UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS

JUDUL: DEVELOPMENT OF A ROCKET RECOVERY SYSTEM

SESI PENGAJIAN: 2012/2013

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MOHD AZRUL HISHAM BIN MOHD ADIB
Examiner   Signature

DEVELOPMENT OF A ROCKET RECOVERY SYSTEM

NUR FITRINA BINTI MAT NAWI

Thesis submitted in partial fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JANUARY 2013

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature	:
Name of Supervisor	: Amir Bin Aziz
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Date	: 11 January 2013

STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature :
Name : Nur Fitrina Binti Mat Nawi
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Date : 11 January 2013

DEDICATION

I specially dedicate to my parents, brothers and sisters, and those who have guided and motivated me for this project.

Mrs. Rahimah bte Che Hussin
Mr. Mat Nawi bin Dollah

Nur Farhana Mat Nawi
Mohd Faizol Mat Nawi
Mohd Farezwan Mat Nawi
Nur Farhanis Mat Nawi
Nur Farahayunie Mat Nawi

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May Allah with His Generosity pay your kindness, and for the all good deeds.

ABSTRACT

The design, fabricate and testing of a rocket recovery system is presented in this report. Recovery system is important for a rocket for low cost of fabricating the rocket and the flight data analysis. The recovery system chosen for the rocket is a parachute recovery system. The recovery system is divided into two parts; the parachute and the ejection system. In this report, six different designs are fabricated. Drop test of the parachutes was conducted to find the design for the parachute. The test shows that the semi-ellipsoidal parachute is the best parachute that can support an empty rocket mass of 2.5kg with the descent range is 5.98m/s. The parachute recovery system constructed in this project will be integrated with the rocket body and powered by a solid propellent rocket motor.

ABSTRAK

Reka bentuk, fabrikasi dan ujian sistem pemulihan roket dibentangkan dalam laporan ini. Sistem pemulihan adalah penting untuk roket untuk kos rendah reka roket dan analisis data penerbangan. Sistem pemulihan dipilih untuk roket adalah sistem pemulihan payung terjun. Sistem pemulihan dibahagikan kepada dua bahagian; payung terjun dan sistem pelepasan. Dalam laporan ini, enam reka bentuk yang berbeza direka. Ujian jatuh payung terjun telah dijalankan untuk mencari reka bentuk terbaik bagi payung terjun. Ujian menunjukkan bahawa payung terjun semi-elipsoid adalah payung terjun terbaik yang boleh menyokong jisim roket kosong 2.5kg dengan pelbagai keturunan adalah 5.98m / s. Sistem payung terjun pemulihan dibina dalam projek ini akan diintegrasikan dengan badan roket dan dikuasakan oleh motor roket berpropelen pepejal.

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LIST OF SYMBOLS

Fd	Drag force
ρ	Air density
CD	Drag coefficient
m	Payload mass
g	Gravitational force
V	Descent velocity
A	Surface area
Do	Nominal diameter
Dp	Parachute diameter
Croot	Length of the fin at the root
Ctip	Length of the fin at the tip
S	Span of the fin
D	Airframe diameter
Troot	Thickness of the fin at the root
Ttip	Thickness of the fin at the tip
Cave	The length of the fin at the centre
m	Mass
P	Pressure
V	Volume
R	Air combustion constant
T	Temperature

LIST OF ABBREVIATIONS

UMP	Universiti Malaysia Pahang
PDS	Parachute Development System
B. C.	Before century
NASA	National Aeronautics and Space Administration
PVC	Polyvinyl Chloride
PSM	Projek Sarjana Muda
UAV	Unmanned Aerial Vehicle
NARAM - 41	41^{st} National Association of Rocketry Research and Development

CHAPTER 1

INTRODUCTION

1.1 PROJECT TITLE

Development of a rocket recovery system.

1.2 PROJECT BACKGROUND

Rocketry is the art of making rockets. It covers all aspects from theory to research to development to launching. Rockets have evolved from gunpowder rockets used by ancient Chinese to giant, complex thrust engines capable of bringing mankind to the moon. There are many types of rockets usage in this modern era; tactical missiles, space launch vehicles, sounding rockets, etc.

The aim of the research is to design and fabricate the complete system of a rocket recovery system. The recovery system of a rocket is very important since it can save the cost of rocket fabricating. Other than that, the recovery system of a rocket also will help the researcher to study the characteristics of flight analysis that have been brought back in the rocket by the recovery system.

1.3 PROJECT OBJECTIVE

The objective of the project is to design, fabricate and testing the rocket recovery system.

1.4 PROJECT SCOPE

The scopes of the project are

i. Design and fabricate design system
ii. Conduct the experiment test
iii. Data analysis and report writing

1.5 PROBLEM STATEMENT

Rocketry is often seen as a sport or a hobby in countries such as the United States, the United Kingdom, Germany, Japan, Russia, Spain and France. It is a hobby practised by young and old and is often used as an educational tool for school children. Rockets are practically built off their backyard. Having developed with interest in rocketry at such young age, these school children are the human resources that propelled these countries to technological advancement in the field of aerospace engineering.

Unfortunately for Malaysia, school children are not taught about rocketry, neither is rocketry a common hobby among the old. Often deemed as weapons of war, rocketry actually brings a lot of benefit to the community. Rather than just being a hobby and an educational tool, sounding rockets provide an option for scientist to study about weather and perform many other experiments during its sub-orbital flight.

1.6 REPORT OUTLINE

The report on this study is divided into five chapters. Chapter 1 provides the general introduction on the study and it includes the objectives, scopes, and outline report of the study was briefly explained.

Chapter 2 presents literature reviews on rocket recovery system. The reviews start with the history and development of rocket technology around the world. The discussion on basic theory of the rocket such as rocket parts is briefly discussed. This chapter also discussed about rocket recovery system design and also rocket recovery ejection system.

Chapter 3 starts with the flowchart of the study. This chapter explains about rocket parachute designing. It also includes the fabrication of deployment system.

Chapter 4 explained about tests that have been carried out during this study. This includes parachute drop test and also ejection charge test.

Lastly, chapter 6 summarized several conclusions and recommendations that could be considered for the next researcher to improve and advancing further the research on development of a rocket recovery system.

CHAPTER 2

LITERATURE REVIEW

2.1 ROCKET HISTORY

One of the first devices to successfully employ the principles of rocket flight was a wooden bird. Aulus Gellius, a Roman, tell a story of a Greek named Archytas who lived in the city of Tarentum, around the year 400 B.C. Archytas had amused the citizens by flying a wooden pigeon made of wood. Escaping steam propelled the bird suspended on wires. The pigeon used the action-reaction principle, which was not to be stated as a scientific law until the 17^{th} century. [1]

Figure 2.1: Hero engine [1]

About three hundred years after the pigeon, another Greek, Hero of Alexandria, invented a similar rocket-like device called an aeolipile. It, too, used steam as a propulsive gas. Hero mounted a sphere on top of a water kettle. A fire below the kettle turned the water into steam, and the gas traveled through pipes to the sphere. Two L-shaped tubes on opposite sides of the sphere allowed the gas to escape, and in doing so gave a thrust to the sphere that caused it to rotate. [2]

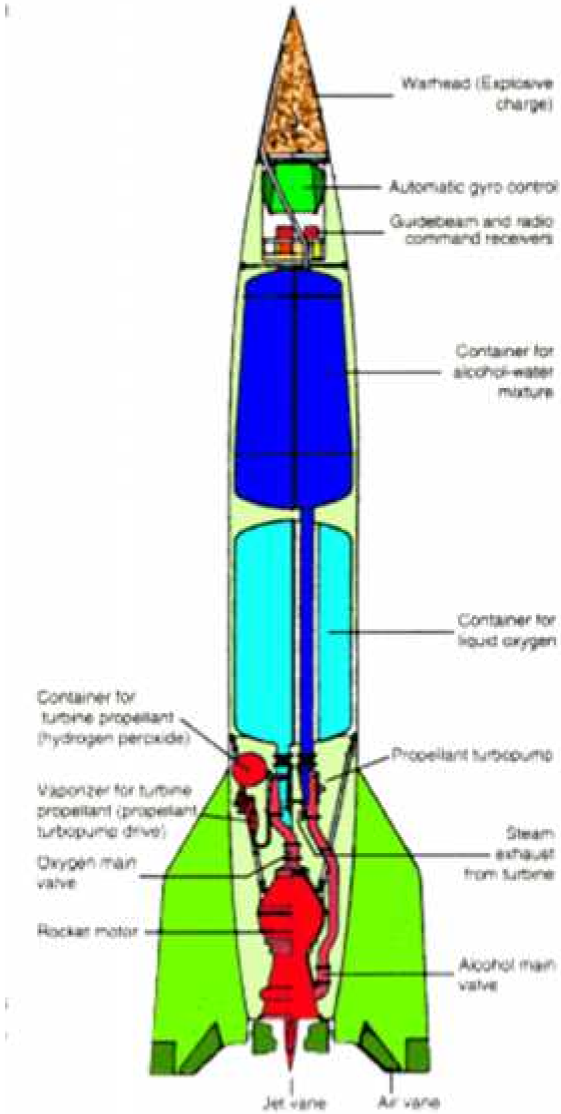

Figure 2.2: German V-2 (A-4) missile [2]

The V-2 rocket (in Germany called the A-4) was small by contrast to today's rockets. It achieved its thrust by burning a mixture of liquid oxygen and alcohol. Once launched, the V-2 was a frightening weapon that could destroy whole city blocks. Fortunately for London and the Allied forces, the V-2 came too late in the war to change its result. United States recognized the potential of rocketry as a military weapon and began a variety of experimental programs. At first, the United States began a program with high-altitude atmospheric sounding rockets. Later, they developed a variety of medium- and long-range worldwide ballistic missiles. These became the starting point of the U.S. space program. Missiles such as the Redstone, Atlas, and Titan would eventually launch astronauts into space. Soon, rockets launched many people and machines into space. Astronauts orbited Earth and landed on the Moon. Robot spacecraft traveled to the planets. Satellites enabled scientists to investigate the world, forecast the weather, and communicate instantly around the earth. The demand for more and larger payloads created the need to develop a wide array of powerful and versatile rockets. [2]

2.2 ROCKET PARTS

These are parts includes in a model rocket namely; nosecone, payload compartment, body tube, launch lug, fins, and motor tube for solid rocket motor.

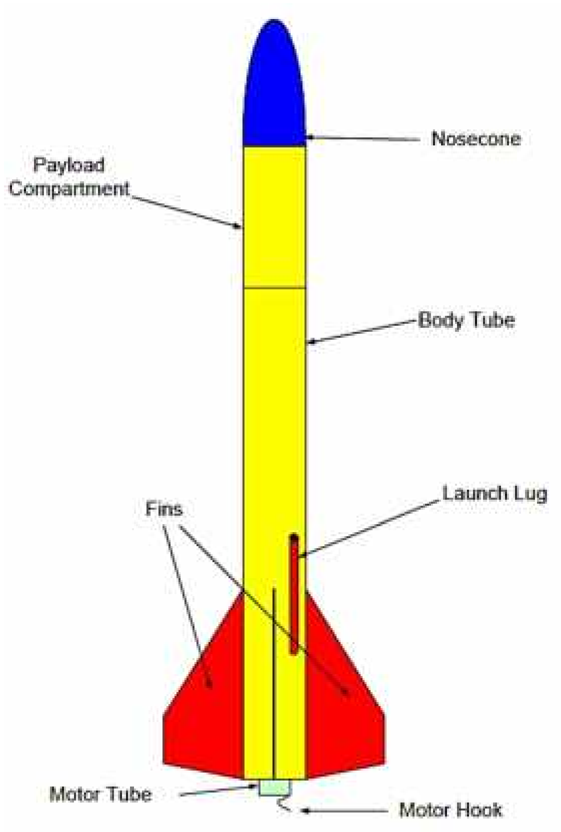

Figure 2.3: Major parts of a rocket [3]

The nosecone has an aerodynamic shape. Normally, nosecones are parabolic or ogive as these shapes performs well at lower speeds. For really high speed rockets a slender conical nosecone is ideal. Nosecone may also hold payload. The payload compartment is for carrying altimeters, cameras, experiments or other payloads. It is an extension to the body tube, but separated from the main body tube by a sealed bulkhead. It connects the payload compartment to the lower body tube. The bulkhead also prevents hot gases from leaking into the payload and damaging experiments. Altimeter measures the changing air pressure to calculate apogee.

The body tube contains parachute and shock cord. Parachute assists in the safe recovery of the rocket. A shock cord connects the parachute to the nosecone. It absorbs the shock of ejection charge and it is attached with a shock cord attachment which has a metal eye for the secure attachment of the shock cord. The launch lug is a hollow tube that is glued to the rocket around its point of balance. This slips over the launch rod, which keeps the rocket pointing upwards ad it accelerates. It helps to guide the rocket upward until it reaches enough velocity for the fins to employ.

Fins are attached to the body tube to make the rocket aerodynamically stable. The fins guide the rocket in a straight path. A motor mount is installed inside back of the body tube. An engine mount holds the rocket engine inside the rocket and an engine retainer prevents the engine from being ejected by the ejection charge.

2.3 ROCKET DESIGN

A rocket had been design based on the guidelines. The rocket should include nosecone, body frame and fins.

2.3.1 Nosecone

Nosecone and fins are one of the crucial aerodynamic components of a rocket. A simple nosecone on top of a rocket is enough to reduce the friction of the rocket. However, more complex shapes may be used to improve the performance of the rocket. There are many common shapes used for nosecone.

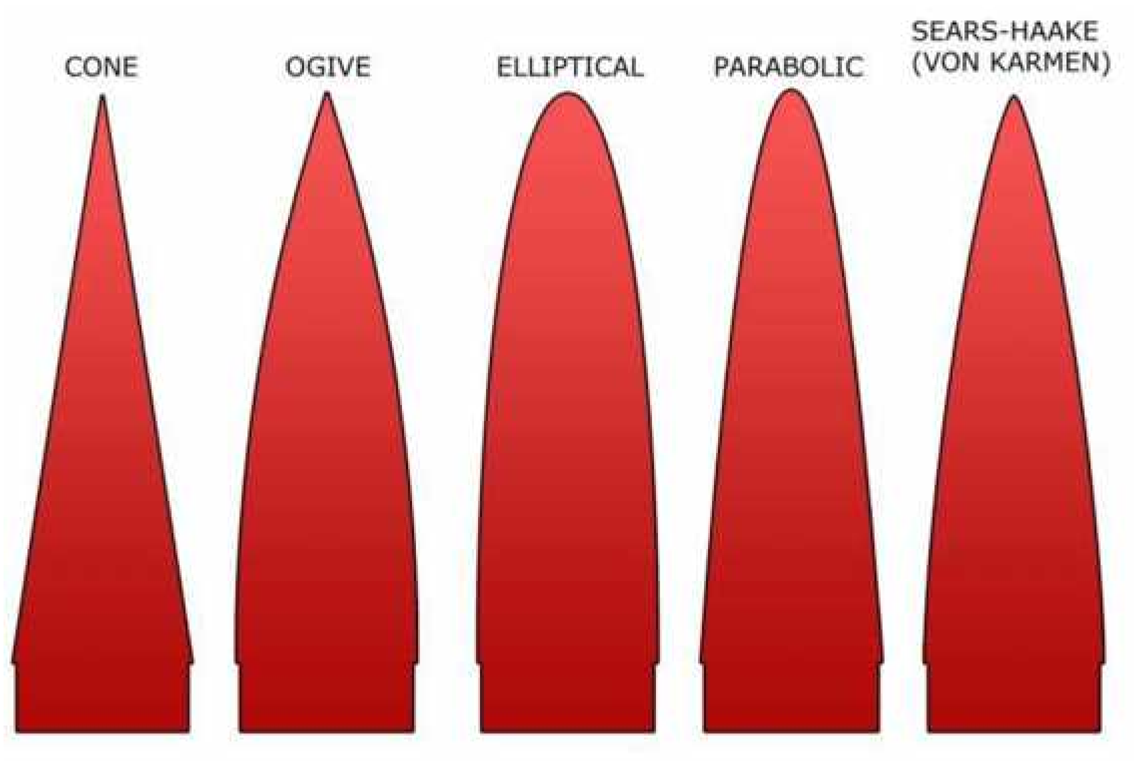

Figure 2.4: Common shapes of nosecone [4]

Nosecone is the tip of the rocket and aerodynamic leading edge. The nosecone has an impact on the characteristic of the rocket. The nosecone also helps to deploy the recovery system allowing the rocket to come back to earth smoothly. When the nosecone is ejected, it will pull the recovery system out of the rocket to allow it to deploy. As such, the nosecone must fit into the rocket body rather than loosely because if it becomes s stuck, the recovery system will not deploy and the rocket will probably lose.

2.3.2 Fins

Fins are important components in building rockets. Because fins give stability, it is important to understand the effect of fins on rocket stability. Fins ensure that the rocket travels in a straight line during flight. It is important to attach the fins firmly to the rocket. A rocket that losses its fins will lose directional stability, causing it to tumble or crash. This is not only cause dangerous, but will result in destruction of the rocket and its payload.

A rocket needs at least three fins to stable. Some would argue that four fins is the optimum number. However many fins attached to the rocket, they should be evenly spaced around the body tube. Fins can be rounded, triangular, square, or any number of different shapes. The important thing is that they are strong enough to take the flight loads. Generally this means using a fin material that is thick enough and strong enough.

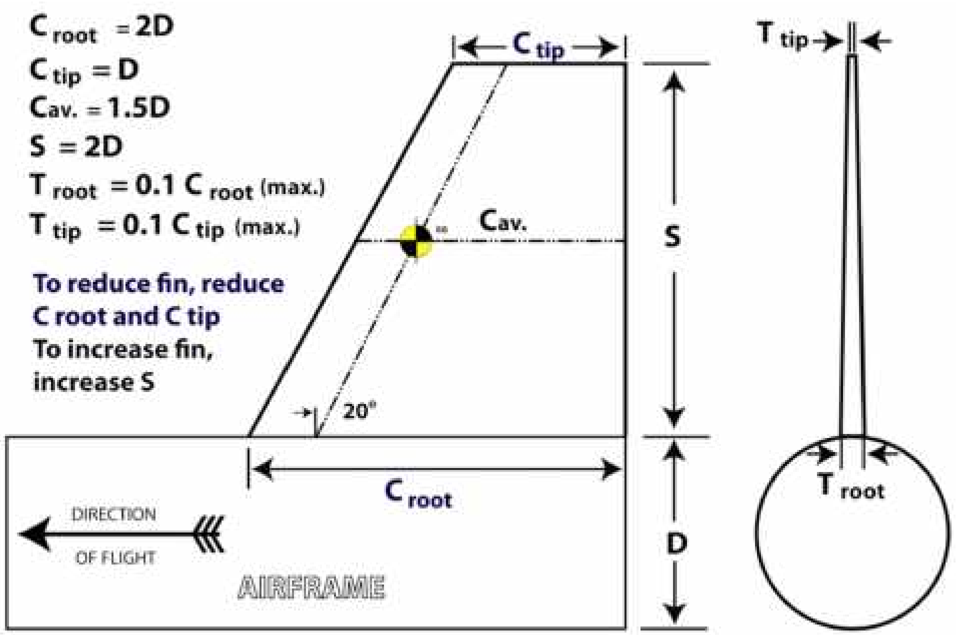

Figure 2.5: Low drag clipped delta fin [4]

These are steps to determine the dimensions of low drag fin:

i. Determine the diameter of the airframe.
ii. Multiply it by 2 to determine the root length and the span (C_{root} and S).
iii. The length of the tip (C_{tip}) is equal to the airframe diameter.
iv. The thickness of the fin at the root (T_{root}) = 0.1 of the root length (C_{root}).
v. The thickness of the fin at the tip (C_{tip}) = 0.1 of the tip length (C_{tip}).
vi. To reduce the fin, reduce the C root and C tip only.
vii. To increase the fin, increase the span (S) only.

2.3.3 Body Frame

There are several inexpensive and strong specialist tubes that can be used in modal rocketry. Spiral wound tubes are purpose made for model rocketry. If it is a need a stiffer rocket then tubes with thicker walls are used. Kitchen roll tubes or domestic materials neither are nor recommended. It would not be strong enough to take the forces on a rocket and will crumple in flight.

The purpose of the airframe tube is to hold the internal stuff. In other words, it keeps the stuff on the inside from falling out of the rocket. It also separates the drag-reducing nose cone from the fin section. If they are too close (in other words, the rocket is very short), the model could be unstable when it is launched. The airframe tube is a flight critical item. That means that if it should bend while the rocket is traveling upward, the flight will go out of control and unstable. The result will be a crash. The tube usually made of PVC tube. But some bigger rockets are made from other materials, like fiberglass, to make it hard and stiff. But for most rockets, PVC tube is plenty strong. PVC tube is actually very durable.

2.4 PARACHUTE RECOVERY SYSTEM

The recovery system is one of the most important parts of a model rocket. It is designed to provide a safe and return the rocket and its payload to earth. It is also to avoid damage the rocket or presenting a hazard to person on the ground. Most recovery systems in use today depend on aerodynamic drag to slow the rocket.

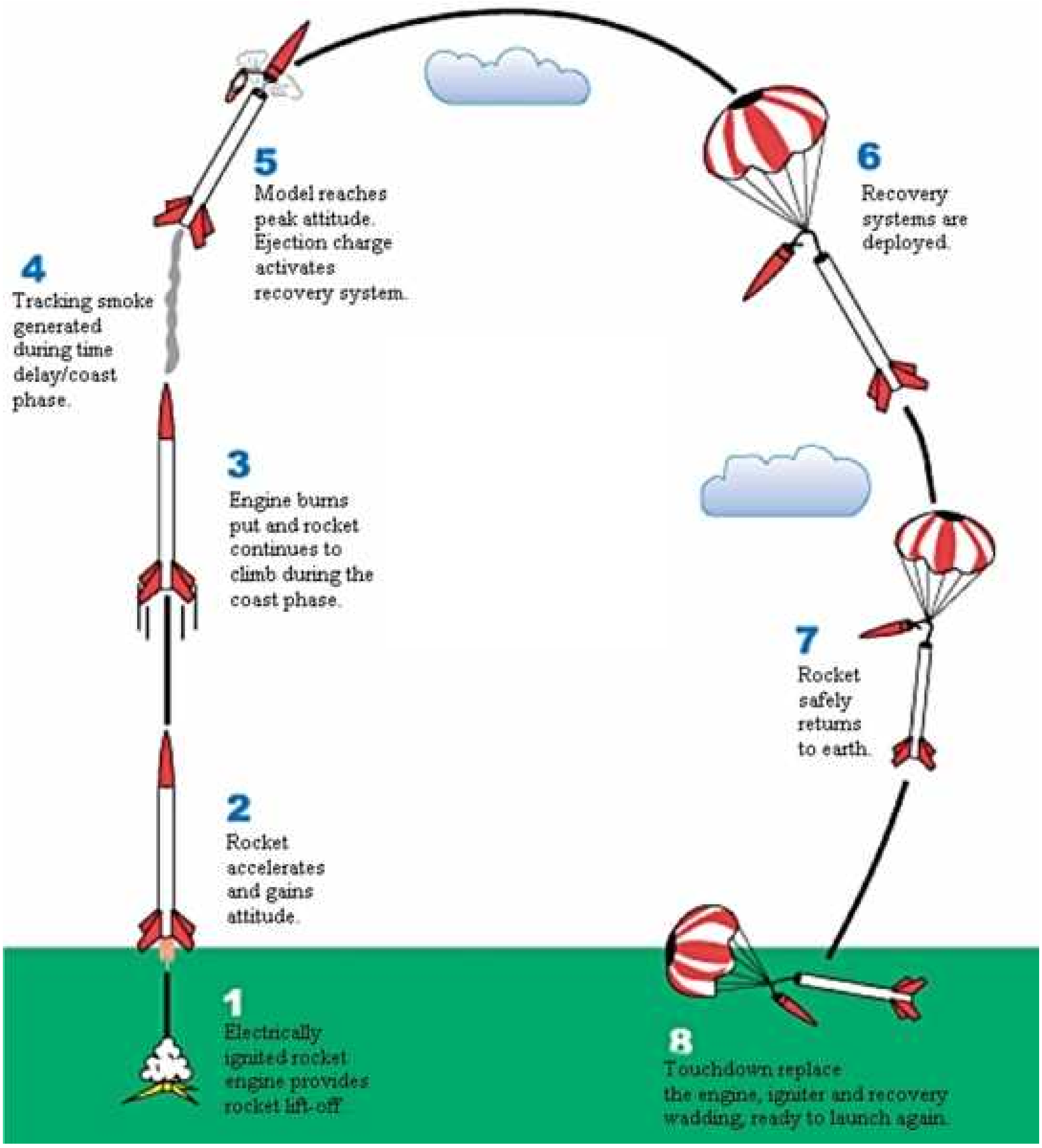

Figure 2.6: Model rocket flight profile [5]

The most common recovery system used on model rockets is the parachute. Several other types of recovery systems are used on certain rockets such as:

i. Featherweight Recovery

A very lightweight, small rocket which upon ejection of the spent engine casing, falls gently back to earth.

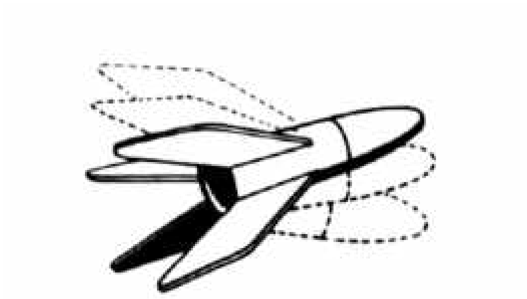

Figure 2.7: Featherweight Recovery [6]

ii. Streamer Recovery

A streamer is a long ribbon made from crepe paper or plastic. Upon ejection from the rocket, the tails of the streamer flutter in the breeze and slow the descent of the rocket. Normally used on lightweight models, streamers may be used interchangeably with parachutes on larger models for flying in a stiff wind. Since a streamer allows the rocket to fall straight, there is less chance of drift on windy days than with a parachute.

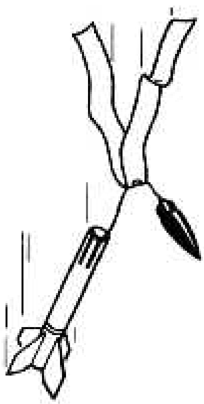

Figure 2.8: Streamer Recovery [6]

iii. Parachute Recovery

The parachute ejects, fills with air and lowers the rocket gently to the ground. The size of the parachute varies depending on the weight of the rocket. Large rockets may use two or even three parachutes.

Figure 2.9: Parachute Recovery [6]

iv. Glide Recovery

The model glides to earth like a conventional airplane. The engine is located in a separate pod which recovers with a parachute. Ejection of the pod leaves the conventional appearing, lightweight glider high in the sky to wheel and turn gently toward earth. Boost gliders can stay aloft for considerable amounts of time.

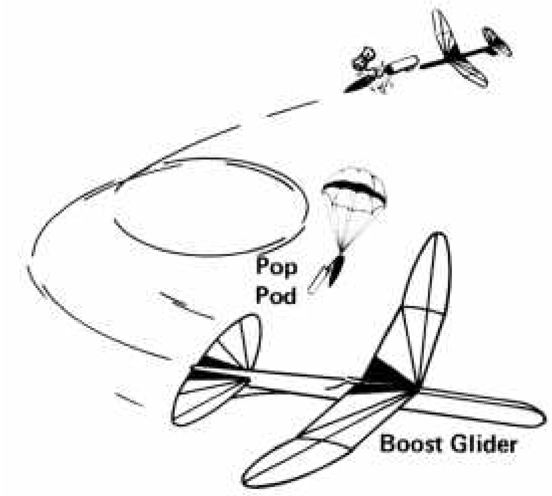

Figure 2.10: Glide Recovery [6]

v. Retro Spin Recovery

The rocket is design in such a manner that drag surfaces are deployed by the engine ejection charge. These deployed surfaces cause the rocket to spin and thus slow its descent.

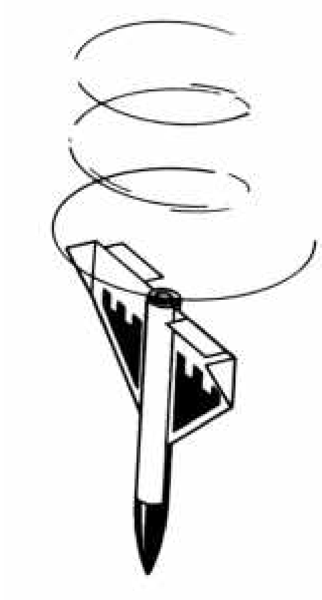

Figure 2.11: Retro Spin Recovery [6]

2.4.1 Parachute

A parachute is used for most model rocket recovery. The size of the parachute increases with the size of the rocket. It uses the ejection charge of the model rocket engine to deploy, push out the parachute. Typically, a ball or mass of fireproof material is inserted into the body before the parachute. This allows the ejection charge to propel the fireproof material, parachute and nosecone without damaging the recovery equipment. Air resistance slows the fall of the rocket, ending in a smooth, controlled and gentle landing.

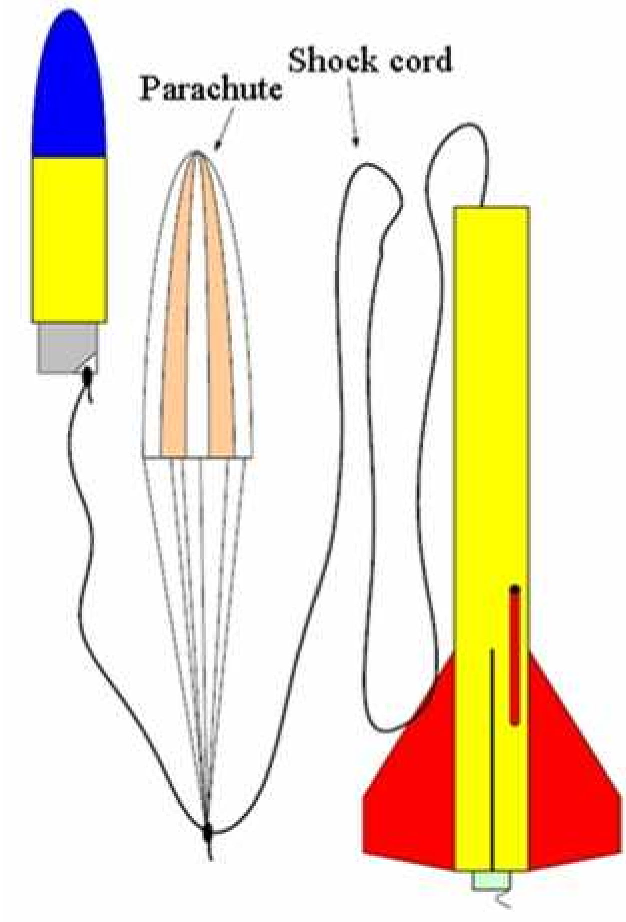

Figure 2.12: Parachute in a rocket [3]

The rocket breaks in half to deploy the parachute. The two halves of the rocket, the main body and the payload compartment, are held together by a shock cord. A parachute is attached to the shock cord about one-third of the way from the nose. It is normal to attach it at this point to prevent the payload compartment from banging into the main body during the descent; this could damage the rocket and interfere with the payload.

This shock cord has to be firmly attached to both the main body and the payload compartment so that it can survive the shock of parachute deployment. It is normal to make the shock cord with elastic material, but a non-melting material. Most model rocket recovery system includes a parachute, usually made from polythene sheet and attached using cotton thread. These parachutes are good for the first few flights but do not last long because it does cotton thread is not a good material to be used.

2.4.2 Parachute Material

The common parachutes are made from polythene. They are not good quality and tend to burn or tear easily. For large, lightweight parachutes it is recommended to use other plastic sheets. These can provide inexpensive parachutes, but will only last a few flights. Nylon parachutes are much more durable. They can be either be bought readymade or can be handmade with a sewing machine. Good windproof nylon can be bought from a few specialist suppliers of outdoor materials. The parachute cords should be of comparable strength and flame resistance to the parachute. Kevlar string is very good for medium sized parachutes, and good quality nylon kite string is a good alternatives [3].

In a research, a student used cotton-polyster fabric as material for his parachute. Lightweight ripstop nylon fabric is preferred for the fabrication of parachute but it is not easily available here. Thus, a strong fabric which could withstand ripping is chosen for the fabrication of this parachute. [7]

Table 2.1: List of materials for parachute [7]

Materials	**Remarks**
Cotton-polyester fabric	Size: 2.0 m x 1.45 m
	2 pieces; white and blue
Braided cotton cord	Length: 15 m
	Thickness: 3mm
Seam binding	Size: 12 mm x 2.74 m
	6 packets

A researcher had discussed about parachute design and sizing in his article. He stressed on care when selecting plastic material for a parachute and one should choose plastic that is strong in resisting tear in both directions. For mass greater than 300 grams, use a cloth material for the parachute, such as cotton, silk, polyester or nylon [8]

Another researcher mentioned the materials usually used for model rocket parachute are polyethylene and Mylar film. Mylar film has a natural tendency to open up flat while polyethylene will fail to open at temperatures below 40 degrees Fahrenheit. Stine also highlighted the Carlisle Method used to fold, roll and pack a model rocket parachute [9]

Table 2.2: Summary of Parachute Material

Material Description	Material Properties	References
Polyethylene		
i. Not good quality and tend to burn or tear easily. ii. For large, lightweight parachutes it is recommended to use other plastic sheets. iii. These can provide inexpensive parachutes, but will only last a few flights. iv. Fail to open at temperatures below 104^{o}C	i. Advantages are its strength, colorfastness and comfort. ii. Its resistance to staining, mildew, abrasion and sunlight; and its good bulk and cover. iii. Lighter than polyester fibres, and they have a lower melting point. iv. Strong and resist soiling and staining. They resist cuts and scrapes, and dry quickly. v. Resist dying so colour has to be added to the fabric as it is manufactured.	[3]and [9]

Material Description	Material Properties	References
Nylon		
i. Much more durable. ii. Do not burn easily. iii. High elasticity. iv. Very resistant to abrasion.	i. Nylon is a synthetically-produced fabric. ii. It was developed as a substitute for imported silk. iii. Density: 1.15g/cm^3. iv. Thermal Conductivity: 0.25 W/mK. v. Melting point: 190 – 350 ^oC. vi. Moisture absorption: 1.1%.	[3]
Cotton-polyster fabric		
i. A strong fabric which could withstand ripping. ii. Lightweight ripstop nylon fabric is preferred for the fabrication of parachute but it is not easily available here.	i. Ratio in the vicinity of 35 percent polyester and 65 percent cotton, although 50-50 blends are also readily available. ii. Stronger material, which is durable and affordable. iii. Density: 1.54–1.56 g/cm^3 Raw conditioned moisture absorption: 8.5%	[7]

Material Description		Material Properties	References
Plastic			
i.	Strong in resisting tear in both directions. For mass greater than 300 grams, he suggested using a cloth material for the parachute, i. e. cotton, silk, polyester or nylon.	i. Density: 1.4089 g/cm^3 ii. Moisture Absorption: 0.1%	[8]

Based on the summary table above, nylon fabric had been chosen as the material for the parachute construction. The density of nylon is smaller than density of plastics and cotton-polyster. The melting point of nylon is also high since it does not burn easily. Moisture absorption of nylon is also smaller than cotton-polyster.

2.4.3 Parachute Shape and Sizing

Commonly used parachute shape are cruciform or cross-type and hemispherical. Cruciform parachute are the simplest shape which consist of two pieces of rectangular cloth overlaid and sewn together as shown in Figure 2.13 below. These parachutes have the smallest drag coefficients, and lower opening force. The small opening force, attributed to gentler parachute inflation, means that the falling body losses more height before full inflation is attained [10]. Cruciform parachutes produce lower oscillation than hemispherical parachutes, which is one of the reasons they have been researched for use in precision airdrop systems are used as drogue stabilizing parachute [11].

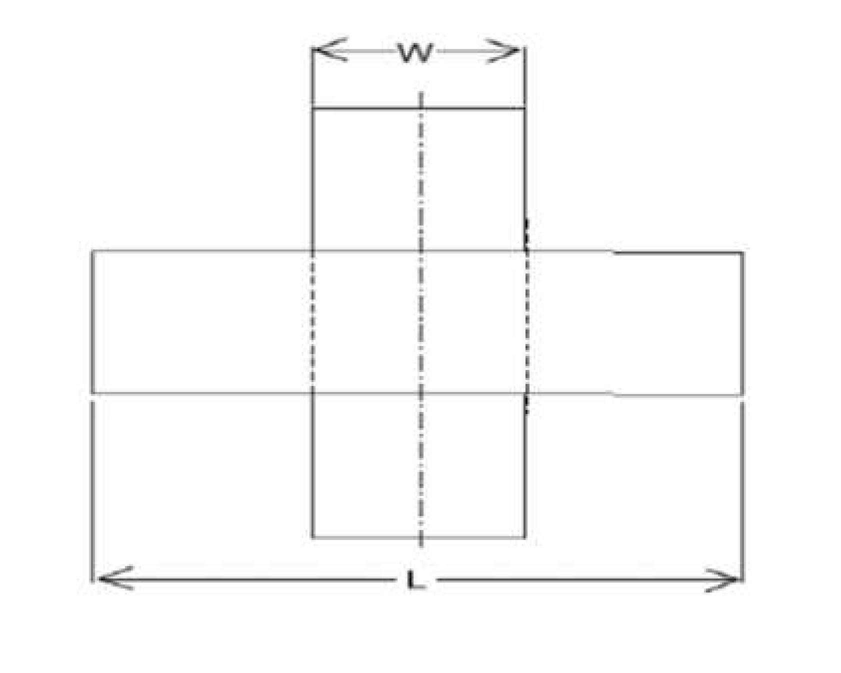

Figure 2.13: Cruciform Parachute Configuration [12]

Hemispherical parachutes have high drag and opening force coefficients [12] affording them the advantage better reliability an opening. Hemispherical non-steerable parachutes are used for aircraft recovery because their simplicity enhances their reliability. Simplicity pertains not only to the parachutes reliability but also to ease of construction and packing. [10]

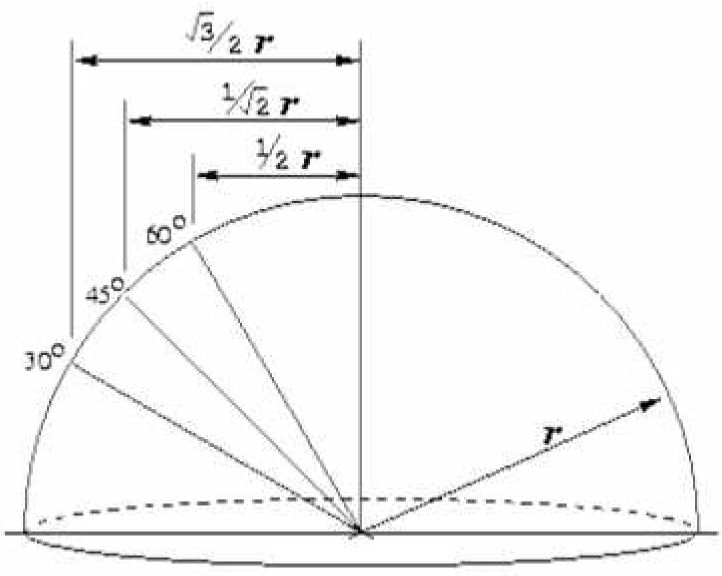

Figure 2.14: Hemispherical Parachute Configuration [10]

Cruciform or hemispherical parachutes are more commonly used in aircraft recovery systems. This parachute recovery system will use a hemispherical parachute design due to the larger drag coefficient than the cruciform parachute allowing for the use of a smaller parachute for the same descent speed. The cruciform parachute has a smaller opening force coefficient which means less shock force occurs during parachute inflation; however this is outweighed by the reliability of the hemispherical parachute. Hemispherical parachutes also have a lower canopy filling constant which reduces filling distance. Therefore less height is lost during inflation. [10]

Other reason for choosing a hemispherical parachute shape is the ease of construction and packing of the parachute. Besides, it has better consistency on opening. Hemispherical parachute also has large inflation shock forces acceptable due to unmanned aircraft and also has large drag coefficient.

Disadvantage of using hemispherical parachutes is their tendency to oscillate. Oscillation is a result of an unstable parachute where the vortex shedding initiates a rocking motion back and forth. Hemispherical parachutes often have a tendency to have large oscillations, up to > 30°. Research has shown however that these oscillations only occur at the higher descent velocities (≥ 9m/s), which is as much as 4 m/s faster than the descent velocity this parachute recovery system is designed to achieve. [10]

Parachutes rely on the aerodynamic drag force, represented by Eq. (2.1), to slow the descent of a body. Assuming that the parachute is in a steady state descent means that the drag forces 'Fd' can be equated to the weight of the descending body, as represented by Eq. (2.2). Rearranging Eq. (2.2) for surface area yields Eq. (2.3).

$$F_d = \frac{1}{2}\rho V^2 A C_D \tag{2.1}$$

$$mg = \frac{1}{2}\rho V^2 A C_D \tag{2.2}$$

$$A = \frac{2mg}{\rho V^2 C_D} \tag{2.3}$$

The unknowns in Eq. (2.3) are, payload mass, *m*, and descent velocity, *V*. All other variables in the equation are already known quantities, $\rho = 1.225 kg/m^3$, $CD=0.7$(standard for hemispherical parachutes) [13], and $g=9.81m/s$. Now that surface area is calculated the nominal parachute diameter can be found. The nominal diameter of a parachute is simply a reference diameter found by using Eq. (2.4), [13]below.

$$D_o = \sqrt{\frac{4A}{\pi}} \tag{2.4}$$

The ratio between inflated diameter, *Dp* and nominal diameter *Do* for a hemispherical parachute is highlighted. This allows for the calculation of the inflated diameter using the Eq. (2.5) below.

$$D_p = 0.66\, D_o \tag{2.5}$$

The sizing of a parachute can be estimated by varying the general drag equation; Eq. (2.3). Hence, it is observed that the required size of the parachute is dependent on the weight of the rocket, the desired descent velocity and drag coefficient of the parachute. [10]

The shape of the parachute canopy does not have a significant effect upon the drag coefficient [14]. However, lesser fabric is required by the semi-ellipsoidal canopy compared to either the hemispherical or parasheet type. This is an important consideration for rockets, where mass and volume must be minimised. [7]

A freelance rocketeer has a detailed description on the parachute recovery system. He explained on the designing and construction of a true parachute, which is a canopy shape. According to him, a parachute is more efficient and requires lesser fabric. In this website, he demonstrated the method in constructing a semi-ellipsoid parachute comprising of 12 gores. He offers full size printable gore patterns for 60, 80, 100 and 150 cm parachutes in his website. The shape is similar to hemispherical but the top is flattened. This form of canopy is more efficient than a hemispherical canopy, in that less material is required to provide equal drag [14]

A researcher executed an experiment to determine the length of shroud line that will produce the most drag and descend the slowest for 50cm parachutes. He performed drop tests from 5 and 10 metres height with varying shroud line lengths (37.5cm, 50cm, 62.5cm, 75cm, and 100cm). The payload mass used in the test is 23.7 grams. From his observations, shorter shroud lines (37.5cm and 50cm) made the parachute unstable and oscillated violently. This made them descended quicker. The 75cm shroud lines parachute stayed aloft the longest. Hence, the optimum shroud line length-to-parachute diameter ratio for 50cm parachutes carrying 23.7 grams of mass is 1.5 [15]

Table 2.3: Summary of Parachute Shape

Shape		Description	Reference
Cruciform	i.	The simplest shape than other shapes	[9] and [10]
	ii.	Have the smallest drag coefficients	
	iii.	Lower opening force	
	iv.	Cruciform parachutes produce lower oscillation than hemispherical parachutes	
	v.	Has a smaller opening force coefficient	
	vi.	Less shock force occurs during parachute inflation; however this is outweighed by the reliability of the hemispherical parachute.	
Hemispherical	i.	Have high drag and opening force coefficients	[12] and [10]
	ii.	Larger drag coefficient than the cruciform parachute allowing for the use of a smaller parachute for the same descent speed	
	iii.	Have a lower canopy filling constant which reduces filling distance	
Semi-ellipsoidal	i.	Lesser fabric is required by the semi-ellipsoidal canopy compared to either the hemispherical or parasheet type.	[7]
	ii.	The shape is similar to hemispherical but the top is flattened.	
	iii.	This form of canopy is more efficient than a hemispherical canopy, in that less material is required to provide equal drag.	

2.4.4 Parachute Deployment System (PDS)

Besides the parachute, the rocketeer also explained on the ejection system designed by him. It uses an airspeed switch, an inertial switch and an ejection charge. Detailed layout of the ejection system is presented. On top of that, he mentioned about the rocket system timer which can be used to initiate the ejection charge as well. Another ejection charge initiator system explained in this website is the altimeter system. In a nutshell, there are 3 triggering systems: airspeed trigger, electronic timer, and altimeter system. What is interesting about his design is it does not require wadding to shield that parachute from the ejection charge [14].

A researcher also mentioned on parachute protection from the ejection charge. Several methods were suggested, namely deployment bag, wadding, piston, canister and baffle. He then touched on the types of ejection systems, namely motor ejection and electronically controlled ejection charge device. He demonstrated two ways of making the ejection charges. The first type is cardboard canister and the second is plastic wrap. For the canisters, a polyethylene tubing is preferred over cardboard is because it is translucent allowing us to ensure the correct placement of black powder and electric match. The construction of plastic wrap ejection charge is similar with the materials (plastic wrap) easily available. Ejection charge is dirty therefore he suggested a PVC pipe fitting to hold the ejection charge and prevent the particles from dirtying the electronics bay [16]

A student had used the ejection system is to deploy the parachute at the apogee for safe landing of the rocket. The altimeter, which is the payload of the rocket, acts as a trigger for the ejection charge as well. Once the rocket reaches apogee, the altimeter will fire electric current down the lines to heat up the tungsten filament of the charge igniters. This heat ignites the ejection charges which then builds up pressure in the ejection cylinders and forces the nose cone to eject; dragging along the parachute out of the body and deploying it [7].

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter will discuss the methods used to fabricate the rocket recovery system. Other than that, this chapter also discuss about method used to eject recovery item from the rocket body. It is also the detail studies on previous findings on rocket recovery system. This is because to understand the basic idea or background of rocket recovery system, the objectives of the research selected, study and investigate on the current problem faced by the system, and the research scope and limitation determined.

Methodology is one of the important things to be considered in order to complete any research. The main reason is because this methodology will make sure the task in a right track until the project is complete. By doing this, it will ensure that the project is following the objectives that have been stated earlier which it will follow the guideline based on the objectives. This chapter discuss the method use to solve problem occurred in this project.

3.2 FLOW CHART

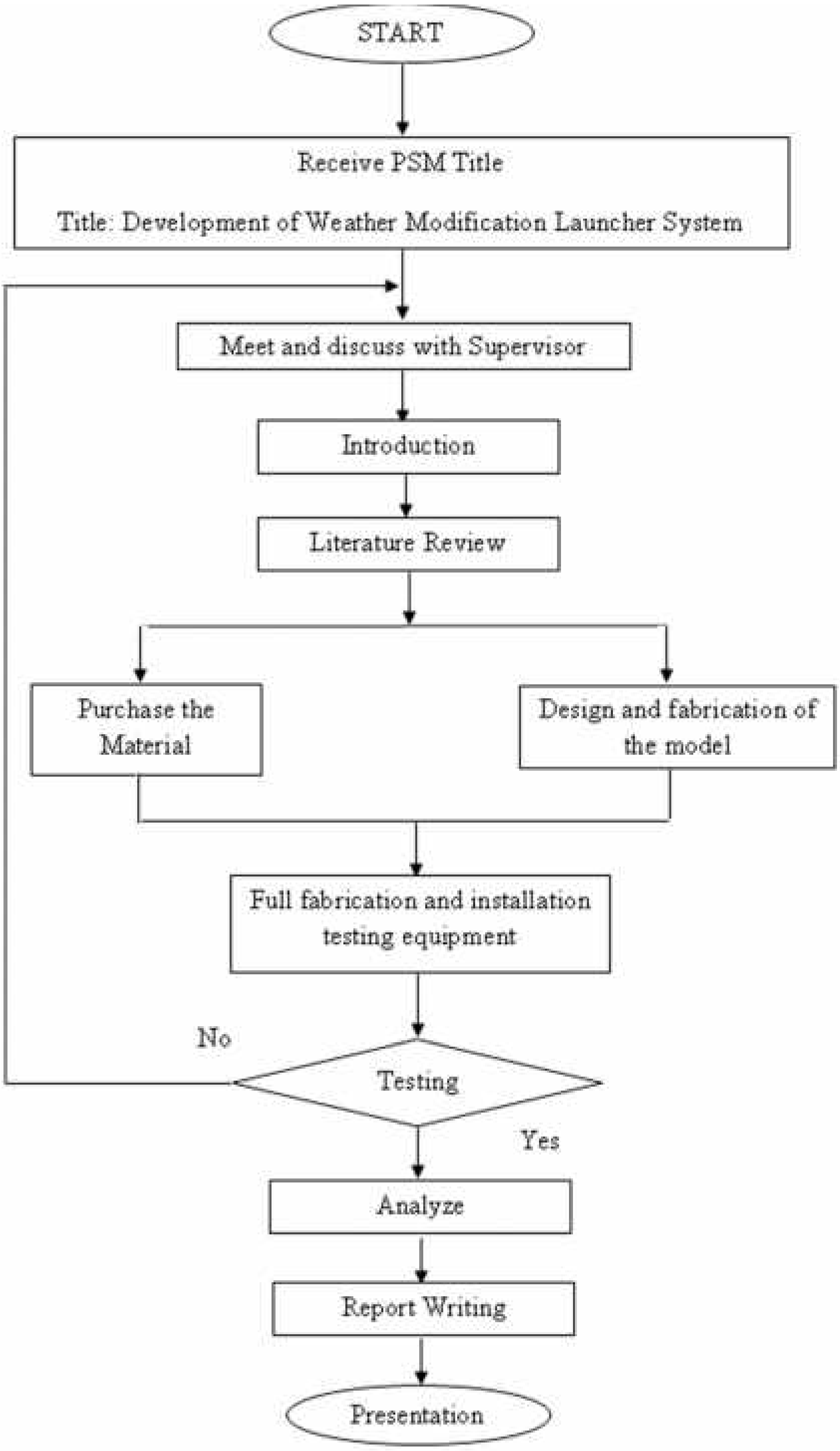

Figure 3.1: Flow chart for Final Year Project

3.3 GANTT CHART

Details	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13
Briefing	■												
Literature review	■	■	■										
Buying material				■									
Parachute sewing					■								
Parachute test 1						■							
Finalize material, design and deployment							■						
Rocket fabrication								■					
Parachute test 2									■	■			
Deployment system fabrication and testing											■		
Final report draft												■	
Presentation													■
Report Writing	■	■	■	■	■	■	■	■	■	■	■	■	■

Figure 3.2: Gantt chart for Final Year Project

3.4 PARACHUTE DESIGNING AND FABRICATION

3.4.1 Design of Parachute

The sizing of a parachute can be estimated by varying the general drag equation, Eq. (2.1). Hence, it is observed that the required size of the parachute is dependent on the weight of the rocket, the desired descent velocity and drag coefficient of the parachute. The shape of the parachute canopy does not have a significant effect upon the drag coefficient. However, lesser fabric is required by the semi-ellipsoidal canopy compared to either the hemispherical or parasheet type. This is an important consideration for rockets, where mass and volume must be minimized [14].

As of the designing phase of parachute, the weight of the rocket is yet to be known. The drag coefficient of the parachute is also unknown at this point. Therefore, a 100cm base diameter parachute is chosen and constructed. The semi-ellipsoidal shape with an aspect ratio of 0.707 is chosen to minimize the fabric used, thus minimizing the mass of the parachute [7]. Figure 3.3 shows the shape of the canopy and the ratio of the semi-minor axis to semi major axis, which is the aspect ratio of the canopy.

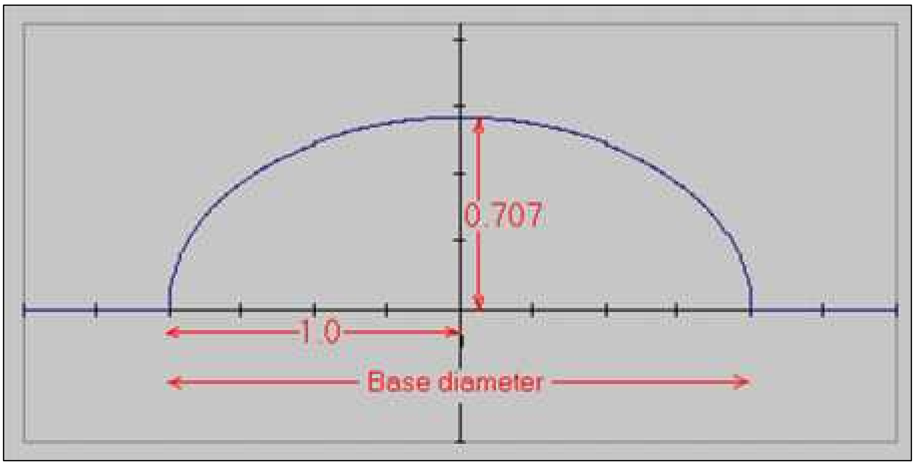

Figure 3.3: Semi-ellipsoidal canopy.[14]

Parachutes are made by joining multiple gores. For this parachute, the number of gores is 12. The gore pattern is plotted using the Parachute Gore Pattern Maker. This spreadsheet may be used to create a flat pattern for a parachute gore. A gore is an individual panel that, when stitched together with adjacent gores, forms the canopy of a parachute. The user inputs the basic parachute diameter, as well as the number of gores desired (minimum of 4). The spreadsheet creates a table of coordinates as well as a plot of a single gore [14].

Table 3.1: Parachute gore coordinates [14]

Parachute Panel Basic Coordinates			
100 cm. Diameter, 12 Gore (reference)			
x	**y**	**x**	**y**
26.18	0.00	0.00	0.00
26.15	2.50	0.03	2.50
26.05	4.99	0.13	4.99
25.89	7.47	0.29	7.47
25.67	9.93	0.51	9.93
25.40	12.37	0.78	12.37
25.08	14.78	1.10	14.78
24.72	17.17	1.46	17.17
24.32	19.51	1.86	19.51
23.90	21.82	2.28	21.82
23.45	24.10	2.73	24.10
22.98	26.33	3.20	26.33
22.50	28.53	3.68	28.53
22.01	30.69	4.17	30.69
21.51	32.81	4.67	32.81
21.00	34.89	5.18	34.89
20.50	36.94	5.68	36.94
20.00	38.95	6.18	38.95
19.50	40.94	6.68	40.94
19.00	42.89	7.18	42.89
18.50	44.82	7.68	44.82
18.01	46.72	8.17	46.72
17.52	48.60	8.66	48.60
17.04	50.45	9.14	50.45
16.56	52.29	9.62	52.29
16.08	54.11	10.10	54.11
15.61	55.92	10.57	55.92
15.14	57.71	11.04	57.71
14.67	59.50	11.51	59.50
14.21	61.28	11.97	61.28
13.75	63.05	12.43	63.05
13.28	64.82	12.90	64.82

When assembled, the parachute canopy is semi-ellipsoidal in shape (a "flattened" hemisphere). This form of canopy is more efficient than a hemispherical canopy, in that less material is required to provide equal drag [14].

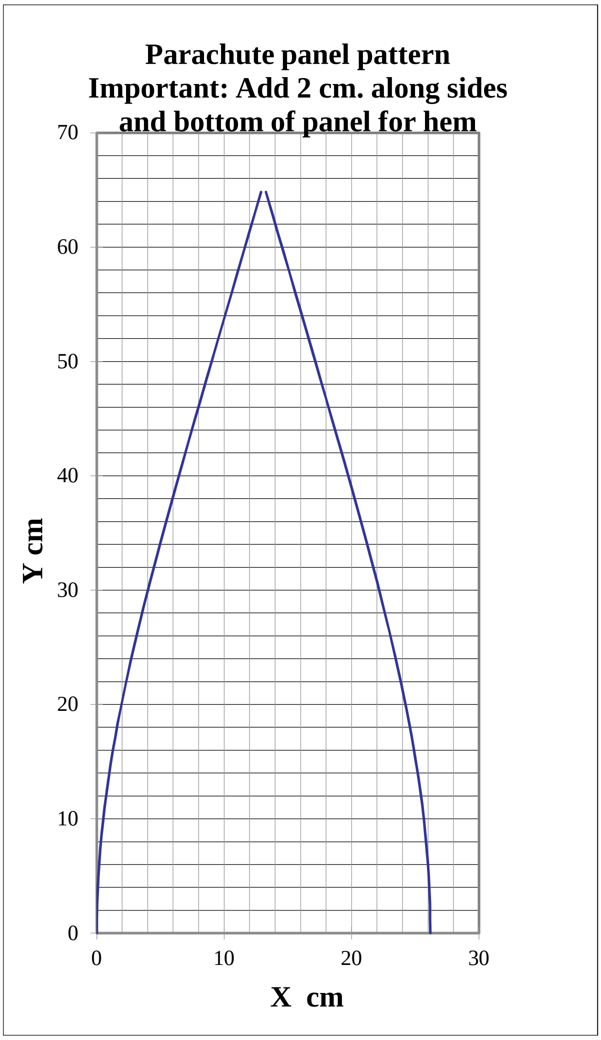

Figure 3.4: Parachute panel pattern [14]

The length of shroud lines has an effect on the performance of the parachute. More specifically, it affects the shape of the canopy which in turn affects the *Cd* of the parachute. As the length of the lines is increased, the *Cd* increases. This effect is more pronounced when the length of shroud lines (L) to diameter (D) ratio is less than 0.5 but become less significant when L/D is more than 1.0[7]. The optimum shroud line length for 100 cm diameter parachute is 112.5 cm [14].

Besides semi-ellipsoidal parachute, there are five other parachute designs such as cruciform, hemispherical, octagon, round and square. The parachutes are designed to be test and analyze to find which design will be the best to take into consideration.

3.4.2 Fabrication of Semi-Ellipsoidal Parachute

Table 3.2 shows the list of materials used for the construction of the semi-ellipsoidal parachute.

Table 3.2: List of materials for parachute

Materials	Remarks
Nylon	Size: 3.0 m x 1.45 m 2 pieces; white and dark green
Nylon cord	Length: 15 m Thickness: 3mm
Seam binding	Size: 12mm x 2.74 m 6 packets

The gore pattern is printed on sheets of A2 paper. A space of 2cm is added to the sides and bottom of the gore patterns for hem stitching. The gore patter is then traced on the parachute fabric and 12 panels are cut out.

Figure 3.5: Outline drawing with gore pattern

The sides and the bottom of the panels are then hemmed. The hemmed panels are then laid up side by side, bound together by 6 pieces of seam binding which span the either arc length of the canopy. Figure 3.6 shows the position of two panels sewn together with seam binding.

Figure 3.6: Two panels sewn together with seam binding.

Two circular caps of 15cm diameter, which form the topside and underside apex caps, are hemmed and sewn onto the apex of the panels.

Figure 3.7: Hemmed apex caps

The hem and the seam binding on the 12 panels provide strength to the canopy against longitudinal stress. The hem on the apex caps provides resistance against hoop stress generated then the parachute is descending.

For the shroud lines, 12 lengths of 120 cm nylon cords are cut and sewn to the underside of the canopy. The stitching length is 7cm and the ends are sewn at the centre of the joint of the panels. The shroud lines are then tied together. The finished parachute, as shown in Figure 3.8, has a mass of 0.2kg and requires a storage volume of approximately 871 cm^3. Figure 3.9 shows the packed parachute to be stored in the rocket body.

Figure 3.8: Parachute canopy

Figure 3.9: Packed parachute

3.4.3 Fabrication of other Parachute

The Table 3.3 shows the material used to fabricate the others parachutes.

Table 3.3: Material of other parachutes

Materials	Remarks
Hemispherical	
Nylon	Size: 1.45m x 3m 2 pieces; pink and blue
Nylon cord	Length: 7m Thickness: 3mm
Cruciform	
Nylon	Size: 1.45m x 1.5m 1 piece; red
Nylon cord	Length: 9 m Thickness: 3mm
Round	
Nylon	Size: 1.45m x 1.5m 1 piece; pink
Nylon cord	Length: 7m Thickness: 3mm
Square	
Nylon	Size: 1.45m x 1.5m 1 piece; peach
Nylon cord	Length: 5m Thickness: 3mm
Octagon	
Nylon	Size: 1.45m x 1.5m 1 piece; green
Nylon cord	Length: 9m Thickness: 3mm

The gore patterns of the parachutes are printed on A2 paper. A space of 2cm is added to the sides of the gore patters for hem stitching. The gore patterns are then traced on the parachutes fabric and are cut out. For hemispherical parachute, 6 gore patterns are cut out to be attached and sewn together to produce hemispherical shape. The figures show the gore patterns for each design of parachutes with the parachutes that have been sewn.

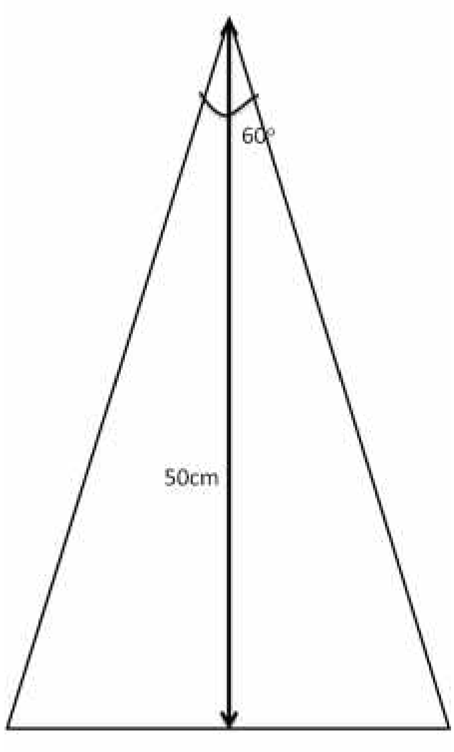

Figure 3.10: Hemispherical gore pattern

Figure 3.11: Hemispherical parachute

As in Figure 3.10, a triangle with angle of 60^o was printed on A2 paper. The gore pattern then traced onto nylon fabric and six panels are cut out. The panels then had sewn side by side together forming a hemispherical parachute as in Figure 3.11. A circular apex also had sewn on the top of the parachute. A nylon cord with 1m length is sewn at every corner of the parachute. Since the parachute has six corners, the parachute used 7 metres of nylon cord including the 10cm of stitching underside of the parachute.

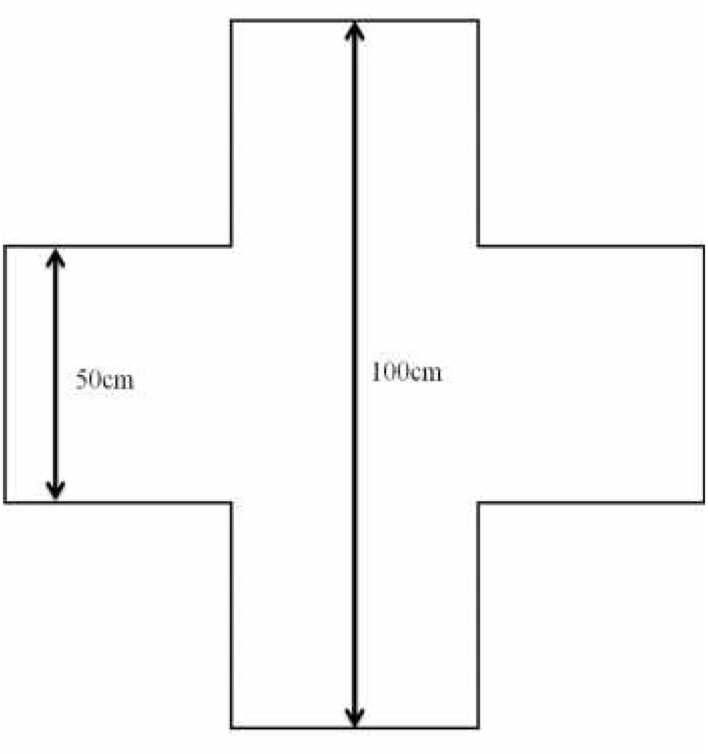

Figure 3.12: Cruciform gore pattern

Figure 3.13: Cruciform parachute

Figure 3.12 shows the gore pattern of cruciform or cross parachute. The pattern is printed out on A2 paper with the actual dimension shown. The gore pattern the traced on red nylon fabric with 2 cm hem. After the nylon had cut out, all sides of the fabric being hemmed and formed a cruciform parachute as in Figure 3.13. Nylon cord with 110 cm length is cut and sewn at corners of the parachute. 10 cm stitch is sewn underside of the parachute.

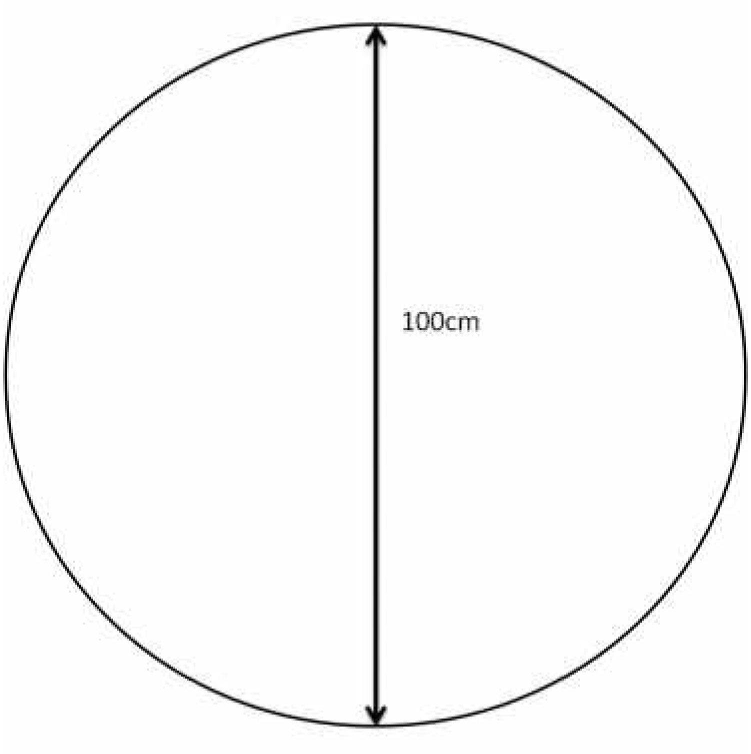

Figure 3.14: Round gore pattern

Figure 3.15: Round parachute

A circular gore pattern with 100cm diameter as in Figure 3.14 is printed out on A2 paper. The gore pattern is then traced on a pink nylon fabric. The fabric then is cut out with 2cm hem. After being hemmed, nylon cord with 110 cm length is then sewn at six corners of the fabric. 10 cm used to stitch underside of the parachute. The complete round parachute is shown in Figure 3.15.

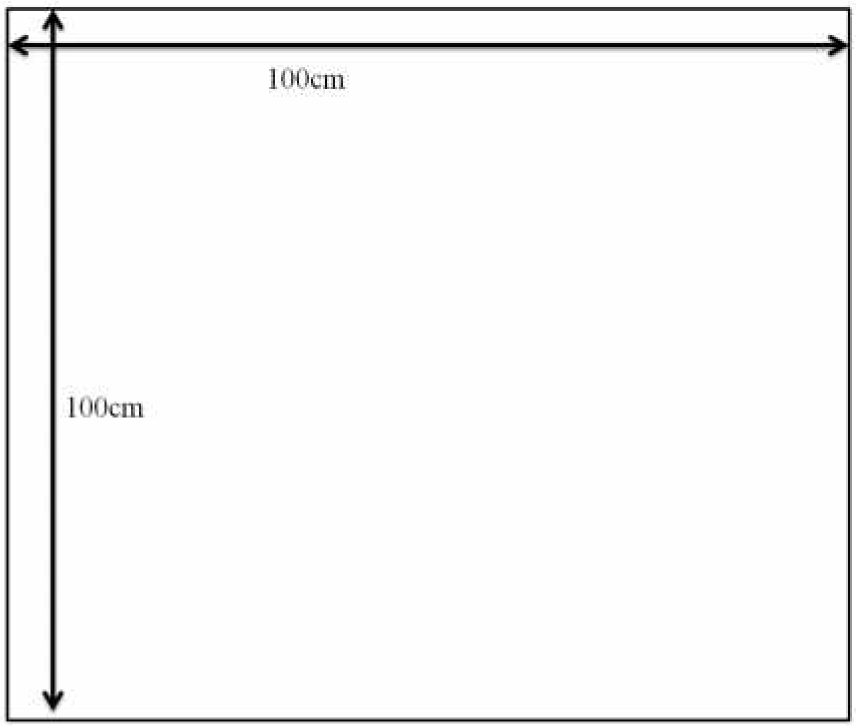

Figure 3.16: Square gore pattern

Figure 3.17: Square parachute

Figure 3.16 is a gore pattern for square parachute. The gore pattern is printed out on A2 paper. The pattern is then cut out and traces on a peach nylon fabric. The fabric is cut out with 2 cm hem. The 2cm hem is then sewn. Shroud lines of nylon cord is then cut into 4 straps of nylon cord with length of 110 cm. Each strap of the cord is then sewn to each four corners of the parachute with stitch of 10 cm. The square parachute is completely sewn is shown in Figure 3.17.

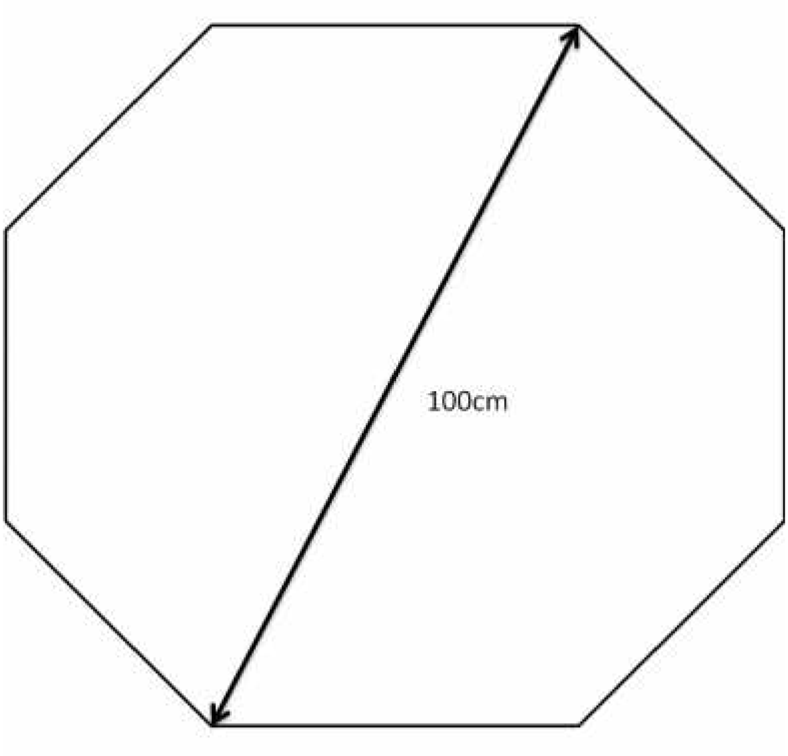

Figure 3.18: Octagon gore pattern

Figure 3.19: Octagon parachute

Same as other previous parachutes, the gore pattern as in Figure 3.18 is printed out on A2 paper. The gore pattern then traced on a green nylon fabric. The fabric then cut out with 2cm hem. As other parachutes, the hem is sewn. 8 straps of nylon cord with 110cm is attached at every eights corners of the parachute with 10 cm stitching underside of the parachute. Figure 3.19 shows the complete octagon parachute.

3.5 PARACHUTE TESTING

A drop test is done at the UMP water tank building to determine to C_d of the constructed parachute. The parachute is attached to different mass of 1.0 kg, 1.5 kg and 2 kg then dropped from the top floor of the building. Time is started when the canopy has opened and the descent has stabilised, which is approximately 30 m from the ground, until it touches the ground. The drop test is performed three times for every different weights and the average descent velocity is calculated. C_d is then calculated using the general drag equation.

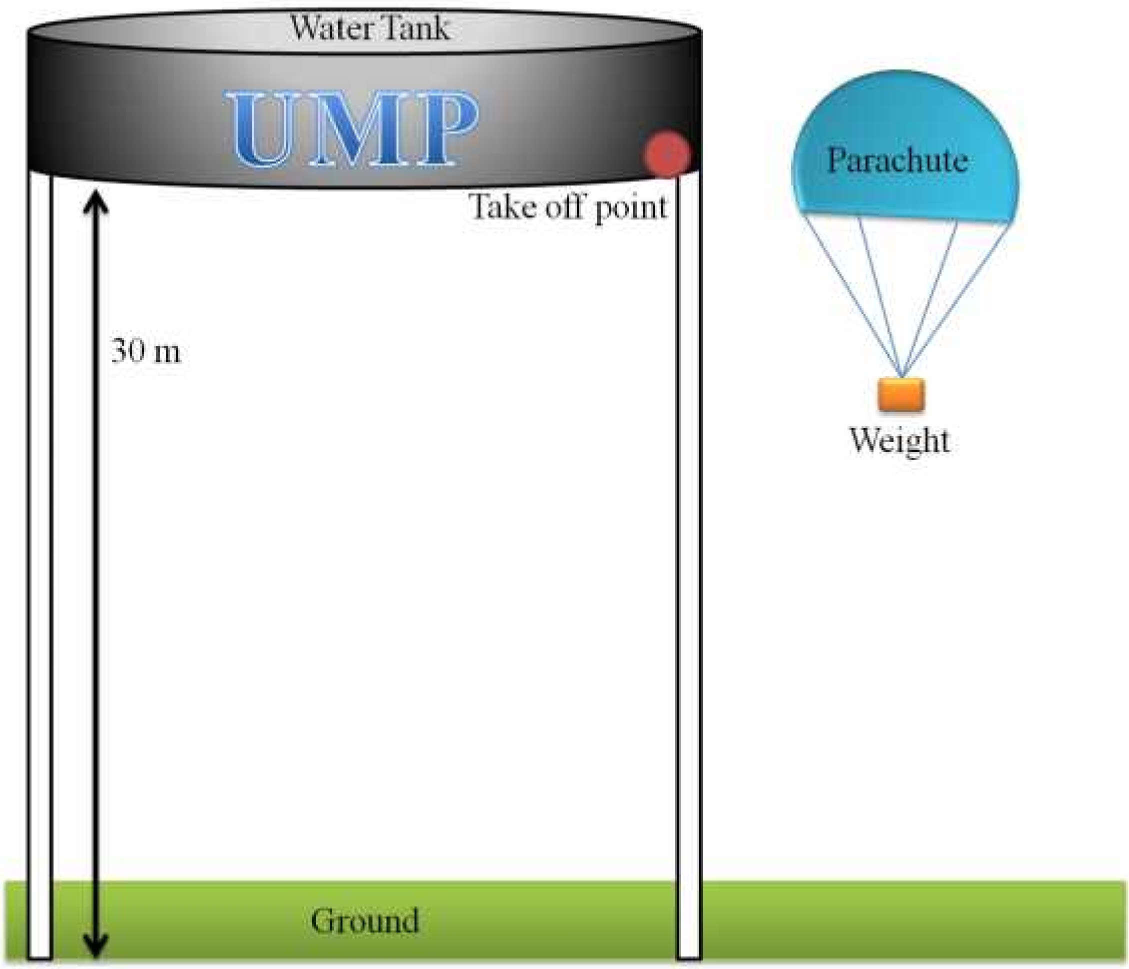

Figure 3.20: Parachute Drop Test

3.6 PARACHUTE DEPLOYMENT SYSTEM DESIGNING AND FABRICATION

Parachute Deployment System (PDS) is an important system for rocket recovery. This system will let the parachute to deploy when the rocket reach at the apogee. This system will include a piston act as the ejector of the parachute. Black powder will be use as the ejection charge of the piston.

3.6.1 Design of Parachute Deployment Ssystem

The PDS will be divided into two parts; the piston as the ejector and the black powder as ejection charge. The PDS is design as Figure 3.21 below.

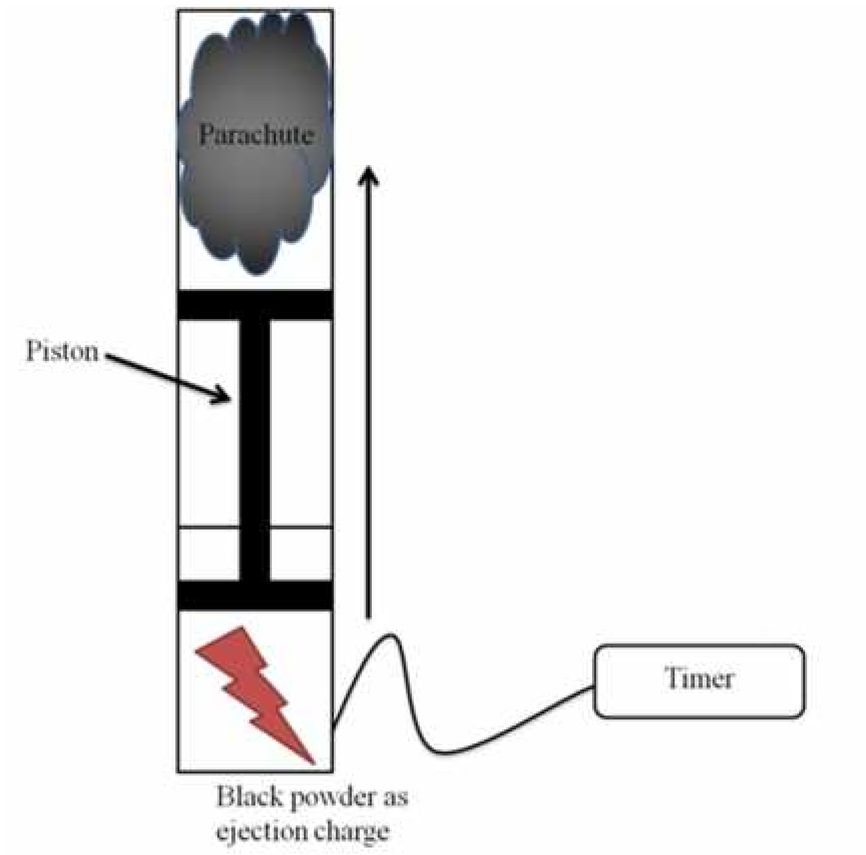

Figure 3.21: Parachute Deployment System

The black powder will act as the ejection charge and it will cause a small blast when igniter receive signal from the timer. Timer will activate the igniter after few seconds of apogee. Effect of the small blast at ejection charge section will push out the parachute and nosecone out of the rocket body. This will deploy the parachute and it will inflate in the air. The parachute will be attached to the rocket body and nosecone so that all the systems will safely landed on ground.

The piston will consist of five parts. The five parts will be assembling together as in Figure 3.22 below.

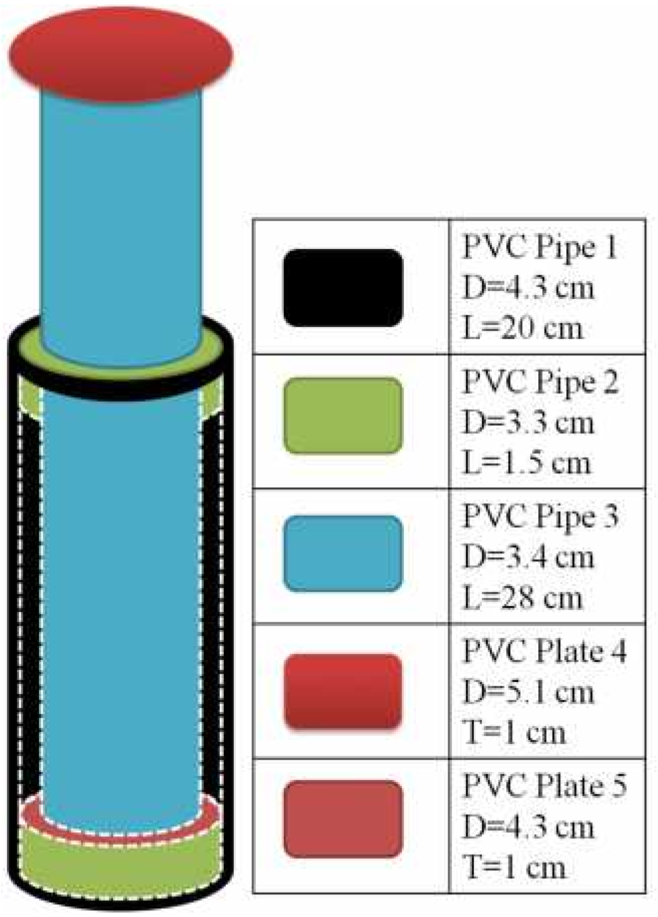

Figure 3.22: Assembled piston

3.6.2 Fabrication of Parachute Deployment System

The piston of the PDS is made by PVC pipe. All five parts of the piston is cut out by their dimensions and being assembled together. Figure 3.23 shows how the PVC pipes and PVC plates are being combined together. The pipes and plates are combined by PVC gum and epoxy.

Figure 3.23: PVC pipes and plates are combined

PVC Pipe 1 will act as the case of the piston. Both PVC Pipes 2 attached at upper and lower parts of PVC Pipe 1 are used to block the PVC Plate 5 to move out of the piston case. PVC Plate 5 acted as the plate to push PVC Plate 4 by PVC Pipe 3. PVC Plate 4 will push out the parachute out of the rocket body. At the lower end of PVC Pipe 1, an end cap will be attached, acting as section for ejection charge takes place. Figure 3.24 shows where the ejection charge of black powder will take place.

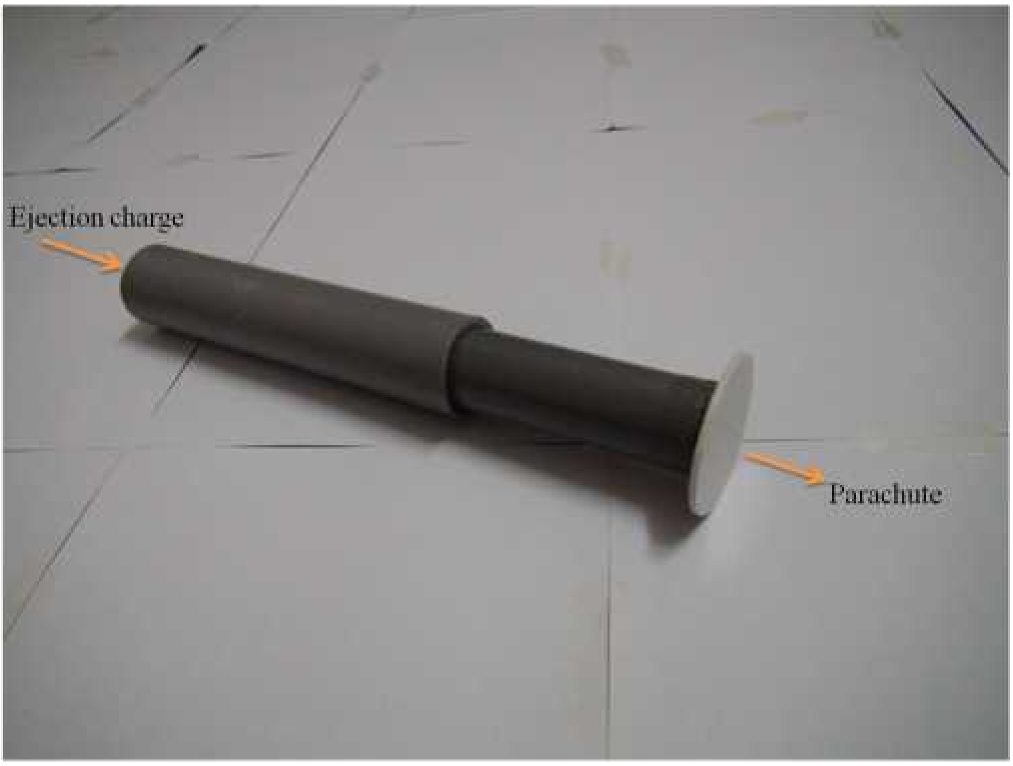

Figure 3.24: Ejection charge and parachute take place

3.7 PARACHUTE DEPLOYMENT SYSTEM TESTING

The PDS will be test to find the suitable ejection charge to push the parachute out of rocket body. Figure 3.25 shows the setups for PDS testing.

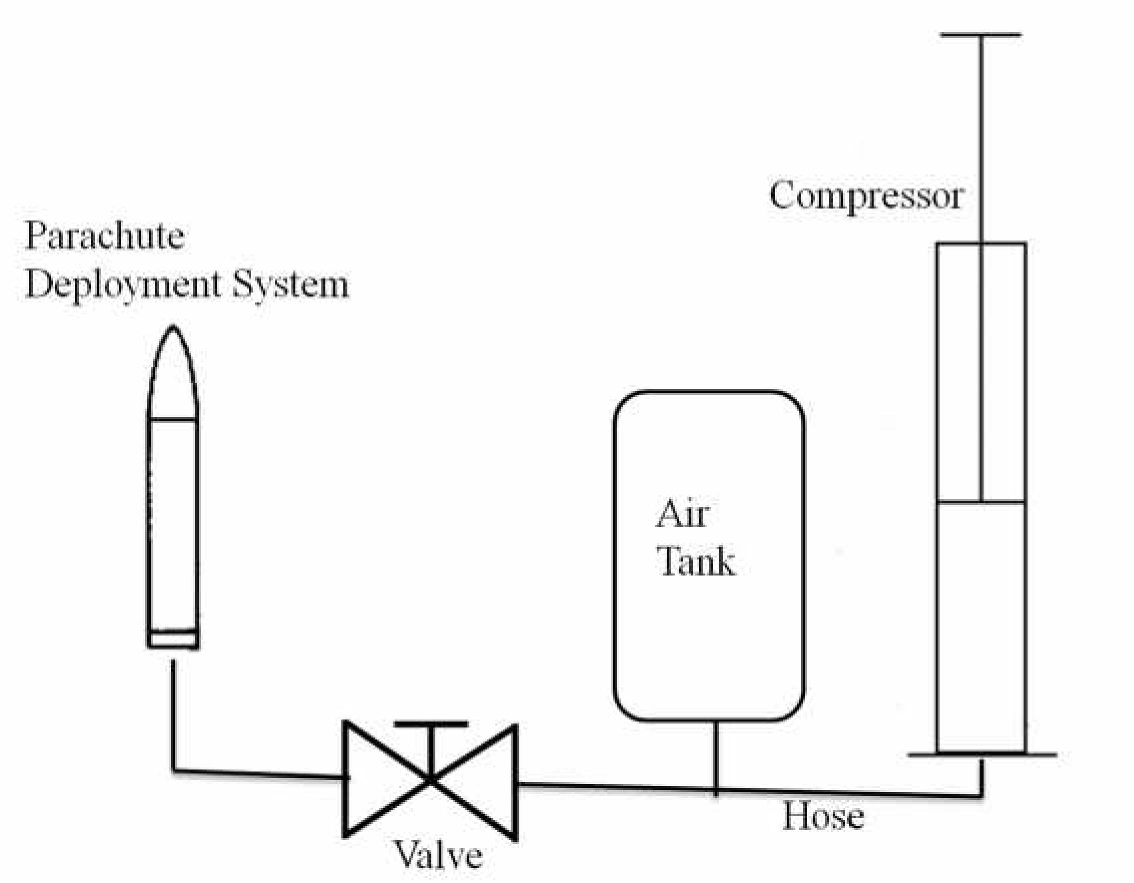

Figure 3.25: PDS testing setups

The compressor will supply air with some pressure reading and being stored in air tank. The valve then will be opened to supply the pressured air to PDS. The piston in PDS will push out the parachute out of the rocket body. This test will find the suitable pressure needed to deploy the parachute.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents and discusses on results of the tests performed. Firstly, the result of the parachute drop test is presented and discussed. Next, the result of the ejection charge test is shown and discussed.

4.2 PARACHUTE DROP TEST

In most rockets, the recovery device is either a parachute or a streamer. The purpose of the recovery device is to slow down the descent of the rocket, so it lands on the ground softly and can be flown again. A parachute is used on heavier rockets, or when it has come down the slowest.

A parachute test had been conducted in order to find out time taken for the rocket falling to the ground by parachute. The objective of this test is to compare which design is better. The parachutes used are hemispherical, semi-ellipsoidal, square, and three other designs. The material for the parachute used is nylon since has good quality and it is also windproof. The different weights used indicate the mass of the rocket body. Time taken for the parachute to land onto ground was recorded. The parachute was launched from 30m height. This parameter was maintained to compare the result of the six parachute designs.

Table 4.1: Figures of test result

Test results	Figures
Parachute is taking off from 30m height	
The parachute starts to descend downward toward ground	
The parachute continue to descend toward ground	

The parachute land onto ground	

Table 4.2: Time recorded for the parachutes to reach ground by different weights.

Parachutes	**Time (seconds)**		
	1.0 kg	**1.5 kg**	**2.0 kg**
Cruciform	6.27	4.55	4.09
Hemispherical	6.37	4.72	4.44
Semi-ellipsoidal	8.30	7.33	6.20
Octagon	6.02	4.58	3.97
Round	5.68	4.45	3.72
Square	6.03	4.70	4.22

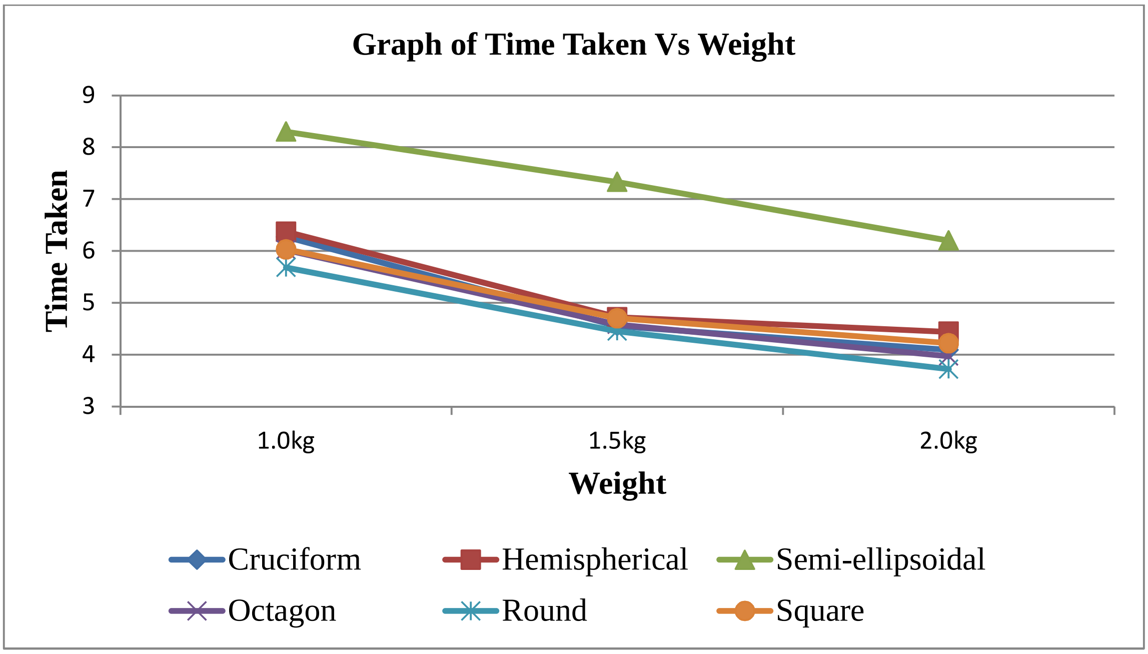

Figure 4.1: Graph of time taken for parachutes landed by different weights.

Table 4.3: Speed calculation for parachutes

Parachutes	$v = \frac{30m}{time}$
Cruciform	4.78 ms^{-1}
Hemispherical	4.71 ms^{-1}
Semi-ellipsoidal	3.61 ms^{-1}
Octagon	4.98 ms^{-1}
Round	5.28 ms^{-1}
Square	4.98 ms^{-1}

Table 4.4: Area calculation for parachutes

Parachutes	$Area = \frac{\pi D^2}{4}$
Cruciform	0.78m^2
Hemispherical	0.78 m^2
Semi-ellipsoidal	0.78 m^2
Octagon	0.78 m^2
Round	0.78 m^2
Square	0.78 m^2

Table 4.5: *Cd* calculation for parachutes

Parachutes	$Cd = \frac{2mg}{\rho A V^2}$
Cruciform	0.90
Hemispherical	0.93
Semi-ellipsoidal	1.58
Octagon	0.83
Round	0.74
Square	0.83

Figure 4.1 shows the time taken for parachutes reach on to ground by different weights and the parachute semi-ellipsoidal gives the best performance during the Drop Test being carried out. The semi-ellipsoidal parachute takes the most time to reach the ground in three different weights. Since the function of parachute is to make longest time to reach ground, so, the semi-ellipsoidal is the best parachute.

In Table 4.2, the table shows that semi-ellipsoidal has performed the lowest speed descent on to the ground compared than other parachutes. Thus, in Table 4.4, the drag coefficient calculated gives the highest value for semi-ellipsoidal parachute. In other hand, the semi-ellipsoidal had suited all the criteria for a good parachute that are; lowest speed and highest drag coefficient.

However, due to the shortness of the drop height and the manner the parachute was dropped, it did not have sufficient time to completely stabilised itself and thus descended with slight oscillation. At the altitude of 1000 m, which is the intended target, the air density is 1.1117 kg/m^3. The parachute is deployed at apogee and estimating the total rocket mass to be2.5 kg, which is the empty weight of the rocket, the estimated descent rate is calculated with the obtained C_d = 1.58. The calculated descent rate of the entire rocket is 5.98m/s. The suitable range for descent rate is between 15 ft/s to 30 ft/s (Nakka, 1999). Converting the range to S.I. unit, it is from 4.572 m/s to 9.144 m/s. Therefore, the rocket should not experience excessive drifting due to wind, nor should it receive high impact upon touchdown.

4.3 PARACHUTE DEPLOYMENT SYSTEM TEST

PDS test had been carried out to find out the needed pressure to deploy the parachute from the payload section of the rocket body. From the PDS test, it shows that required pressure to eject the parachute out of the rocket body is 1 bar. From this, the mass of black powder need to be calculated to find the suitable amount for ejection charge take place.

The mass of the black powder, *m* can be calculated by using Ideal Gas Law.

$$m = \frac{PV}{RT} \tag{4.1}$$

P is the pressure required to deploy the parachute. Pressure required can be estimated from PDS test. *V* is the volume of the piston that ejects the parachute. The value can be attained from the dimensions of the piston; D=4.3 cm and L=12 cm. *R* is the combustion gas constant. *T* is the combustion gas temperature for black powder.

P = 1 bar = 0.1 MPa.

$V = \pi .r^{2}.h = \pi$ x (2.15cm) x (17cm) = 246.87cm^3

R = 8.3145 cm^3.MPa/mol.K

T = 1500^{o}C = 1773.15 K [17]

Mass of black powder = ((0.1) (246.87)) / ((8.3145) (1773.15))

Mass of black powder =0.00167kg=1.67 gram

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

5.1 INTRODUCTION

In this chapter, the conclusion of the project is explained. Then, the future work of this project is outlined.

5.2 CONCLUSIONS

Parachutes were designed, fabricated and tested by performing a drop test. From the test that had been carried out, the semi-ellipsoidal parachute had shown the characteristics of the best parachute that are lowest speed and largest drag coefficient. Based on the results of the drop test, the semi-ellipsoidal parachute is able to support the empty weight of the rocket with a descent velocity of 5.98 m/s.

Besides, based on the test that has been carried out, the shape of parachute that should not be considered is round shape. This have been proved by the data calculated that results in highest descent speed and the smallest value of the drag coefficient. Other than that, octagon and square shape of parachute also should not to take into consideration.

Other than that, based on PDS testing, the required pressure need to deploy the parachute is 1 bar. The mass of black powder needed to be used as ejection charge is then calculated using Ideal Gas Law. The amount of black powder need to attain is 1.67 grams.

5.3 RECOMMENDATIONS

Due to the limitation of materials and time, this project has yet to achieve its full potential. The following works should be continued and considered.

1. Perform wind tunnel testing to determine the drag coefficient of the parachute. Compare this result with the results from parachute drop test.
2. Further study on the parachute ejection system.
3. Perform test launch once solid and positive results have been obtained from the parachute ground test
4. Perform ground test for parachute to inflate with black powder as ejection charge.

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APPENDIX A

Parachute Drop Test

Figure: Cruciform inflated parachute in air

Figure: Hemispherical parachute inflated in air

Figure: Semi-ellipsoidal parachute inflated in air

Figure: Octagon parachute inflated in air

Figure: Round parachute inflated in air

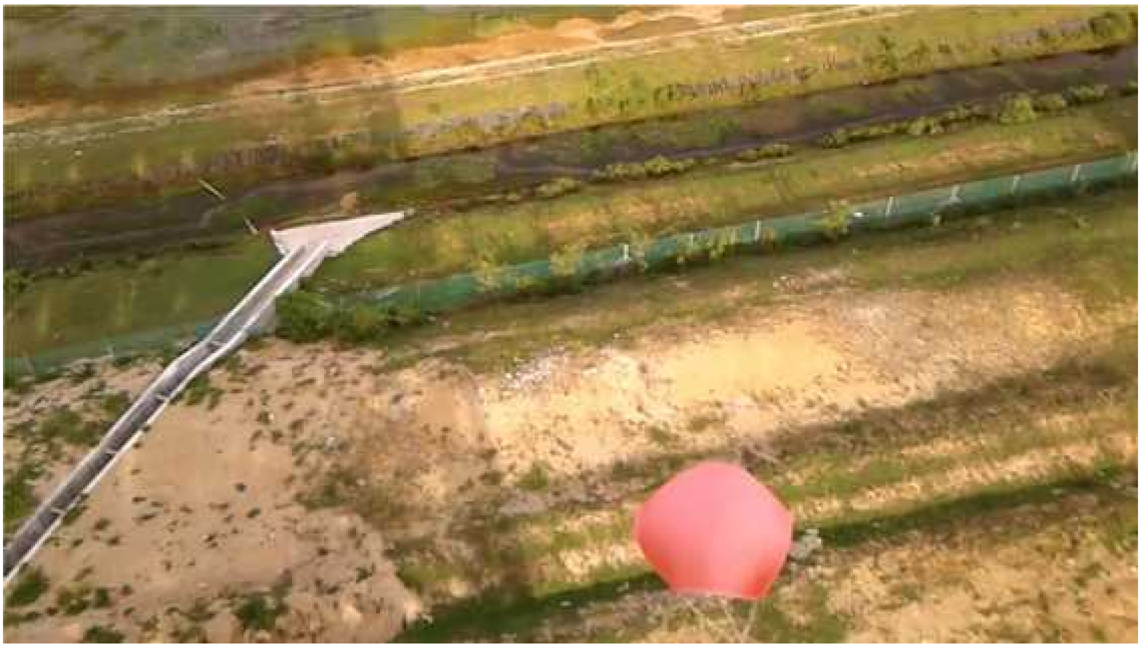

Figure: Square parachute inflated in air

Table: Time recorded for parachutes landed with 1.0 kg of weight

Trial	Cruciform	Hemispherical	Semi-ellipsoidal	Octagon	Round	Square
1	5.05 s	5.91 s	8.00 s	5.32 s	5.40 s	5.60 s
2	5.46 s	6.05 s	7.77 s	6.02 s	6.34 s	6.14 s
3	6.22 s	5.30 s	9.12 s	6.73 s	5.30 s	6.34 s

Table: Time recorded for parachutes landed with 1.5 kg of weight

Trial	Cruciform	Hemispherical	Semi-ellipsoidal	Octagon	Round	Square
1	5.30 s	5.92 s	8.20 s	5.04 s	5.11 s	5.52 s
2	6.04 s	5.16 s	6.70 s	4.11 s	4.59 s	5.60 s
3	6.12 s	3.08 s	7.10 s	4.60 s	3.65 s	5.29 s

Table Time recorded for parachutes landed with 2.0 kg

Trial	Cruciform	Hemispherical	Semi-ellipsoidal	Octagon	Round	Square
1	4.76 s	6.23 s	4.03 s	4.10 s	3.04 s	4.54 s
2	4.00 s	6.27 s	4.75 s	4.11 s	4.92 s	4.11 s
3	3.50 s	6.10 s	4.55 s	4.02 s	3.21 s	4.02 s

APPENDIX B

Parachute Deployment System Testing

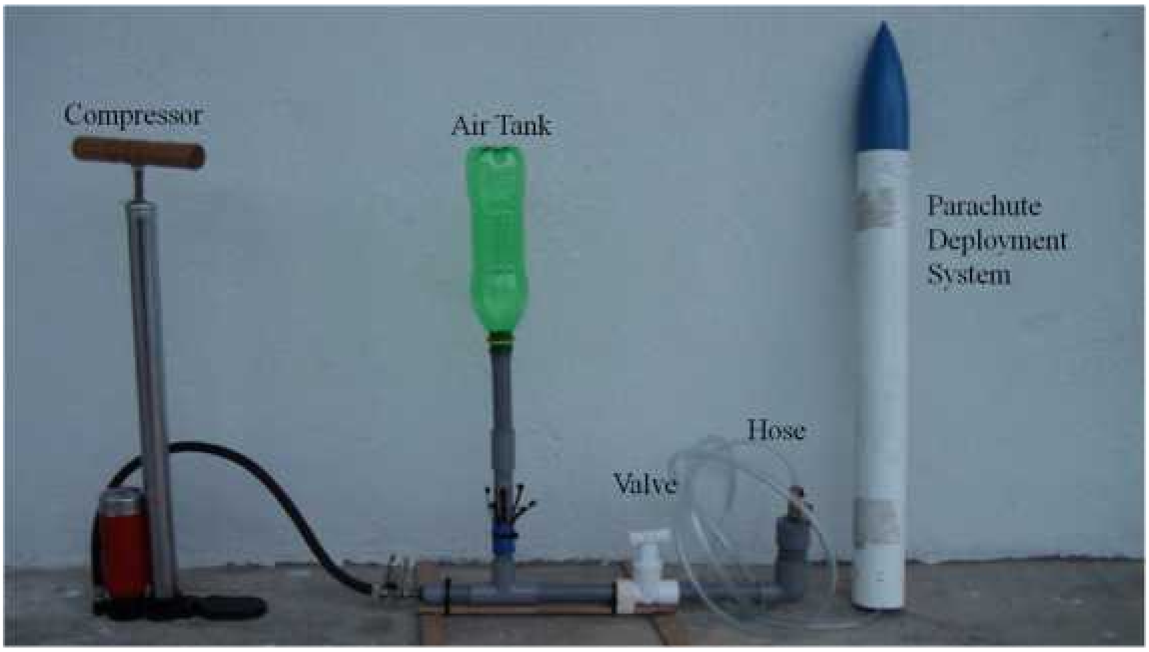

Figure: PDS testing setup

Figure: Pressure gauge

Figure: Parachute pushed out by the piston at 1 bar