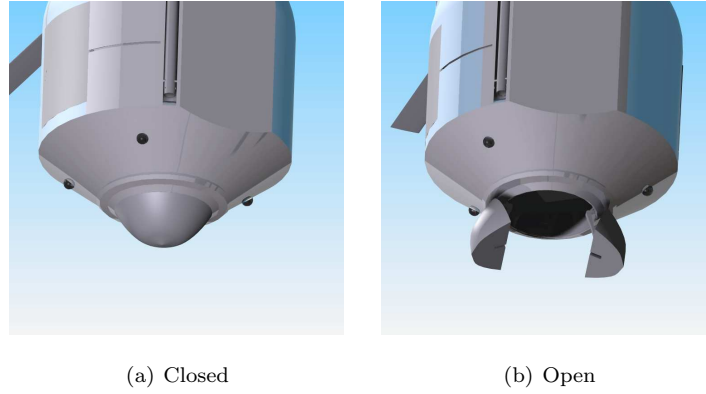


Figure 2.26: Bottom door design

### 2.7.4 Hoist

In hover mode, the winch can be used for both entrance and egress from the hovering vehicle. This method is valid also for injured personnel which is a main demand of the mission (specified in [1] Pg.17). When the the vehicle hovers above the injured crew, the bottom door opens, and the electric winch begins descending the conected cable. Once it reaches the ground, the crew members attach themselves to the cable, using a carabiner, by a special harness that's already on them. The winch is human controlled by a simple up/down switch installed at the cable's end.

When the person arrives inside the vehicle, the only thing that is left for him to do is to shift himself to the bed and to release himself from the cable (all of these actions can be done even single handedly). Once the crew member is on the bed, he may pull the handle under his seat, opening an additional surface that completes the seats surface (Sub-Section 2.7.1, Figure 2.25). The bed designed for this vehicle allows operation in routine mode on one hand, with no injured crew, and a suitable bed for injured crew on the other hand, requiring minimal actions from the injured person. In case there are more than 2 SOF personnel on the site - the *Waterspout* can land and emergency care can be given on board through the sliding side doors when serious injuries take place.

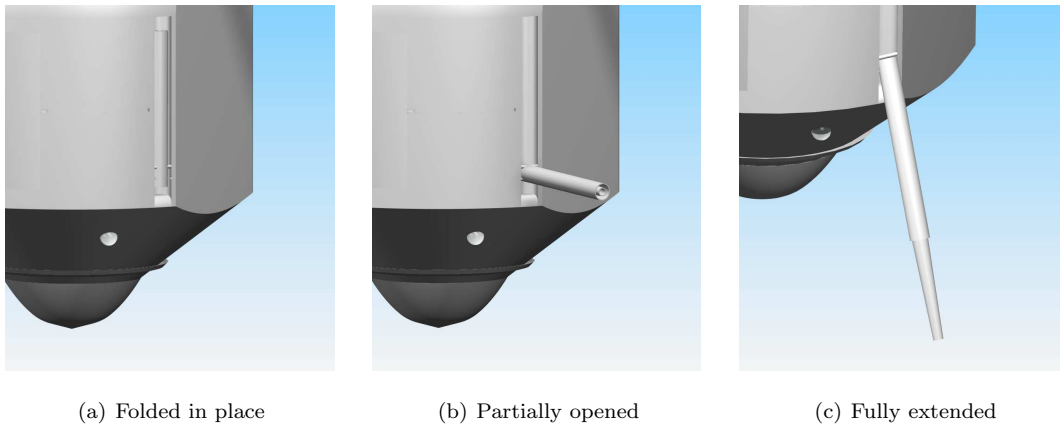
## 2.8 Landing Gear

One of the requirements derived from the RFP [1] is landing in case of emergency. This requires landing capabilities in any scenario - both on water and on ground. Thus the *Waterspout* was equipped with landing gear: 3 poles built to fold into place on the circumference of the vehicle, in a way that doesn't interrupt the entrance/egress path (see Figure 2.28(a)). When the mission requires landing or in emergency situation, each landing pole turns out, rotating around an axis, spreads out using an hydraulic system, and locks open by a pin at an angle of  $160^\circ$  for maximum stability. (see Figure 2.28(b)). Once open, the last step before actual landing is deployment of a telescopic



Figure 2.27: Bottom door open, hoisting cable loose

extension hiding within each pole providing height (see Figure 2.28(c)). When taking off, the landing gear returns to its folded position for a smooth flight.



(a) Folded in place

(b) Partially opened

(c) Fully extended

Figure 2.28: Landing gear pole

## Chapter 3

# Water and Submarine Interface

### 3.1 Flotation and Stability

One of the requirements dictated by the RFP [1] is that the ARV be able to remain afloat at SLS3 for no less than 30 minutes. This requires the design to be stable while floating. To examine the vehicle stability on water a Simulink model was created, shown in Figure 3.1. Due to the vehicle being axisymmetric, only one degree of freedom was considered: the tilt angle of the fuselage relative to the water surface (or to the horizon in case of wave inputs).

#### 3.1.1 Stability Model

A schematic description for the *Waterspout* in floatation mode is shown in Figure 3.2. Axis origin is fixated at the lowest point of the conic bottom, the “x” axis is directed to the left (radial direction) and the “y” axis is directed upwards. The equation of motion for this simulation is the moment equation which was written as:

$$\sum(Moments) = I\ddot{\theta} = f(\theta) + g(\dot{\theta})$$

where  $I$  is the vehicle’s moment of inertia (calculated about an axis that goes through C.G., and is perpendicular to the axis of symmetry).  $f(\theta)$  represents the moments that act on the helicopter by differential buoyancy forces as a result of changing the tilting angle of the helicopter. Any angular movement changes the vehicle’s center of volume while the center of gravity remains in place.  $g(\dot{\theta})$  represents the moments that are caused from the movement of the vehicle’s bottom through the water. These forces are in fact drag forces that develop on the bottom and add a damping effect to the vehicle’s angular motion.

Drag on the bottom was evaluated as the drag that would act on an equivalent cylinder-shaped body with about the same cross-section and dimensions:  $F = \frac{1}{2}\rho_w V_w^2 SC_d$  where  $V_w = R\dot{\theta}$ ,  $R$  is the distance between C.G. and a typical reference point for all the parts that are in the water. A corresponding  $C_d = 0.9$  value for the equivalent cylinder was found by evaluating the average

Reynolds number while  $S$  denotes the surface area of a cylinder which is equivalent to the entire under-water parts of the Watersoput. Note that the resulting moment depends on  $\dot{\theta}^2$  which makes this model non-linear by nature, therefore, no small angles assumption was utilized.

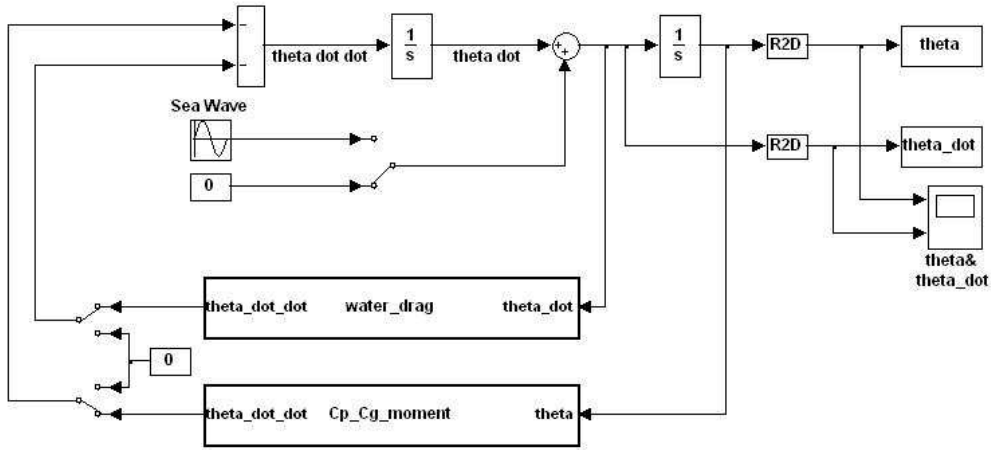


Figure 3.1: Stability analysis - Simulink model

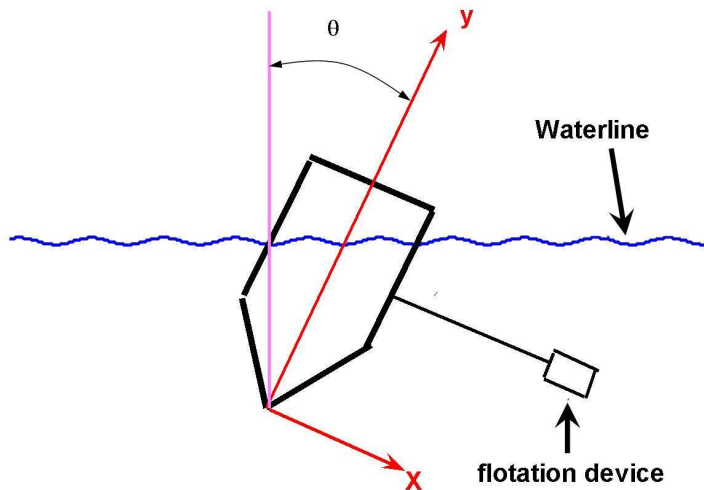


Figure 3.2: Schematic model for stability analysis

### 3.1.2 Stability Results

According to the definitions of SLS3, the ARV should withstand wind speeds of 7-10 [knots], wave lengths of 14-16[m], and wave heights of 0.5-1.3[m]) [31]. Stability of the vehicle alone was initially tested (without any floatation devices additions), in which case  $f(\theta)$  depends only on the fuselage structure shape. After several test to the model, it was found that the fuselage itself (the volume that is underwater) was not stable for  $\theta_{initial} > 3^\circ$ , for the estimated C.G. position of 1.2[m]. Since the

anticipated oscillations for the *Waterspout* are considerably greater, it was concluded that flotation devices are needed in order to stabilize the vehicle at larger angles.

### Flotation Devices

The design solution was to extend the landing gear outboard in flotation mode, locking them in place at an angle of  $80^\circ$  relative to their original vertical axis for maximum stability. Once locked in, a flotation device inflates, positioned at the end of each pole (Figure 3.3(a)) with dimensions of  $40 \times 40 \times 50 [cm^3]$  (Figure 3.3(b)). When the vehicle takes off, the buoys are deflated and returned to their location hiding inside the three landing gear poles (closed position can be seen in Figure 2.28(a)).

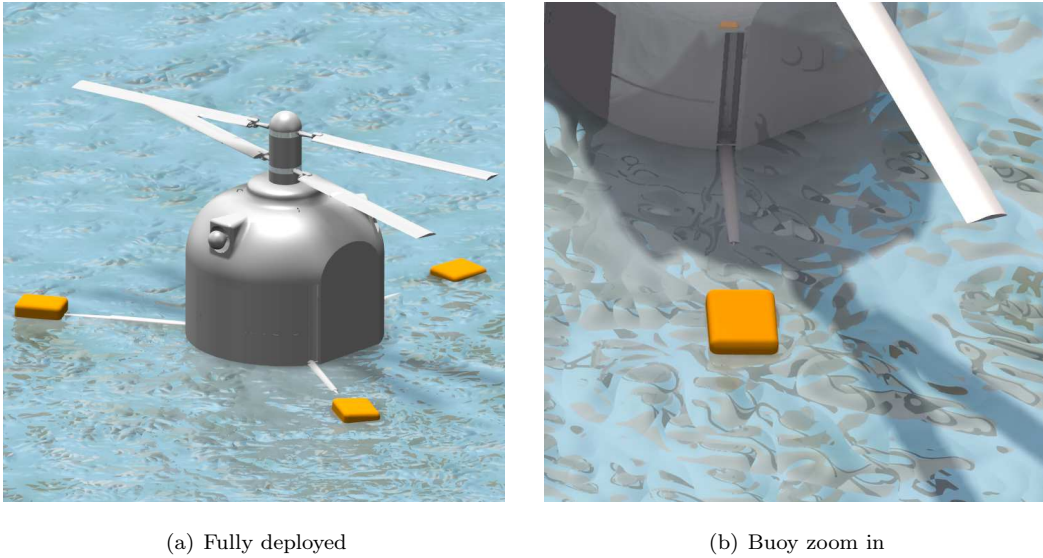


Figure 3.3: *Waterspout* stabilizing flotation device

After modeling the flotation devices in the Simulink model, an important verification was made of the oscillating frequency of the dynamic model: If the frequency of the vehicle's oscillations would differ by an order of magnitude from the wave frequency, then the wave input would cause the *Waterspout* to resonate. The response of the model to increasing  $\theta_{initial}$  was investigated up to  $\theta_{initial} = 15^\circ$ , and as seen in Figure 3.4, the *Waterspout* oscillations frequency is in fact an order of magnitude greater than the highest wave frequency according to SLS3 conditions (which was calculated as:  $1/14[m] = 0.07[Hz]$ ). This is considered a positive sign that any wave that will hit the fuselage will not cause the vehicle to diverge due to resonant response.

As is accustomed in dynamic models, the response of the vehicle to initial conditions was examined for  $\theta_{initial} = 15^\circ$  (Figure 3.5(a)), and  $\dot{\theta}_{initial} = 1[rad/sec]$  (Figure 3.5(b)). The latter test was made in order to simulate a single wave hitting the fuselage at a velocity of approximately  $1[m/s]$ . It is clear that the dynamic system shows stability for all initial conditions tested. The oscillatory

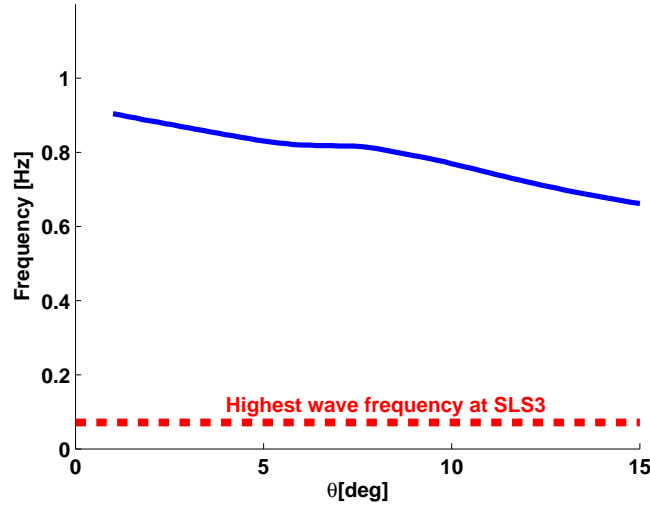


Figure 3.4: *Waterspout* dynamic model frequency, as affected by different initial conditions in  $\theta$

motion of the vehicle is dampened within about 30 seconds to less than one degree.

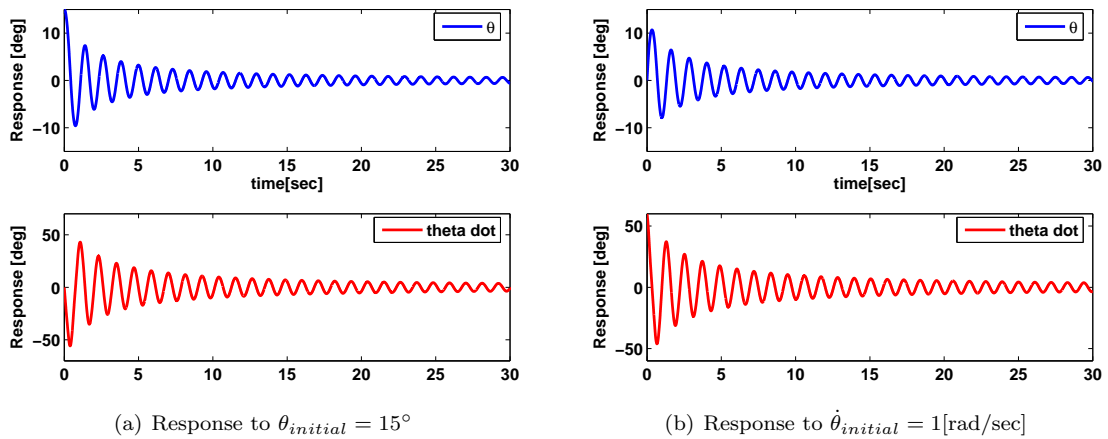


Figure 3.5: Stability characteristics without wave input

An additional examination was made in order to simulate a continuous wave input at SLS3. A wave input was injected as a sine input added to the  $\dot{\theta}$  channel. The frequency of the wave was  $0.07[Hz]$  which is the worst case-scenario for the waves at SLS3 (see above). The response of the dynamic model (shown in Figure 3.6) starts with an expected transient phenomenon which decays after about 2 minutes with only minor oscillation amplitude of approximately  $2^\circ$  with a low angular rate (relative to the initial angular rate caused by the wave for example). This examination verifies the stability of the *Waterspout* at SLS3 conditions, as required by the RFP.

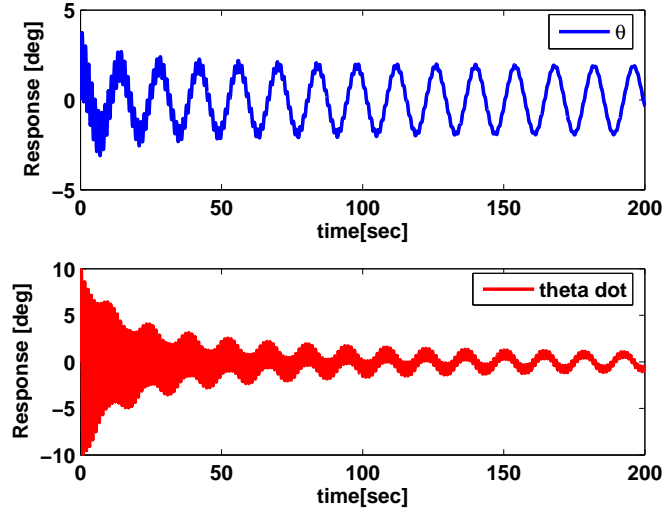
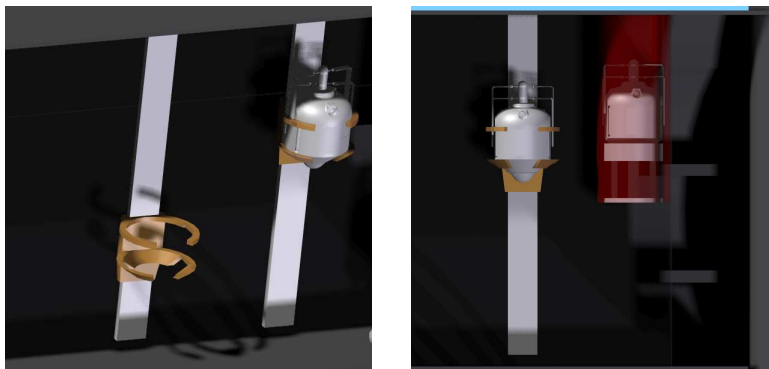


Figure 3.6: *Waterspout* dynamic model response to a continuous wave input

## 3.2 Launch/Retrieval Mechanism

### 3.2.1 System

The launch mechanism is compiled of several stages. Once the launch alert is given there are two scenarios: The vehicle is already in the launch pad, or the vehicle is still in storage. The main idea is that at least one vehicle will always be on the launch pad, but we considered both cases in this report. When the vehicle is not in the launch pad mechanical arms shown in Figure 3.7(a) will transport the vehicle from its storage onto the platform, which will insert the vehicle to the launch compartment. The storage area will hold a number of vehicles in an elevated position above the hanger area, as specified in Sub-Section 3.3.3.



(a) *WaterSpout* held in place by mechanical arms, storage compartment

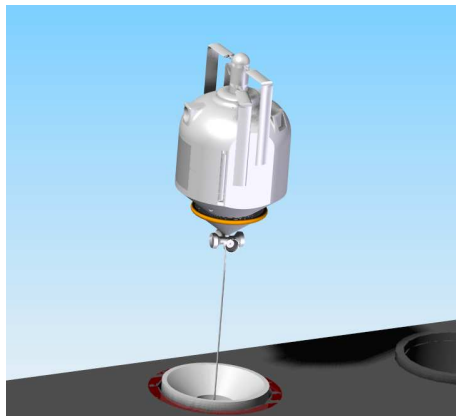
(b) *Waterspout* sitting in the launching silo

Figure 3.7: *Waterspout* related layout inside the SSCN

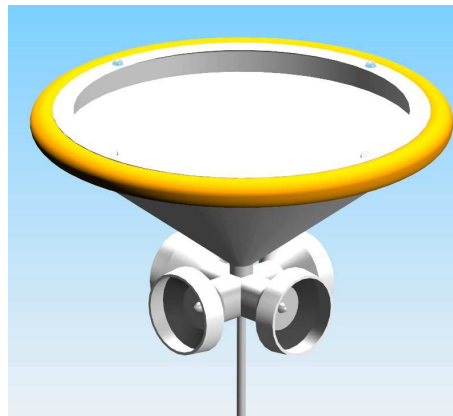
The next launch stages are the same for both cases:

- SOF crew enters the vehicle. Launch crew secures the cable to the vehicle and seals both doors.
- The compartment is pressurized and filled with sea water while the cable prevents the vehicle from floating.
- Once the launch tube is filled the outer submarine tube door opens and the vehicle and launch platform rise together, as seen in Figure 3.7(b). The platform keeps the vehicle at an upright position so that when the top of the vehicle will be exposed to the ocean and might encounter strong currents and tilt the vehicle, danger to the crew and the outer hatch sealing will be minimized.
- Once the platform's reaches the outer submarine hatch it is stopped and the vehicle continues to rise using its positive buoyancy alone (Figure 3.8(a)) while the cable restrain it until it arrives at the water surface.

Retrieval process: Once the vehicle lands on the water, the submarine will launch the retrieval cable whose components are the cable, a 1[m] capture cone (Figure 3.8(b)), a set of cameras enabling both regular and infra red images, and four water jet stream motors providing two degrees of freedom motion (ready made and picked from [32]). This device was named 'The clamp' because of its appearance.



(a) Cable connected vehicle rising through the water



(b) The launch and retrieval mechanism - 'Clamp'

Figure 3.8: The launching method

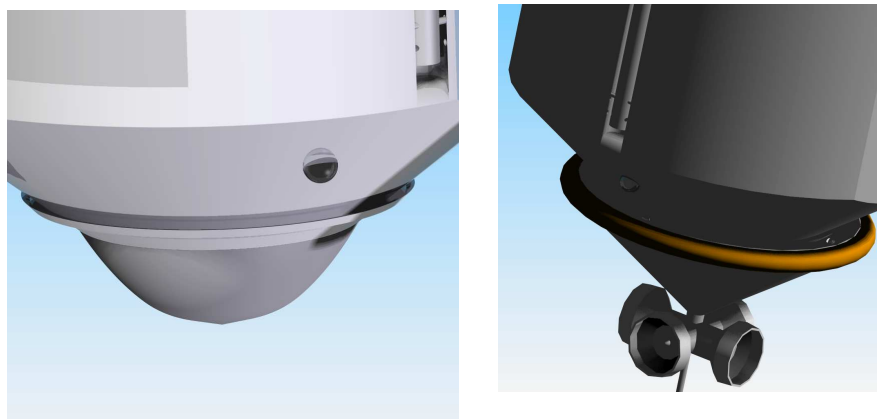
The clamp is designed to be a stand alone robotic mechanism which will lock on an infra red signal from the bottom of the vehicle (see Sub-Section 3.2.1). The clamp can rise as fast as it's pulley will allow, this is because it not sensitive to pressure changes. While the clamp is launched,

the platform will rise from the bottom of the launch tube as before until the outer submarine hatch where it waits for the vehicle to descent and secure itself to it. Once secured it will descent inside the tube, again keeping the vehicle in an upright position, the outer submarine hatch doors will close and the chamber will be emptied.

Although the retrieval mechanism that was planned is sufficient for the safe retrieval of the vehicle, it is important to have an emergency procedure to ensure the retrieval of the vehicle from the surface. Therefore the clamp mechanism will be designed to be operated manually from the submarine (rather than automatically) or even physically by a diver that will exit the submarine along with the clamp.

### Helicopter End

Once the vehicle lands on the water it will activate a light beacon from the bottom of the vehicle, whose main function is to direct the retrieval mechanism from the submarine. Furthermore the vehicle has a parametric socket around the cone shaped bottom seen in Figure 3.9(a), which is located above the bottom door line. The clamp mechanism, has the complementary protrusion which will lock onto the vehicle and secure it once contact will be made (see Figure 3.9(b)). This is a simple mechanic lock designed to enhance the reliability of the retrieval process.



(a) Helicopter bodys' socket (where the 'clamp' catches on) (b) The helicopter attached to the 'clamp'

Figure 3.9: The retrieving mechanism catching on

### Cable Strength

Launch/retrieve cable loads were calculated by estimating the vehicle's volume at about  $7.5[m^3]$  which creates a total positive buoyancy force of about  $6.5[tons]$  on the cable (After reducing the gravity that works on the vehicle). Using steel with  $E_{steel} = 200[GPa]$ , and the simple formula:  $A_{cable} = F/E_{steel}$ , a cable diameter of  $1.5 [cm]$  was calculated.

## 3.3 Submarine Interface

### 3.3.1 Submarine Modifications

Primarily, the design of the *Waterspout* ARV was based on the idea of avoiding modifications of the existing SSCN's external hatches. However, the ARVs' design requires a few changes in the internal submarine design. Although the vehicle comfortably fits and can be launched from the existing missile silos, creating a convenient storage, maintenance and operation environment in the given sub volume was still needed (with a maximum of 20 missile silos for conversion [1]). The launch compartment is shorter than the original missile tube, but still allows the positioning of the vehicle beneath it prior to loading. A system that secures the launch/retrieval mechanism (Sub-Section 3.2.1) is installed inside the tube, including the elevating platform that slides on vertical rails along the launch compartment walls (Sub-Section 3.3.2).

Rails are also installed along the submarines internal volume, serving as a path for the carrying platforms (Sub-Section 1.3.1). In addition, creating a hangar large enough to allow maintenance on two vehicles simultaneously (for example) requires at least 4 silo volume units put together. The storage space is customizable, depending on the number of vehicles on the SSCN (defined by additional requirements, not in this RFP). In order to place the vehicle in the storage units one above the other as described in Sub-Section 3.3.3, mechanical arms should be installed as in Figure 3.7(a).

### 3.3.2 Storage Concept

After returning from its mission the vehicle will be lowered by the platform that brought it up(see Figure 3.7(b)). When the platform and vehicle arrive to the bottom of the tube they are loaded on a carrier (see Sub-Section 1.3.1) that takes them to the maintenance or to the storage space. There, mechanical arms will hold the vehicle, letting the platform return to the launching pad. Vehicles can be stored one above another with a maximum of 2 vehicles fitting in the given height (storage shown in Figure 3.7(a)). When the final number of silos is decided upon, and the number of required launch pads is set, the rest of the space can be used for storage and maintenance area.

### 3.3.3 Space Utilization Options

The first example for utilizing space is setting two launch pads, four hangars and two silo spaces as storage. Total hangar measures are 6[m] depth, 4[m] width and 5[m] high, which leaves some space above the hangar for the sub usage. In the remaining storage space, four vehicles can fit in. In this setting the total number of silos required is eight. The second example sets four launch pads, eight hangers and 4 silo spaces as storage. Eight vehicles can fit in the storage, and the total number of silos used is sixteen. The third example sets just one launch pad, four as a hangar and one silo as storage place. Hangar measurements are the same as in the first example, and two vehicles can fit in the storage space with a total of 6 silos used.

# Appendix A

## Detailed Weights Table

Blade assembly	15[kg]	Hub and hinges	35[kg]
Basic structure	60[kg]	Anti-RADAR coating	6[kg]
Landing gear	10[kg]	Air induction	15[kg]
Engines	100[kg]	Transmission	65[kg]
Automatic flight control system	10[kg]	Hydraulic group	23[kg]
Electrical group	15[kg]	Generator	15[kg]
Avionics	150[kg]	Furnishing	10[kg]
Winch	6[kg]	Emergency equipment	13[kg]
fuel	200[kg]	Anti-icing group	10[kg]
Contingency-5% of empty weight	28.4[kg]	Crew	270[kg]
Equipment	130[kg]	Oil	10[kg]
<b>Empty weight</b>	<b>596[kg]</b>	<b>Gross Weight</b>	<b>1196[kg]</b>

Table A.1: Waterspout detailed weights table

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