CHAPTER 2

REVIEW OF LITERATURE ON PARACHUTE DECELERATION SYSTEM

Notations

M	Mach number
D_o	Nominal diameter (m)

Abbreviations

CM	Crew Module
CPAS	Crew Parachute Assembly System
DGB	Disk-Gap-Band
NASA	National Aeronautics and Space Administration
PRU	Pyro-release Unit
SRE	Space Module Recovery Experiment

2.1 Introduction

There are many decelerator devices used for controlling the descent speed of the vehicle, missile and aircraft (Brandon *et al*., 2010; Dawning *et al*., 1954). Devices as retro-rockets, rotating fins, drag plates are bulky and heavy, and thus costly to carry in space. On the other hand, a parachute is a low cost and reliable alternative that can be easily packed in a small space. Besides, it is comparatively very light in weight. Cruz and Lingard (2006) came with an inflatable aerodynamic deployable parachute as an inflatable device that was designed to greatly increase the drag on an entry vehicle. Nearly five decades have passed since the NASA first proposed the use of parachute technology for the use of planetary entry vehicles. For these reasons, all space missions, except space shuttle, had used the inflatable aerodynamic deployable parachute as a decelerator for recovery of the crew modules.

The parachutes are designed based on shape and size of the canopy, and based on its features. While many parachutes are constructed with solid textile canopies, most high-performance parachutes incorporate slotted textile configurations to relieve stresses at high deployment velocities. Knacke (1986) has provided technical history of parachute development since World War-I. The first available sketch of the parachute devices was drawn by Leonardo da Vinci around 1485. Surprisingly, the people began to use this in flight three centuries later. Some details related to parachute design and development are available in the work of Knacke (1963) and Ewing *et al*. (1978), while a detail on testing of spacecraft parachute recovery systems is available in the work of Christine (2013). The Air Force and NASA conducted early inflatable aerodynamic deployable (parachute) testing independently. The collected data was analyzed by the Goodyear Aerospace Corporation and others (Nebikar, 1961 & 1965; Bloetscher, 1967). Inflatable aerodynamic deployable systems reached their peak in terms of technology-readiness by the mid-seventies during the mission planning phases of the Viking, Pioneer Venus and Galileo missions. These planetary missions were the first to require deployable decelerators during atmospheric descent. Moog *et al*. (1973) and Gillis (1973) have provided details on Viking decelerator system consisting of a single-stage, mortar-deployed, 16m diameter Disk-Gap-Band (DGB) parachute. In the later stages of the technology development, parachute deceleration systems were used for many manned space missions, namely, Apollo (USA), Soyuz (Russia) and Shenzhou (China), and also for various experimental studies, viz Gemini

(Norman, 1967), Orion (Carol *et al.*, 2011), Mercury (Buhler, 1961), SRE (Sidana *et al.*, 2005) and many more as shown in Figure 2.1. The parachute system of Soyuz and Shenzhou (www.spaceflight.com) were nearly identical. Important features, including difference between these systems, are explained in the next sections.

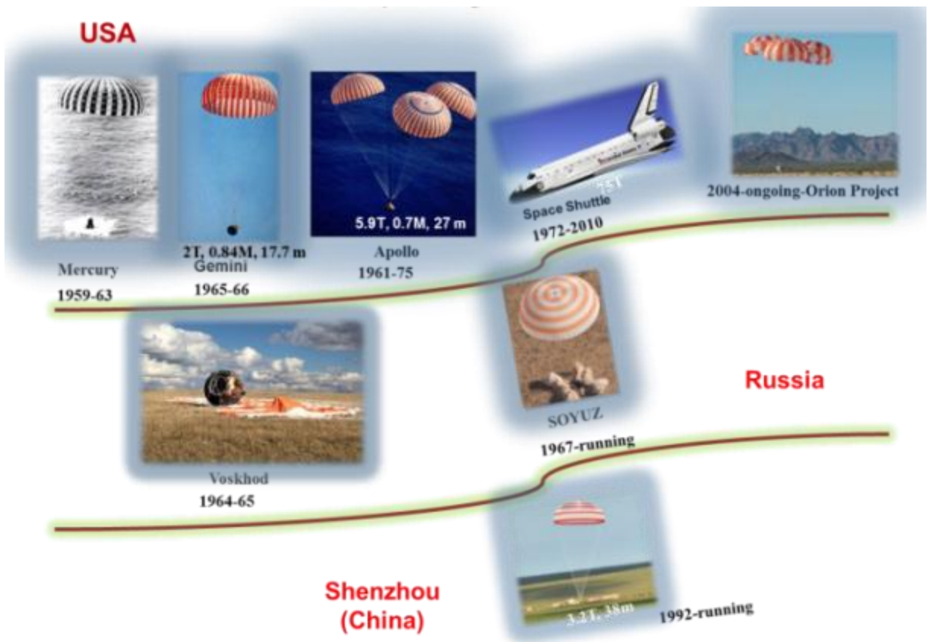

Figure 2.1: Worldwide human space recovery systems

2.2 Apollo's Crew Module Earth Landing System

The Apollo's earth landing system was the first parachute system used as a decelerator for landing of a manned Crew Module. This was the most thoroughly engineered and tested parachute deceleration system used in manned space mission. It was designed for the normal re-entry and also for all the cases of abort mission (West 1973). The earth landing system consists consisted of two mortar-deployed parachutes and three mortar deployed pilots which in turn deployed the three main parachutes. The Apollo program actually qualified for three landing systems (Benson, 1966), i.e., Block I, Block II, and Block II-heavy. All these parachutes were designed to be human-rated, but only the Block II-heavy system was used for manned mission. The Apollo program was built on the experience of both the Mercury and Gemini programs (Logsdom and Roger, 2008). The other details of the system are being provided in the following sub-sections.

2.2.1 Design Feature

The Apollo earth landing deceleration system had the following design features.

(i) Parallel fully automatic sequencing systems were used for all deployment functions.

(ii) It had a provision to manually deploy the drogue parachutes above 7.6 km altitude in the case of command module stability problems.

(iii) A time-controlled deployment sequence was used for pad abort, and a time and baro-switch controlled sequence for high altitude abort.

(iv) Steel riser segments were used in the areas where contact with the vehicle was likely.

(v) The sequencing system that controlled automatic parachute deployment contains two baro-switch units, one each for drogue and main parachute deployment.

(vi) Dual reefing-lines with three cutters in each were used for the drogue parachute and the first reefing stage of the main parachute. Single reefing-line with dual cutters was provided in the second stage reefing of the main parachute.

(vii) All pyro units used double initiators actuated by the both sequencing systems.

The recovery sequence was initiated automatically through the closure of baro-metric switch or through time-delay relays. The normal recovery sequence of re-entry landing system is shown in Figure 2.2 (Knacke, 1968). Apollo pad abort parachute deployment sequence is illustrated in Figure 2.3. This mode is operational prior to launch. During pad abort or low altitude abort, astronaut can select to override the drogue parachutes and deploy the main parachutes immediately as long as the dynamic pressure and the altitude are within the allowable main parachute deployment limits.

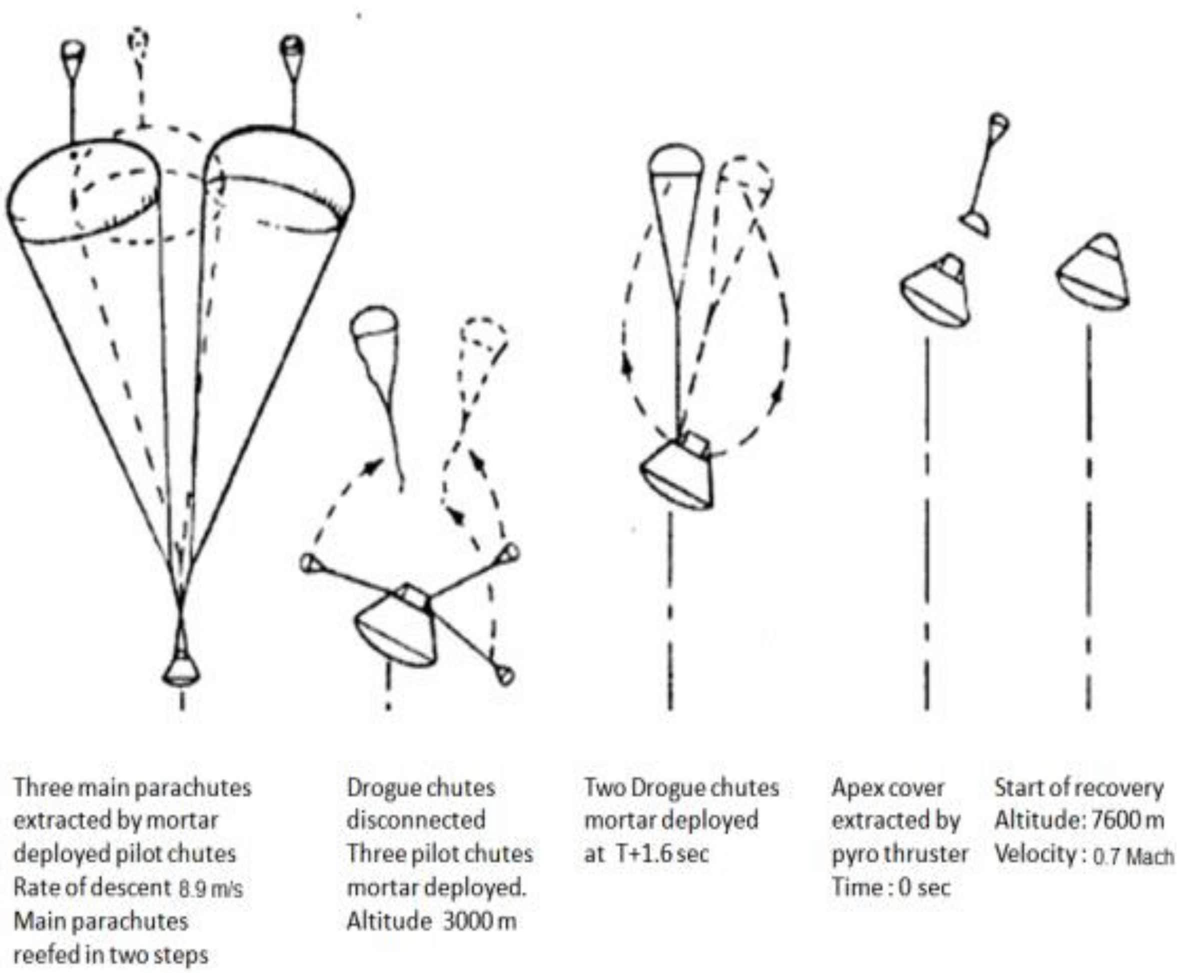

Figure 2.2: Sequence of deployment of Apollo parachute system (Ewing *et al.*, 1978)

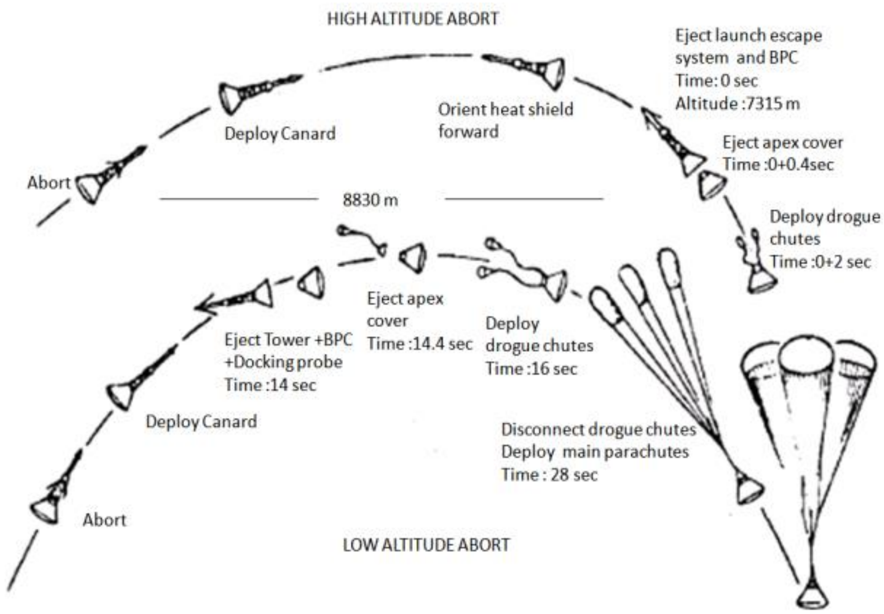

Figure 2.3: Abort sequence of Apollo parachute system (Ewing *et al*., 1978)

2.2.2 Parachute specification

The Apollo recovery system was a two-stage deceleration system. Table 2.1 shows the summary of parachutes used in the Apollo mission.

Table 2.1: Specification of Apollo command module recovery system (Ewing *et al.*, 1978)

Parachute	**Construction type**	D_o	**Remarks**
Pilot chute	Ringslot	2.21 m	No reefing single parachute
Drogue parachute	Conical ribbon	5.065 m	Single stage cluster of two reefed parachutes
Riser	Textile riser, 4-ply-steel cable	60.96m+54.864m	
Main parachute	Ring-sail	26.27 m	Two stage cluster of three reefed parachutes
Riser	Textile, 4-ply steel cable	12.80+ 23.77m	

Some of the strong and weak points based on significant amount of research done on Apollo man mission are as follow.

Strong Points

(i) Cluster of parachutes made the system more stable against oscillations.

(ii) Redundancy in stages avoided the use of failure detection and backup parachute activation system.

(iii) Terminal velocity is to be maintained at the same level both for the nominal and abort missions.

(iv) The system could work satisfactorily in the case of pad abort by overriding the first stage deceleration.

Weak Points

(i) If apex cover failed to separate, the deployment sequence could not be initiated.

(ii) Leading parachute had to experience excessive load in the event of lead/lag inflation

of the main parachutes.

(iii) Reserve parachute system was not available.

2.3 Soyuz Parachute Landing System

Soyuz parachute landing system (Robert, *et al.*, 2013) consisted of a primary system with a full backup system available in the module. In addition to the parachute system, the module was equipped with an impact attenuation system using retro rockets to further reduce the landing speed of the module. The module allowed land recovery in normal missions. The other details of the system are provided below.

2.3.1 Sequence of Operation

Parachute sequence begins with the deployment of pilot chute and drogue parachute at about 10 km altitude. At 5 km altitude, the drogue parachute is released to extract the main parachute from the container. The main parachute (Figure 2.4) supports the CM to descend at terminal velocity of 8 m/s (Ostroumov and Glazkov, 1999). The thermal shield which is covering the blunt end of the CM is jettisoned at 3 km altitude. Gamma-ray altimeter commands the firing of four to six solid propellant rocket motors at an altitude between 1.1 m and 0.8 m from the earth to reduce the final landing speed between 0 to 3 m/s. The number of retro-rockets to be fired prior to landing will depend on the terminal velocity of the crew module (www.russianspaceweb.com). The reserve parachute (backup system) was designed to be deployed at an altitude of 3-6 km at dynamic pressure of 400 -16,000 Pa after failure of the main parachute while separating itself with the main parachute. Drag area of the reserve parachute was nearly half of the main parachute. This causes reduction in the opening load and mass of the reserve parachute. Reduced drag area of the reserve parachute, of course, increases the terminal velocity to 10 m/s, which is higher than the terminal velocity of CM under primary parachute.

Figure 2.4: Soyuz main parachute prior to landing

The Soyuz parachute system (with primary and reserve parachutes) had a total operational reliability of 0.960 with associated confidence level being 95%. The exclusive use of either of the two parachute systems provided a design reliability of 0.93.

2.3.2 Parachute Specification

Table 2.2 shows the set of parachute systems had been used as a decelerator in recovery of the Soyuz module.

Table 2.2: Details of Soyuz parachute

Parachute	**Construction type**	**Size, D_o Normal mode**	**Size, D_o in Backup mode**
Pilot chute	No details	No details	No details
Drogue parachute	No details	5.528 m	5.528 m
Main parachute	No details	35.706 m	27 m

This recovery system for Soyuz module faced a lot of challenges, but finally the mission was successful. Some of the strong and weak points of the system are described below.

Strong Points

(i) The existence of redundancy in apex cover helps crew in activating the backup system during the failure of the primary apex cover.

(ii) Apex cover ejection is side wise. It takes very less time to come out of the wake region and to avoid re-contact with CM.

(iii) Retro-rocket assisted landing allows the capsule to be recovered even in marshy land.

(iv) Provision of dedicated reserve parachute for abort deployment.

Weak Points

(i) Single parachute in series makes the system less stable than the cluster one.

(ii) It had encountered one catastrophic failure.

(iii)The same reliability was not assured for nominal and abort-case deployments.

From Table A.1 provided in Appendix-A, one can easily notice the differences in the deceleration system used in Apollo and Soyuz.

2.4 Orion's Crew Module Recovery Parachute System

Orion's parachute system was designed to ensure a safe landing for astronauts returning to earth in the crew module at a speed exceeding 11,176 m/s. While the Earth's atmosphere will initially bring the speed of the spacecraft down from 8,941 m/s to 145 m/s, the parachutes were needed to provide a safe landing speed at 9 m/s or less. The deployment sequence of the system, known as high-altitude abort Crew Parachute Assembly System (CPAS), is shown in Figure 2.5.

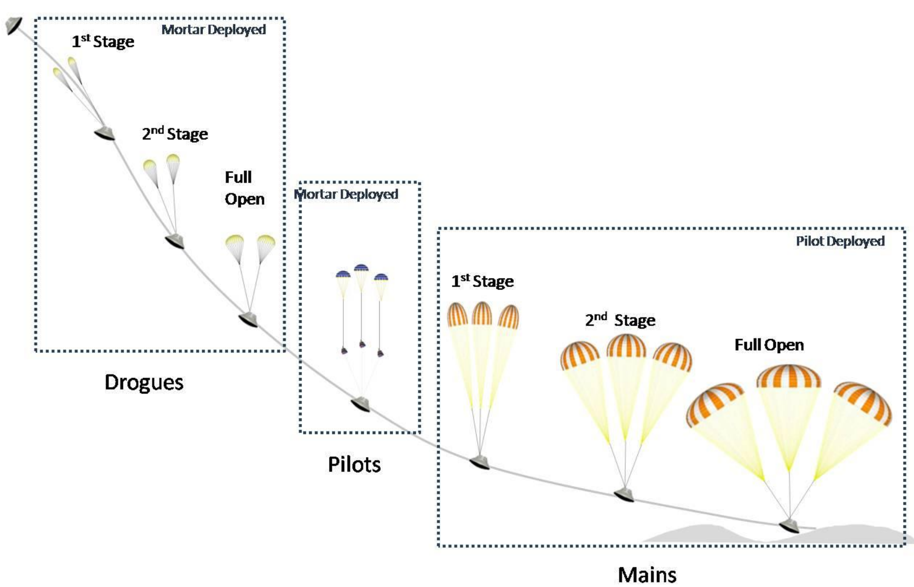

Figure 2.5: Deployment sequence of CPAS in nominal and high-altitude ascent abort (Carol *et al*., 2011)

Orion’s parachute system (Figure 2.6) consisted of a total of 11 parachutes (Taylor *et al.*, 2007), deployed at 3 km altitude to work at a speed of 58 m/s. The main parachutes are to slowdown the speed of the crew module to a landing speed of 7.6 m/s.

Figure 2.6: Orion’s parachute system returning from space (www.nasa.gov.com)

Orion’s parachute system was designed to withstand the failure of either one drogue or one main parachute ensuring secure landing in an emergency. It was witnessed during the successful pad abort and also during flight tests (Morris *et al.*, 2011). Before the crew actually fly in the spacecraft, the system was to undergo additional tests to validate the design and to demonstrate repeatability (Kolesar, 2013; Stuart, 2012).

2.5 Space Module Recover Experiment (SRE)

SRE was the India’s first space experimental mission conducted successfully in 2007. In this experiment, a recovery system for 500 kg payload was designed and developed by India for microgravity study. The recovery system comprised of two stages: PDS and forced gas-based floatation system. The stage-1 decelerator used a conical ribbon of 3m diameter to stabilize the payload and retard the speed from 110 m/s at 5 km to 56 m/s at 2 km above mean sea level enabling the deployment of the main parachute. The main parachute (second stage deceleration) was of 13 m diameter, aero-conical in shape and to provide minimum oscillation during terminal descent. The final touchdown speed was to be less than 15 m/s. The deployment was initiated through pyro-gun lid plate that pulled out the pilot chute. Pilot chute pulled out the drogue parachute (I-stage) and got detached through pyro-release unit (PRU) which in turn pulled out the main parachute which further retarded the payload till touchdown as shown in Figure 2.7.

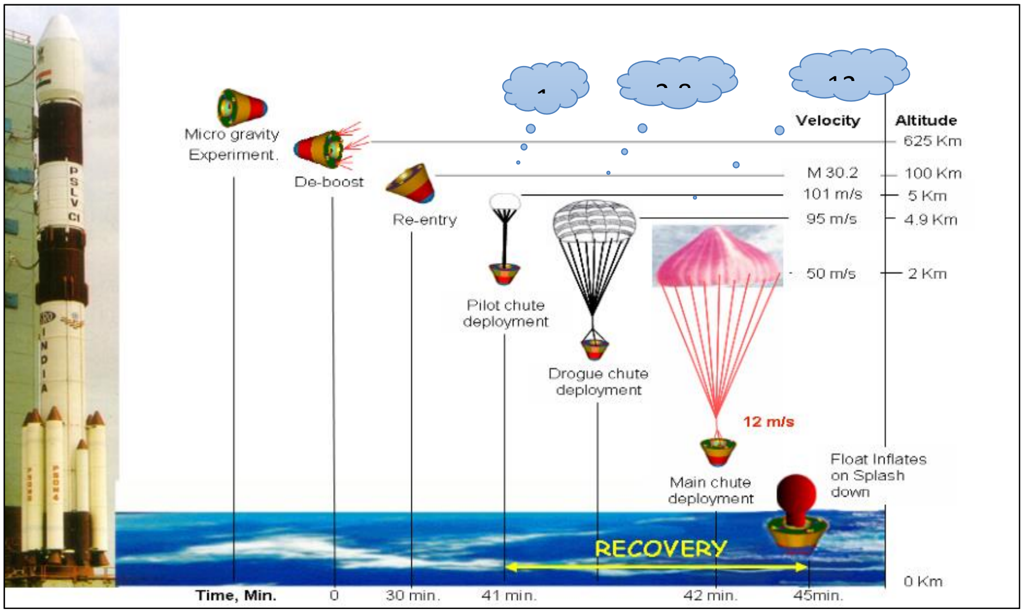

Figure 2.7: Sequence of recovery system operation of SRE (Sidana *et al.*, 2005)

It was surprise that no redundant parachute system was used. Reliability of parachute system was established through various testing such as, wind tunnel test, static ground test, bench test, packing and fitment test, aircraft gravity test, helicopter altitude drops test and dynamic test, etc.

2.6 Other Types of Parachutes used in Space Missions

Parachutes are designed according to the specific requirements. Johnson (1989) invented the ringslot/solid-canopy parachute to decelerate the F-111 crew escape module to an impact velocity of 8 m/s. The disk-gap-band parachute (Eckstrom *et al.,* 1969) was developed and patented by Eckstrom in the mid-1960s under a contract to NASA. A conical ribbon parachute with figure-eight shape design features was also developed (Maydew and Johnson, 1972). Table 2.3 shows the types of parachutes used as pilot chute and main parachutes for various space missions.

Table 2.3: Worldwide type of parachutes used in space missions (Lingard, 2008)

Mission	**Pilot chute (D_o)**	**Main chute (D_o)**	**Deployment conditions**		
			Altitude (km)	**Speed (M)**	**Dynamic pressure (Pa)**
Viking	Not known	DGB (unreefed)-mortar deployed (16.2 m)	**6.4**	1.6	200-500
Pioneer Venus	mortar deployed (0.76 m)	Conical ribbon (4.94 m)	67.1	0.8	3300
Galileo	Conical ribbon, mortar deployed (1.14 m)	Conical ribbon (3.8 m)	Not known	Pilot 0.91-1.01 Main 0.87-0.97	4875-7648
Mars Pathfinder	Not known	DGB, mortar deployed (12.7 m)	7.5-12.1	1.7-2.30	580-700
Cassini Huygens	DGB, mortar deployed (2.59 m)	DGB (8.3 m)	141-180	1.38-1.73	287-440
MER	Not known	DGB (14.10 m)	Not known	1.49-2.30	569-830

From the above table, it is noticed that mortar–type pilot chute deployments were consistent and reliable. Conical ribbon parachutes were used both for pilot as well as main parachute. However, DGB was also equally used as a main decelerator for the recovery of a space payload.

2.7 Summary

In this chapter, relevant and detailed literature review of the inflatable aerodynamic parachute systems have been presented that are used worldwide for various space missions. A comparison of the features of some parachute systems used for re-entry module has also been presented in this chapter.

Besides, their merits and demerits as well has also been discussed from application point of view. The review exhibits that the parachutes used as deceleration system in earlier missions are not applicable to the planned mission, and thus requires a fresh system to be designed, tested and developed.