CHAPTER 8

RELIABILITY ANALYSIS OF PARACHUTE DECELERATION SYSTEM

Notations

σ_x	Standard deviation for strength X
σ_y	Standard deviation for Stress Y
μ_x	Mean of strength (N/m^2)
μ_y	Mean of stress (N/m^2)
μ_U	Mean value of U
σ_U	Standard deviation value of U
σ_x^2	Variances of the stress
σ_y^2	Variance of strength
k	Minimum number of units required for system success
m	Maximum number of canopies
n	Total number of units in parallel
p	Expected probability of failure
A	Area (m^2)
L	Lift force due to helium gas
N	Number of trials
P	Probability
Q	Unreliability
R	Reliability

T	Total tension in tether (N)
U	Random variable representing excess value of X over Y ($=X-Y$)
X	A random variable representing strength (N)
Y	A random variable representing stress (N)
$\bar{R}$	Reliability to be allocated to the 'n' sub systems
$f(x)$	Probability of failure occurs exactly at X time in N trials
$g(x)$	Probability Density Function (PDF) for strength variable X
$f(y)$	PDF for the stress random variable Y
$F(y)$	CDF for stress variable Y
$G(x)$	Cumulative Distribution Function (CDF) for strength variable X
F_p	Packing failure
L_f	Allowable free lift (%)
$\mathrm{P_d}$	Probability of failure of entire cluster
$\mathrm{P_r}$	Expected probability of failure
$\mathrm{Q_i}$	Reliability of component i
$\mathrm{Q_s}$	System Unreliability
R_i	Reliability of component i
R_j	Reliability allocated to j^{th} sub system.
R_p	Packing reliability
R_s	System reliability
R_{Sn}	Reliability of component, n
W_j	Weightage factor
Xi	Importance of the i^{th} minimal cut set in the fault tree structure

Abbreviations

FMEA	Failure Mode and Effects and Analysis
FTA	Fault Tree Analysis
RBD	Reliability Block Diagram
TCS	Top Cover Separation

8.1 Introduction

The chutes and parachutes considered under the present study have all the components made of textile materials. Strength and reliability are the important requirements of textile fabric for smooth operation. Parachute strength has been estimated and discussed in Chapter 5. Risk analysis and failure analysis model of the decelerator system has already been presented in Chapter 6 & 7 respectively. Based on the failure rate or stress-strength variation, the reliability of the system needs to be determined for reliable operation of the deceleration system. This chapter is discussing the methodology and establish the reliability of the parachute deceleration system. Reliability referred to textile materials means capacity to retain their usability when exposed to a certain external load or impact.

The reliability analysis is performed to identify the design improvements at an early stage of system development. Based on the reliability analysis, the design of parachute can be improved, over-designing can be prevented and testing time can be optimized. Many of the unforeseen eventualities will require rigorous testing. Based on the test data, the stated issues are once again looked into.

8.1.1 Uncertainty Related to Parachute

There are many uncertainties involved in parachute operation particularly related to load sharing among cluster parachutes, reefing lines-cutter, delay mechanism, opening of parachute sequence and improper packing (Bledsoe *et al.,* 2009). It is necessary to take account of the uncertainty involved. The reliability engineering effort, during design should address all of the anticipated and possibly unanticipated causes of failure propagation, and in manufacturing and services, to ensure that their occurrence is prevented or minimized. Uncertainties involved with the parachute are listed below.

a) **Measurement errors.** In reality dimension of parachute is never perfect as it is made of flexible textile fabrics. Thus, it is bound to have a measurement error.

b) **Modeling error**. Designing of parachute, particularly based on analytical tools, use of certain assumptions that may be true in real world application.

c) **Navigational errors**: It refers to errors in the determination of the longitude, latitude and the heading.

d) **Atmospheric uncertainties**: This error is because of the fact that it is very hard to correctly predict the true conditions of the flight/landing site atmosphere.

8.1.2 Factors for Poor Reliability of Parachute

As discussed above, a parachute has to function under various uncertainties, and this makes parachute performance to be stochastic. Maydew and Peterson (1991) have brought out major causes of unreliability in parachute operation. In designing for reliable performance, and also for assessing the reliability of a given design, the possibility of failures from all factors carrying poor reliability must be addressed. Since every parachute system goes through design, development and testing, design errors are generally eliminated during development.

In many missions, the tear of a gore panel in a canopy does not necessarily means a failure of a mission. Also, the case, where the trajectory deviates from the specified target due to failure of gore panel, is counted as mission failure even though the mission is successful. On the other hand, in such a mission, the failure of the riser or a suspension-line could very well result in a major damage or destruction to the CM or mission.

Failures of the mechanical devices used in parachute systems are more straightforward than failures in the fabric portion. Such devices are reefing-lines cutters; inter stage bridle lines, deployment-initiation devices, etc. Here, the reliability is related to the functioning of mechanical device in an environment of low temperature, shock vibration, acceleration, and possibly other interfacing factors. In such cases, assessment of reliability is a matter of testing adequate numbers of such devices under simulated conditions reflecting their use environment.

Human errors in manufacturing, assembly or inspection are more difficult to deal with than mechanical devices.

8.2 Development of the Reliability Model

Reliability is an important design parameter and must be incorporated into a product at the design stage. Many of the design variables are random, and hence the design methodology must consider them as random variables (Haugen, 1991 and Kececioglu, 1991). The reliability of a parachute system for the aerospace application must be relatively high. The factors which tend to reduce the reliability need be identified and are to be corrected before operation.

A space recovery parachute is a "one-shot" system. The probability distribution best describing such a system is the binomial distribution. It mathematically expresses the probability, P_r, that failure will occur exactly '*k*' times in '*n*' independent trials of the system, where *p* is the expected probability of failure is given by equation (9.1).

In the case of multi-use parachute system, it is necessary to establish the effect of prior use on reliability. Such factors as wear, age, damage on landing, weakening of fabric members by previous loading, and effect of exposure to sunlight during previous uses, must be evaluated with respect to their effects on overall reliability.

In the case of multi-stage parachute system, in which each canopy must open sequentially to decelerate the CM, the reliability of each canopy is considered as a series term in a simple product model. Clusters of parachute canopies used to decelerate a single load are composed of components in parallel from a physical view point. From a probabilistic viewpoint, however, their treatment depends on the design of the parachute system. If the system can operate successfully only with all canopies in the cluster successfully deployed, then each canopy is represented by a series term in the model, and the cluster is treated as a number of separate independent components. However, if the load is decelerated successfully even if one (or more) of the parachutes in the cluster fail, the situation is a series-parallel one from a probabilistic view point. In general, the probability of failure of an identical canopy, P_r, out of a total of *n* in the cluster, when the probability of failure of a single canopy is *p* ($k = 1$), is to be calculated using equation (8.1).

$$P_r = \binom{n}{k} p^k (1-p)^{n-k} \quad (8.1)$$

If 'm' is chosen as the maximum number of canopies (out of total N canopies) which can fail without affecting the success of the mission, then the probability of failure of the entire cluster, P_d, will be estimated by equation (8.2),

$$P_d = \prod_{r=m+1}^{N} P_r \quad (8.2)$$

The additional complexity which arises in the reliability evaluation is due to reuse of the recoverable and re-usable parachute system. After the mission, if the returned parachute is refurbished as a new, re-use factor may be ignored. The use of the binomial distribution to calculate parachute system reliability is discussed in detail by Jailer *et al.* (1960). The highest possibility of a lines breaking is experienced either in the opening shock or in the snatch force.

8.2.1 Stress-Strength Method

The stress-strength interference model is the one that is used to compute reliability. It is found to be useful in situations where the reliability of a component or system is defined by the probability that a random variable *X* is greater than another random variable *Y* (Baohai *et al.*, 1997). A component is deemed to have failed when its strength is lower than the applied stress. This model is not restricted to stress and strength. It can be applied to any situation or problem where the random variable *X* represents any performance related characteristic of the system under question and *Y* serves as a criterion that determines failure (Weerahandi and Jonson, 1992). Design for reliability is the probabilistic approach to design (Kececioglu and Cormier, 1968). The design variables are random variables and hence the design methodology must consider them as random variables. The reliability computations for the various distributions, such as, Exponential, Lognormal, Gamma, Weibull and several extreme value distributions have been developed by Kapur and Lamberson (1977). There are systems (physical components) which survive due to their inherent strength. If a higher load is applied, and then their strength is unable to absorb the excess load and fail. Figure 8.1 shows $g(x)$ as the pdf for the strength variable '*X*' and $f(y)$ as the pdf for the stress variable '*Y*' (Donald *et al*., 1991).

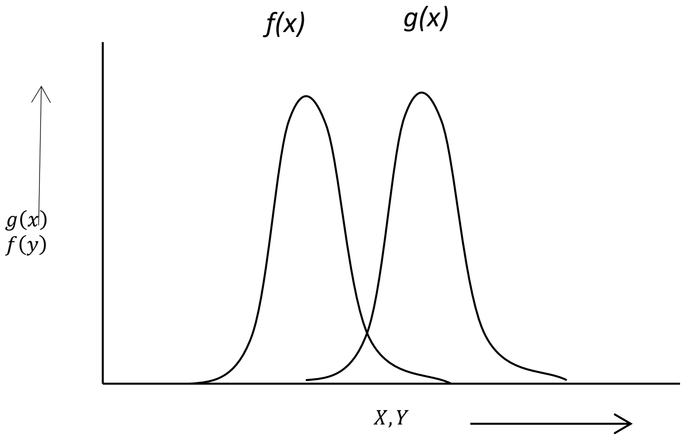

Figure 8.1: Stress-strength distribution

In determining the reliability, *R*, of a product, it is assumed that the stress and the strength are independent random variables and have relation as given in equation (8.3).

Reliability = *R* = P[Strength > Stress]

$$R = P(X > Y)$$

$$= \int_{-\infty}^{+\infty} g(x)\{\int_{-\infty}^{x} f(y)dy\}dx$$

$$= \int_{-\infty}^{+\infty} g(x)F(x)dx$$

$$= \int_{-\infty}^{+\infty} f(y)\{\int_{y}^{+\infty} g(x)dx\}dy$$

$$= \int_{-\infty}^{+\infty} f(y)\{1 - G(y)\}dy) \tag{8.3}$$

where P($X > Y$) is a measure of reliability relationship which represents the probability that the strength exceeds the stress.

Let a product has strength X, with mean as μ_x and standard deviation as σ_x. Similarly, let the stress variable Y is normally distributed with mean as μ_y and with the standard deviation as σ_y. The reliability R for this mode of failure can be derived from equation (8.4), with the final expression as given in equation (8.5).

$$R = P(X > Y) = P[(X - Y) > 0] \tag{8.4}$$

It is known that $U = X - Y$ is also normally distributed with

$$\mu_u = \mu_x - \mu_y$$

$$\sigma_u^2 = \sigma_x^2 + \sigma_y^2$$

Therefore,

$$R = P[U > 0] = \phi[Z > \{\frac{-\mu_U}{\sigma_U}\}] = \phi[Z < \{\frac{\mu_U}{\sigma_U}\}]$$

or

$$R = \phi\{\frac{\mu_x - \mu_y}{\sqrt{\sigma_x^2 + \sigma_y^2}}\} \tag{8.5}$$

where $\phi(.)$ is the standard N (0,1) normal cumulative distribution function for the standard normal variable.

The factor of safety, represented by a number n, is the ratio of strength (X) to the stress (Y) and is given by equation (8.6). Since, both X and Y are random variables, therefore,

$$n = \frac{\mu_x}{\mu_y} \tag{8.6}$$

The least complex approach to the study of the reliability of a single use system consists of testing a number of systems to determine the failure rate of the sample, with an adequate confidence level (confidence coefficient). The reliability of the system can be calculated by subtracting probability of failure from unity. A reliability of 0.999 at 90% confidence coefficient will mean a large number of sets of samples are tested and the reliability of the systems in the sets will be 0.999 at least 90% of the time. In calculating system reliability by this method from series of test results, the confidence coefficient used must be selected. In practice 100% confidence coefficient will not have any significant meaning. It must be realized that the higher is the confidence coefficient, lower will be the reliability and vice versa (Montgomery and Runger, 2007).

The choice of a confidence coefficient for reliability calculation in practical cases is decided by the amount of test data available for study. The cost of performing the testing is the controlling factor in the choice of confidence coefficient.

8.2.2 Operational Reliability

The specific concept of operational reliability, that is, of the parachute packing reliability, which will probably be one of the more important factors in the overall result, will be described here in detail. On the basis of the past experience with similar parachutes, the maximum likelihood of estimate of the packing reliability R_o is given by equation (8.7).

$$R_o = \frac{N-F_p}{N} \quad = 1-F_p/N \tag{8.7}$$

The value of F_p can be obtained from Table 8.1 for a confidence level and number of failures. The operational reliability in parachute is number of packing failure divided by total packing performed. More number of packing tests gives higher reliability of parachute operation. The human error in the parachute packing process is major source of parachute system failure. For detailed elaboration on this matter, one can refer to work of Jailor *et al.* (1960).

Table 8.1: R_o for selected confidence level and number of failures from a series of trials (Jailer *et al*., 1960)

No. of failures	**90%**	**94%**	**95%**	**96%**	**96.5%**	**97.5%**	**98%**	**98.7%**	**99%**
0	2.28	2.94	3.00	3.22	3.37	3.68	3.87	4.36	4.58
1	3.89	4.68	4.74	5.02	5.19	5.56	5.79	6.36	6.61
2	5.32	6.22	6.30	6.61	6.80	7.21	7.46	8.10	8.38
3	6.68	7.67	7.75	8.09	8.30	8.75	9.03	9.71	10.00
4	7.99	9.07	9.15	9.52	9.74	10.2	10.5	11.2	11.6
5	9.28	10.4	10.5	10.9	11.1	11.6	12.00	12.8	13.1
6	10.5	11.8	11.8	12.2	12.5	13.0	13.4	14.2	14.5

8.2.3 Component Reliability and Confidence Level

Reliability of each component of the system is used in computing the reliability of the complete system. One can use laboratory test data, engineering computation, or actual field use experience with identical components in other system to compute the reliability of the components and then of the complete system. Table 8.2 provides approximate value of confidence (Jailor *et al.,* 1960) required for each component to achieve an overall confidence of 90% in the final result. To avoid complexity in the evaluation of the reliability model, it was recommended by Jailor et al. (1960) that the number of components should not be more than 12.

Table 8.2: Approximate confidence coefficient for given number of components (Jailer *et al*., 1960)

No. of components	2	3	4	5, 6	7, 8, 9	10, 11, 12
Confidence coefficient for individual component	0.95	0.965	0.975	0.98	0.987	0.99

8.3 Computation of Reliability of Parachute Deceleration System

8.3.1 Reliability Block Diagram

RBD is a functional group of the item being used in the further elaboration to show interdependencies among all elements (subsystems, equipment, etc.). It is a graphical depiction of the parachute system's components and connectors which can be used to determine the overall system reliability. Each block of the RBD represents one element of function contained in the item. All blocks are configured in series, parallel, standby, or combinations thereof as appropriate (Mary and Marvin, 2014).

8.3.1.1 RBD of TCS Chute

TCS chute is designed to carry away the forward heat shield of CM. Two chutes are connected with forward heat shield in a cluster in which one chute is function as an active redundancy. If one fails, the other chute will be used for performing the operation. Its RBD is shown in Figure 8.2.

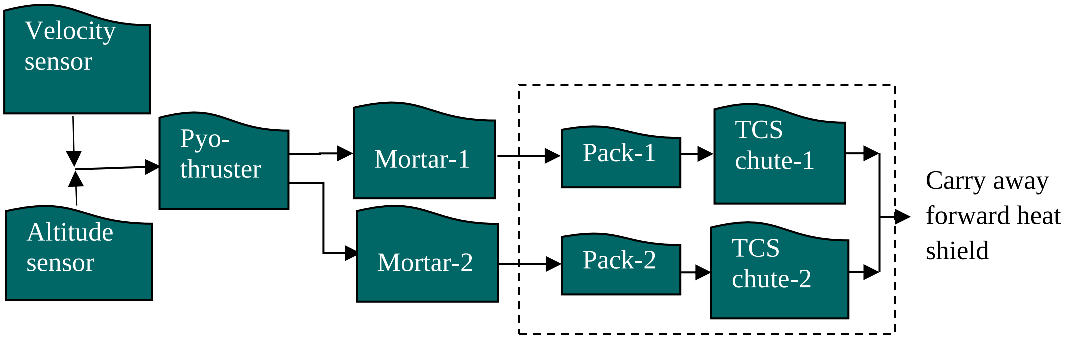

Figure 8.2: RBD of TCS chute

Using the RBD of TCS chute, the reliability of overall functionality of TCS chute can be determined using equation (8.8).

Reliability of TCS Chute,

$$R_{TCS} = R_{sensor} \times R_{pyrothuster} \times R_{mortar} \; x \; R_{chutes}$$

where, $R_{sensor} = 1 - (1- R_{altitud-sensor})(1- R_{velocit-\,sensor})$

Considering only the chutes for TCS reliability analysis,

$$R_{canopy\ 1} = R_{canopy\ 2} = R_{suspension\ lines} \times R_{riser} \times R_{packing}$$

Therefore,

$$R_{TCS} = [1- (1- R_{canopy1})\ (1- R_{canopy\ 2})] \qquad (8.8)$$

8.3.1.2 Pilot Chute

The pilot chutes are deployed individually by mortars in different directions to pull out the drogue parachutes in free stream air. RBD for the pilot chute is depicted in Figure 8.3.

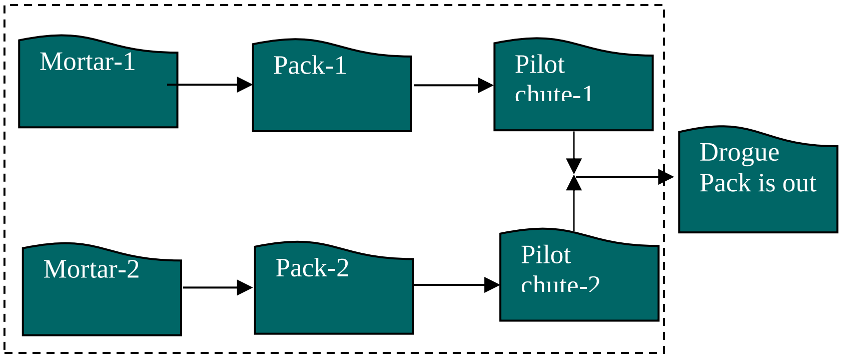

Figure 8.3: RBD of pilot chute

The pilot chute system is constituted of two canopies arranged in the parallel combination; thus, the reliability of the pilot chutes is as given by equation (8.9).

$$R_{pilot\ chute} = 1 - (1- R_{canopy\ 1})\ (1- R_{canopy\ 2}) \qquad (8.9)$$

where,

$$R_{canopy\ 1} = R_{canopy\ 2} = R_{suspension\ lines} \times R_{riser} \times R_{packing}$$

8.3.1.3 *Drogue Parachute*

The drogue parachute is the first stage decelerator and the most critical subsystem. The reliability of this subsystem has a greater significance to the overall system reliability. RBD of the two drogue parachutes, which are arranged in parallel combination, is shown in Figure 8.4.

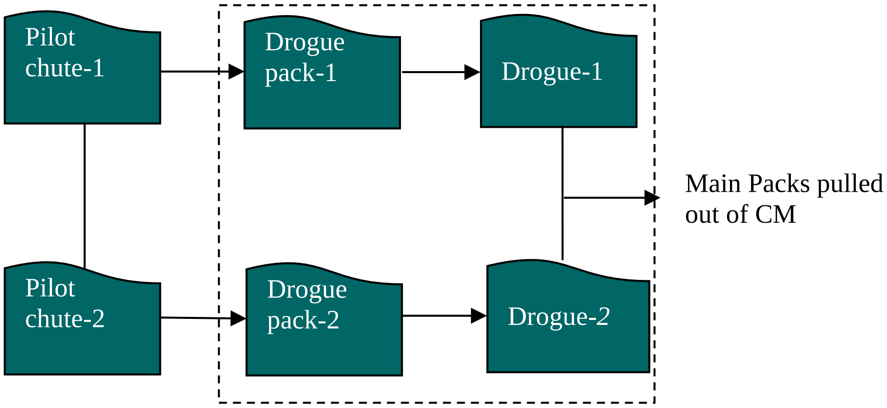

Figure 8.4: RBD of drogue parachute

Reliability of drogue parachute will be governed by reliability of suspension-lines, riser, PRU and parachute packing, and can be determined by equation (8.10).

$$R_{drogue} = 1 - (1 - R_{canopy\ 1})(1 - R_{canopy\ 2}) \tag{8.10}$$

where,

$$R_{canopy\ 1} = R_{canopy\ 2} = R_{suspension\ lines} \times R_{riser} \times R_{disconnect} \times R_{packing}$$

8.3.1.4 *Main Parachute*

The main parachute is a second stage decelerator and is a very important part of the complete system for final safe landing of CM. Since this parachute's diameter is large and hence sudden opening drag force would be very high. Therefore, the parachute is opened in two stages, first in reefed condition which decelerate the CM from 7 km to 3 km and then parachute disreefed and fully opened. Similarly, one more parachute used which works as active redundancy. RBD of the two main parachutes with reefing-lines cutters is shown in Figure 8.5.

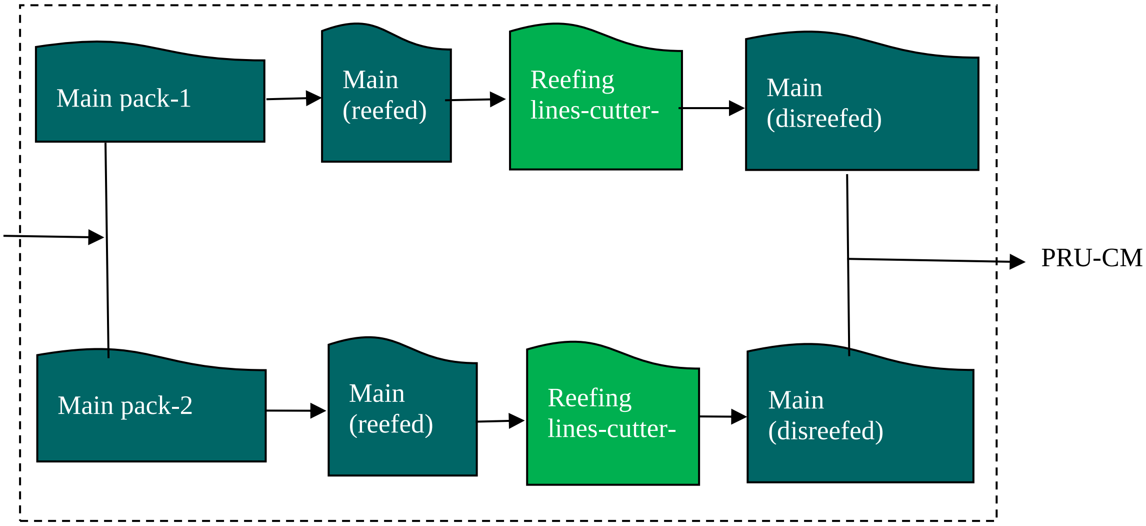

Figure 8.5: RBD of single main parachute and reefing-lines cutters

The reliability for the main parachute system is given by equation (8.11).

Reefed parachute

$$R_{reefed} = R_{suspension-lines} \times R_{riser} \times R_{packing} \times R_{pin}$$

Disreefed parachute

$$R_{disreefed} = R_{suspension-lines} \times R_{riser} \times R_{packing} \times R_{reefing\ line\ cutter}$$

$$R_{main} = 1 - (1 - R_{reefed}\ x\ R_{cutter}\ x\ R_{disreefed})^2 \qquad (8.11)$$

In the use of equation (8.11) in further work, R_{cutter} is ignored as the designing of cutter is not the focus of the current research and not directly involved in parachute design.

In order to compute the complete decelerator's reliability to a preselected confidence level, it is necessary to compute each component's reliability. The components of a parachute that are most likely to fail are evaluated individually. Materials tests indicate that there is an appreciable batch to batch variation in breaking strength of the various textile items used in parachute construction. Investigation of the results on tensile strength tests on a number of parachute materials is essentially normal. Thus, it is assumed that both the load values and the materials breaking strength data are distributed normally.

8.3.2 Allocation (Target) of Reliability

The target reliability is allocated for the different individual component/subsystems based on mission requirements. Indicative values given by Michael (2010) are taken as the reliability for the analysis of the decelerator under study. The reliability targets set the design target for the designer and indicate the scope of improvement/development if the target reliability is not achieved. Tables 8.3 to Table 8.5 summarize the target reliability for TCS/pilot chutes and drogue and main parachutes.

Table 8.3: Allocated reliability for the TCS/Pilot chute

Part/subsystem	**Target reliability**
Chute	0.9966967
Suspension-lines	0.9999998
Riser	0.9999983
Operational	0.9999000

Table 8.4: Allocated reliability for the drogue parachute

Part/subsystem	**Target reliability**
Drogue parachute	0.996699
Suspension-lines	0.999900
Riser	0.999993
Operational	0.999900

Table 8.5: Allocated reliability for the main parachute

Part/subsystem	**Target reliability**
Main parachute	0.9956148
Suspension-lines	0.9999998
Riser	0.9999998
Reefing-line cutter	0.9999700
Adapter pin	0.9999999
Operational	0.9970000

From the above tables, desired overall system reliability has been worked out as,

Parachute operational reliability (packing) = $R_{operational} = R_{TCS/pilot}\ x\ R_{drogue}\ x\ R_{main}$

$= 0.9999000 \text{ x } 0.9999000 \text{ x } 0.9970000$

$= 0.9968006$

Overall reliability target allocated for the system

$R_S = R_{operational} \times R_{TCS/pilot\ chute} \text{ x } R_{drogue(allocated)} \times R_{main(allocated)}$

$= 0.9968006 \text{ x } 0.9966967 \text{ x } 0.996699 \text{ x } 0.9956148$

$= 0.985886$

R_S is the parachute system target reliability required for successful recovery of re-entry CM.

8.3.3 Reliability Estimation of TCS/Pilot Chute

The TCS/Pilot chutes each consists of two canopies (with one as an active redundant) which are deployed to finally carry away the forward heat shield from the CM and help in deployment of the drogue parachute. The canopy for the two chutes is identical with 16 suspension-lines and a riser which have material specification (Table 5.4) as cordage para-aramid, BS 3924 N (max) and webbing kevlar 44 mm, BS 88290 N (max). The material test for the strength is the static test. The stress (load) data was gathered from various trials carried out during static and dynamic tests. Since all these materials are sewed, the tensile strength value reduces by 20% (Knacke, 1992). The material strength test data is shown in Table 8.6. In this table, the value of tensile strength (BS) is entered after reducing by 20% due to assumed loss of 20% during sewing.

Table 8.6: Test data on stress-strength of components of TCS/Pilot chutes

Trial data, F_D (N)	Suspension-lines (16 lines)		Riser (single layer)	
	Lines Strength (N)	Stress per lines (N)	Strength (N)	Stress (N)
26010	3151	1625	73312	26010
19427	3264	1214	76576	19427
19860	3264	1241	77896	19860
20030	3139	1251	78088	20030
20095	3173	1255	77376	20095
24040	3149	1502	78032	24040
28700	3187	1793	77680	28700
21926	3197	1370	77640	21926
20950	3123	1309	72400	20950
18710	3153	1169	70632	18710
	μ_X = 3180	μ_Y = 1373	μ_X = 75963	μ_Y = 21975
	σ_X = 49	σ_Y = 204	σ_X = 2765	σ_Y = 3262

Reliability of Suspension-lines

$$R = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\} = \phi\{(3180\text{-}1373)/\sqrt{(49^2 + 204^2)}\}$$

$$= \phi(8.61) = 0.999999$$

Reliability of Riser

$$R = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\} = \phi\{(75963 - 21975) / \sqrt{(2765^2 + 3262^2)}\}$$

$$= \phi(12.62) = 0.999999$$

As described above, a cluster of two chutes are used to carry away the forward heat-shield whereas only one chute is designed to fulfill the operational requirements. Therefore, these two chutes are treated as to be in parallel for reliability estimation. The critical contributory elements for failure of chutes are suspension-lines, riser and operational reliability (i.e., packing), excluding the associated metal parts and non-critical parts and or which are not directly contributing in parachute performance.

Operational /packing reliability

On parachute packing, a total of one hundred ten tests were conducted but no failure was noticed. Using Table 8.1 and equation (8.7) for no failure, packing reliability at 95% confidence coefficient is,

Packing reliability = R_o = 1 - 3/110

= 0.972727

Reliability of one chute is given as,

$$R_{canopy1} = R_{canopy2} = R_{suspension\ lines} \times R_{riser} \times R_{\mathrm{o}}$$

$$= 0.999999 \text{ x } 0.999999 \text{ x } 0.972727$$

$$= 0.97273$$

Considering the system with two canopies in parallel, each of the TCS/Pilot chute system reliability will be

$$R_{TCS/pilot\ chute} = R = [1- (1- R_{canopy1})\ (1- R_{canopy2})]$$

$$= 0.9992563$$

Therefore, the reliability of TCS/Pilot chutes with all contributory failure elements at 95% confidence level is 0.9992563 which is more than 0.9966967 (target reliability) and 0.999 (reliability value used in Apollo mission) as basic requirement in other space decelerators.

8.3.4 Reliability Estimation of Drogue Parachute

Drogue parachute is to stabilize and decelerate the payload to a certain required terminal speed for opening of the main parachute. The cluster of two conical ribbon parachutes had been selected for construction. This drogue parachute has 24 suspension-lines made of tape para-aramid, 15696 N, BS and riser is made of webbing para-aramid, 88290 N, BS, 44 mm, 4 mm thick with 7 layers to provide more strength (Table 5.6). Table 8.7 shows the test result with material strength after the deduction of 20% in the test tensile strength due to the seam joint effect.

Table 8.7: Test data stress-strength of components of drogue parachute

	Suspension-lines		**Riser (7 layers)**	
F_D (N)	Per lines strength (N)	Stress per lines (N)	Per riser strength (N)	Per riser stress, (N)
70490	12557	2937	73312	10070
84760	12568	3532	76576	12108
80890	12649	3370	77896	11556
82521	11937	3438	78088	11789
75650	12471	3152	77376	10807
84521	12430	3522	78032	12074
83221	12864	3468	77680	11889
85236	12208	3551	77640	12177
82675	12552	3445	72400	11811
123000	12624	5125	70632	17571
142900	12623	5954	73312	20414
	$\mu_X = 12499$	$\mu_Y = 37721$	$\mu_X = 75963$	$\mu_Y = 12933$
	$\sigma_X = 246$	$\sigma_Y = 912$	$\sigma_X = 2765$	$\sigma_Y = 3126$

Suspension-lines reliability

$$R_{suspension\text{-}lines} = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2+\sigma_Y^2}}\} = \phi\{(12499\text{-}3773) / \sqrt{(246^2 + 912^2)}\}$$

$$= \phi(3.945) = 0.999960$$

Riser reliability

$$R_{riser} = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2+\sigma_Y^2}}\} = \phi\{(75963 - 12933)/\sqrt{(2765^2 + 3126^2)}\}$$

$$= \phi(15.10)$$

$$= 0.999999$$

Operational /packing reliability

On this parachute pack, a total of 110 tests were conducted and one failure was noticed. So, from Table 8.1 and equation (8.7), the packing reliability at 95% confidence level was determined as

$$R_{packing} = 1 - 4.74/110$$

$$= 0.95691$$

Canopy reliability will be

$$R_{canopy} = R_{suspension\ lines} \times R_{riser}\ x\ R_{packing}$$

Thus, $R_{canopy1} = R_{canopy2} = 0.999960\text{x}\ 0.999999\text{x}\ 0.95691$

$$= 0.956871$$

Thus, the Reliability of drogue parachute system can be calculated as,

$$R_{drogue} = 1 - (1 - R_{canopy\ 1})(1 - R_{canopy2})$$

$$= 1 - (1 - 0.956871)\ (1 - 0.956871)$$

$$= 0.998140$$

Reliability of drogue parachute at 95% confidence is 0.998140 which is less than 0.999 (Apollo) but more than the target reliability of 0.996699. Low achieved reliability is due to low packing reliability.

8.3.5 Reliability Estimation of Main Parachute

The objective of this system is to further reduce the terminal speed from 80 m/s to less than 10 m/s for safe landing with single canopy and to less than 8 m/s with a cluster of two. The parachute system consists of 96 suspension-lines and 2 risers each of 4 layers. Material specification of the suspension-lines and riser are cordage para- aramid, BS 3924 N and webbing Kevlar 44 mm, BS 88290 N (Table 5.9). Table 8.8 shows the mean breaking strength of suspension-lines and riser (after a deduction of 20% for loss due to seam joint).

Table 8.8: Test data on stress-strength of components of main parachute

F_D (N)		**Suspension-lines**			**Riser (4 layers)**		
		Per lines strength (N)	Stress on per lines (N)		Per riser strength (N)	Per riser stress (N)	
Reefed	Disreefed		Reefed	Disreefed		Reefed	Disreefed
98100	109000	3151	1022	1135	73312	12263	13625
74300	80300	3265	774	836	76576	9288	10038
162000	149000	3264	1688	1552	77896	20250	18625
81400	95000	3139	848	9810	78088	10175	11875
90400	89200	3174	942	929	77376	11300	11150
75740	80266	3149	789	836	78032	9467	10033
60820	77830	3187	634	811	77680	7603	9728
135400	132200	3197	1410	1377	77640	16925	16525
98267	78776	3123	1024	821	72400	12283	9847
98389	77682	3155	1025	809	70623	12299	9710
97812	79205	3139	1019	825	73312	12227	9901
99500	78551	3281	1036	818	70056	12437	9819

98560	88910	3380	1026	926	72661	12320	11113
89425	89442	3224	931	932	71882	11178	11180
87561	78391	3497	912	817	71267	10945	9799
88926	78667	3136	926	819	71772	11116	9833
98965	75621	3184	1031	788	71223	12370	9453
97865	74337	3196	1019	774	70654	12233.13	9292
		$\mu_X = 3213$	$\mu_Y = 1003$	$\mu_Y = 933$	$\mu_X = 74026$	$\mu_Y = 12038$	$\mu_Y = 10743$
		$\sigma_X = 97$	$\sigma_Y = 233$	$\sigma_Y = 215$	$\sigma_X = 3077$	$\sigma_Y = 2793$	$\sigma_Y = 3191$

A. Suspension-lines reliability:

(i) Reefed

$$R = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\} = \phi\{(3213 - 1003)/(97^2 + 233^2\}$$

$$= \phi(8.77)$$

$$= 0.999999$$

(ii) Disreefed

$$R = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\} = \phi\{(3213.4 - 933.1)/(96.521^2 + 214.74^2\}$$

$$= \phi\ (9.68)$$

$$= 0.999999$$

B. Riser reliability

(iii) Reefed

$$R = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\} = \phi\{(74026-12038)/(3077^2 + 2793^2\}$$

$$= \phi(14.92)$$

$$= 0.999999$$

(iv) Disreefed

$$R = \phi\{\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2+\sigma_Y^2}}\} = \phi\{(74026 - 10743)/(3077^2 + 3191^2\}$$

$$= \phi\ (19.83)$$

$$= 0.999999$$

C. Operational /packing reliability

Total 180 packing tests were conducted on the main parachute and one failure was noticed on peck-cover. Using Table 8.1 and equation (8.7), packing reliability at 95% confidence level will be

$$R_{packing} = 1- 4.74/180$$

$$= 0.97367$$

D. Reliability of adapter pin

Adapter is a metal shackle which works as an interface between suspension-lines' loops and risers. The weakest parts in adapter are pins (4 in numbers), which are made of high strength steel. Two pins are used in one parachute. Reliability of the pin is taken from the standard failure reliability data as 0.99996 made available by Jones (2011). Thus, the reliability of two pins in one parachute

$$R_{pin} = 0.99996 \text{ x } 0.99996 = 0.99992$$

E. Reliability of reefing-line cutter

The main parachutes are inflated in two stages: first in reefed mode, and then in disreefed mode for the rest of the descent phase. There are two reefing-line cutters for de-reefing each canopy of the main parachute for increased reliability in operation.

Reefing-line cutter reliability, *R*, is the probability that the reefing-line cutter will cut the reefing-line within ± 4 % of the preset time delay after the lanyard has been pulled and is given by equation (8.10).

$$R = 1 - Q \tag{8.10}$$

where *Q* accounts for all the factors A through E given in Table 8.9 (Maydew,1991). Since *Q* is equal to 0.01, each pin has a reliability of 0.99. Bradley (1971) and Pepper *et al.* (1973) performed a considerable number of environmental tests on reefing-line cutters. They concluded that the reliability of the cutter should be at least equal to 0.999.

Table 8.9: Failure probability for various factors working on reefing-line cutter

Event	**Event description**	**Probability of failure**
A	Failure of the firing pin to strike and transmit the energy required to fire the primer, given that sufficient force is transmitted to the lanyard by the parachute system	0.002
B	Failure of the lanyard to pull out to operate the firing pin, given that event A has not occurred	0.003
C	Failure of the spring to deliver an appropriate load to strike the cartridge after the preset time delay, given proper thermal battery operation	0.004
D	Failure of the electrically fired cartridge to deliver sufficient energy to the cutter, given that a correct signal is received from the electronics	0.0005
E	Failure of the cutter to shear the wire and sever the reefing lines, given that the cutter receives an appropriate amount of energy from the Cartridge	0.0003
Q	Failure of the reefing-line cutter to sever the reefing lines	0.01

Since each cutter has the reliability of 0.99 being less than required value of 0.999, two cutters were chosen in parallel to provide the desired/specified reliability value as

$$R_{reefing\text{-}line\ cutter} = (1 - R)\ (1 - R)$$

$$= 1 - (1 - 0.99)\ (1 - 0.99)$$

$$= 0.9999$$

(i) Reliability of reefed parachute

Since $R_{canopy} = R_{suspension-lines} \times R_{riser} \text{ x } R_{packing} \text{ x } R_{pin},$

thus,

$$R_{canopy1} = R_{canopy2} = 0.999999 \text{ x } 0.999999 \text{ x } 0.97367 \text{ x } 0.99992$$

$$= 0.973580$$

Therefore, the reliability of the main parachute system at the reefed stage will be

$$R_{main-reefed} = 1 - (1 - R_{canopy1})(1 - R_{canopy2})$$

$$= 1 - (1 - 0.973580)\ (1 - 0.973580)$$

$$= 0.999302$$

(ii) Reliability of disreefed parachute

Since $R_{canopy} = R_{suspension-lines} \times R_{riser} \text{ x } R_{packing} \text{ x } R_{cutter} \text{ x } R_{pin},$

thus, $R_{canopy1} = R_{canopy2} = 0.999999 \text{ x } 0.999999 \text{ x } 0.973670 \text{ x } 0.999900 \text{ x } 0.999920$

$$= 0.973493$$

Therefore, the reliability of the main parachute system at the disreefed stage will be

$$R_{\mathrm{main-disreefed}} = 1 - (1 - R_{canopy1})(1 - R_{canopy2})$$

$$= 1 - (1 - 0.973493)\ (1 - 0.973493)$$

$$= 0.999297$$

Overall reliability of the main parachute system has to be taken as that for the disreefed one because the components considered at the reefed stage does not include line-cutter.

8.3.6 Overall Reliability of Parachute Deceleration System Reliability

The overall system reliability depends upon the components' arrangement in the complete system with CM. Jailor *et al*. (1960) dictate the use of only drogue and main parachutes' reliability in computing the overall system reliability. However, it is not correct. A failure of TCS chute itself is sufficient to cause failure of the mission. Since TCS chute, pilot chute, drogue parachute and main parachute systems are in series, the overall reliability of the parachute deceleration system will be

$$
\begin{aligned}
R_{PDS} &= R_{TCS} \text{ x } R_{pilot} \text{ x } R_{drogue} \text{ x } R_{main\ disreefed} \\
&= 0.999256 \text{ x } 0.999256 \text{ x } 0.998140 \text{ x } 0.999297 \\
&= 0.995955
\end{aligned}
$$

Therefore, the overall reliability of recovery parachute system at 95% confidence is 0.99596 and is above the target reliability 0.98589 and is more than 0.96 achieved by Soyuz.

8.4 Summary

Reliability study helps in identifying the weakness in design and provides scope for further improvement of the various components. Component having sufficient design margin but low reliability will lead to failure of the system. From this perspective, reliability block diagram, subsystem reliability, allocation of reliability of critical components and a comparative reliability matrix has been presented in this chapter.

Based on the test data and available literature, reliability of parachute deceleration system has been carried out with achieved reliability values presented in Table 8.10 to Table 8.12.

Table 8.10: Reliability matrix of TCS/pilot chute system

Description	**Target reliability**	**Estimated reliability**
Overall	0.9966967	0.9992563
Suspension-lines	0.999998	0.999999
Riser	0.9999983	0.999999
Operational	0.9999000	0.972727

Table 8.11: Reliability Matrix of drogue parachute system

Description	**Target reliability**	**Estimated reliability**
Overall	0.996699	0.998140
Suspension-lines	0.999900	0.999960
Riser	0.999993	0.999999
Packing	0.999900	0.956910

Table 8.12: Reliability Matrix of main parachute system

Description	**Target reliability**	**Estimated reliability**	
		Reefed	**Disreefed**
Overall	0.9956148	0.973580	0.999297
Suspension-lines	0.9999998	0.999999	0.999999
Riser	0.9999998	0.999999	0.999999
Reefing-lines cutter	0.9999700	-	0.999900
Adapter pin	0.9999999	0.99992	0.99992
Parachute operation	0.9970000	0.97367	-

The results of the component-reliability analysis offer an excellent basis for the study of design changes to further improve the reliability of the parachute system. Component-by-component reliability study carried out here will specifically indicate those portions of the system where additional design efforts may bring their reliability upto the level of the other components. This may call for redesign of auxiliary devices or hardware items, or choice of other materials for fabric portions of the canopy. Generally, to obtain better reliability, one goes for fabric with high strength value. It is desirable but may not necessarily increase the reliability if the particular material chosen has a relatively high standard deviation of tensile strength. Thus, while selecting the materials for various components of the parachute, one should focus on selecting materials with low standard deviation while the mean strength should be sufficiently more than the mean stress.