CHAPTER 6

RISKS AND HAZARD ASSOCIATED WITH PARACHUTE DECELERATION SYSTEM

Notations

N	Number of scenarios
C_i	Consequences or evaluation measure of scenario i
P_i	Likelihood or frequency of scenario i,
S_i	Scenario of the events

Abbreviations

AAD	Auto Activation System
CM	Crew Module
ISO	Standardization of International Organization
OBC	Onboard Computer
RoD	Rate of descend
RLV	Re-usable Launch Vehicle
TCS	Top Cover Separation

6.1 Introduction

Parachute system is simple in design and fabrication, but very complex in packing and sequential deployment. It experiences always the risk of entanglement, tear of fabric, stitching failure, re-use of materials with exhausted life, human error etc. A novel design may have the possibility of risk in the first use even though most care might have been taken during the design and development. These risk-hazard events are identified through screening tests. This chapter covers the all-possible risks and hazards associated with parachute operations and way to avoid possible errors.

According to ISO (2018), risk is defined as an effect of uncertainty on the objectives. When there is a source of danger (hazard) and when there are no safeguards against the exposure of the hazard, there is a possibility of loss and injury. This possibility is referred as risk. The loss or injury could result from human error, military activities, operation of equipment, or involvement of personnel. Risk can be viewed qualitatively and quantitatively. Quantitative risk analysis involves an estimation of the degree or probability of loss. Risk analysis in general, involves the following:

i. Identifying the factors that can go wrong in parachute operation that could lead to an outcome of hazard exposure (packing, deployment, loading, landing separation and location),
ii. Determining of likeliness of this to happen (point no. (i)), and
iii. Determining the expected consequences if it happen.

Therefore, risk can be defined quantitatively, as the following set of triplets:

$$\text{Risk} = (S_i, P_i, C_i),\ i = 1, 2, 3, \ldots n.$$

where S_i is scenario of events that leads to hazard exposure, P_i is the likelihood or frequency of scenario i, C_i is the consequence (or evaluation measure) of scenario i, and n is the number of such scenarios.

6.2 Risk and Hazard Analysis

Risk is a potential of loss resulting from exposure to a hazard. Hazard is something with the potential to cause harm like human error, exposure to environment, deviation from design parameters, etc. These hazards will result in high stress upon components, failure of joints and functional degradation. Hazard is classified in various categories according to criticality and impact on the system as described in Table 6.1.

Table 6.1: Hazard severity classification (Jones, 2011)

Description	**Category**	**Mishap**
Catastrophic	1	Death or system loss
Critical	2	Severe injury, severe occupational illness, or major system damage
Marginal	3	Minor injury, minor occupational illness, or minor system damage
Negligible	4	Less than minor injury, occupational illness, or system damage

The probability of occurrence of a hazard is about likelihood of happening during parachute operation. A classification of hazard based on its occurrence is listed in Table 6.2.

Table 6.2: Classification based on occurrence of hazard (Jones, 2011**)**

Description	**Risk Level**	**Specific Individual Item**	**Fleet or Inventory**
Frequent	A	Likely to occur	Continuously experienced
Probable	B	Will occur several times in life of an item	Will occur frequently
Occasional	C	Likely to occur sometime in life of an item	Will occur several times
Remote	D	Unlikely but possible to occur in life of an item	Unlikely but can reasonably be expected to occur
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced	Unlikely to occur, but possible

Many hazards can be identified for any system. Each hazard has a typical severity and frequency of occurrence. If a hazard has several risks and thus several levels of severity, then the most severe one is assigned to the hazard. If the risks associated with hazard have several levels of frequency of occurrence, then the highest frequent level is assigned to the hazard. The risk level of each hazard puts the hazard at some place in the risk assessment matrix. Table 6.3 is a sample of parachute hazard risk assessment matrix. A level of acceptance is associated with each risk level. A person may assign a risk as 'undesirable', while another person may call the same risk 'acceptable with review'.

Table 6.3: A sample hazard risk assessment matrix

Frequency of Occurrence	**Hazard Categories**			
	1 Catastrophic	**2 Critical**	**3 Marginal**	**4 Negligible**
A Frequent	1	3	7	13
B Probable	2	5	9	16
C Occasional	4	6	11	18
D Remote	8	10	14	19
E Improbable	12	15	17	20

Hazard Risk Index	**Suggested Criteria**
1-5	Unacceptable
6-9	Undesirable
10-17	Acceptable with review
18-20	Acceptable without review

Loss of altitude awareness is a common hazard in space mission and can lead to a fatal mishap. The severity of loss of altitude awareness is ‘Catastrophic’ (Category 1). The occurrence can be frequent or at level A. Thus, the hazard as loss of altitude awareness is Catastrophic-Frequent. This is denoted by 1 in the risk matrix. This hazard is definitely at the ‘unacceptable’ risk level. In such cases, there is a need to identify ways that can reduce the risk index of the hazard. Changing either the severity or frequency of occurrence or both can reduce the risk index. One way to reduce the severity is to add an additional device for parachute initiation, like adding one more option to initiate the parachute inflation by using over-ride switch. One of such devices is a reliable Automatic Activation Device (AAD), which will trigger the parachute operations and ascertain the recovery of module.

There are several ways to reduce the frequency of occurrence. The crews can use a visual window, atmospheric sensor, altimeter, or look at the ground every few seconds or pay attention to module velocity and feeling of parachute opening forces. If all of these measures are used, the frequency of occurrence may get reduced to ‘Remote’. These devices allow the crew to become aware of loss of altitude well in time for necessary remedial actions.

6.3 Risk Analysis of Parachute Deceleration System

Several risks emerge within a complex system. It mostly exists between human and environmental interface. Risk is generally analyzed for identifying interdependence among different risks and their sources, consequences, likelihood, and their frequency of occurrence. The first step in the risk analysis is to structure the future possible events into classes of scenarios as a set of mutually exclusive and collectively exhaustive elements, discrete or continuous. Each of these scenarios is a conjunction of events leading to a particular outcome. A detailed risk-based analysis of Re-usable Launch Vehicle (RLV) operation has been described by the Roscoe (1998) for re-entry vehicle. A study carried out by Bricknell *et al.* (1999) on military parachutists shows hazardous duty pay for military parachuting as it is associated with a significant additional risk of injury. This risk is reflected in an increased incidence of admission due to acute injury to muscular skeletal trauma. Similar risks could also be found to crew members on altitude loss or high ground impact.

6.3.1 Hazard-Risk Assessment Matrix for TCS/Pilot Chute

Pilot chute is to be deployed through mortar at 7 km altitude. Its function depends on the external sources (OBC, sensors). Anything including external source that can potentially generate adverse events will consequently create damage to the deceleration system. Considering the intrinsic and extrinsic sources, the severity level and frequency of occurrence for the pilot chute has been investigated and the same is shown in Figure 6.1.

(High)

Probability of occurrence level

(Level of probability -->)

Level A - Frequent				
Level B - Reasonably Probable				
Level C - Occasional			Pre-matured breakage of Apex weak-tie	
Level D - Remote	Breakage of S/S lines	Unbroken of Apex weak-tie	Abrasion of Pack cove r fabric	S/S lines-riser joint fail
Level E - Extremely Unlikely				-Mortar fails -Pack cover mouth locked -Canopy tear -Breakage of Riser - Breakage of extraction bridle
	Category IV -Minor	**Category III-Marginal**	**Category II - Critical**	**Category I - Catastrophic**

(Low)

Severity classification
(Level of severity --->)

Figure 6.1: Hazard risk assessment matrix for TCS/pilot chute

6.3.2 Hazard-Risk Assessment Matrix for Drogue Parachute

The drogue parachute is the most critical and important parachute to decelerate the CM. its function depends upon the success of the pilot chute and its success will support the deployment of the main parachute for safe landing of CM. So, drogue parachute is required to be assessed by intrinsic multi-risk assessment. The possible risks hves been investigated and are listed in the matrix given in Figure 6.2.

(High)

Probability of occurrence level (Level of probability -->)

Level A - Frequent				
Level B - Reasonably Probable				
Level C - Occasional				Pilot chute fails to extract drogue parachute
Level D - Remote	Breakage of S/S lines		Abrasion on Pack cover fabric	-Prematurely Breakage of Apex weak-tie -S/S lines-riser joint fails
Level E - Extremely Unlikely		Apex weak-tie unbroken	-Breakage of Extraction bridle -PRU design fault	-Pack cover mouth locked -Failure of pilot chute -Breakage of Riser
	Category IV - Minor	**Category III - Marginal**	**Category II - Critical**	**Category I - Catastrophic**

(Low)

Severity classification
(Level of severity --->)

Figure 6.2: Hazard risk assessment matrix for drogue parachute

6.3.3 Hazard-Risk Assessment Matrix for Main Parachute

The main parachute is the final stage of recovery process. Its functionality depends upon mainly two intrinsic sources, viz., the success of drogue parachute and its disconnection from CM. Any mishap in the main parachute operation would lead to the total potential loss in terms of human casualties, besides economic loss or loss of mission. In Apollo 15 spacecraft, failure occurred abruptly. An inspection of recovered parachute showed that one of the risers' link had a broken stud and others were cracked, and that resulted harder landing. From this view, the hazard is evaluated by taking into account the characteristics of the risk sources and functionality of the main parachute. The same has been listed in the matrix given in Figure 6.3.

(High)

Probability of occurrence level
(Level of probability -->)

Level A - Frequent				
Level B - Reasonably Probable				
Level C - Occasional				Burning of main Risers
Level D - Remote	Failure of one parachute	Drogue parachute not disconnected from CM	-Abrasion on Pack cover fabric -Breakage of S/S lines - Pre-maturely breakage of Reefing lines	- Pre-maturely breakage of Apex weak -Failure of drogue parachute
Level E - Extremely Unlikely	Entanglement of parachutes	-Delay in reefing lines-cutter -PRU not activated	-Apex weak-tie unbroken -Adapter smaller pin fail	-Breakage of Adapter bigger pin -Breakage of Riser -Pack cover mouth locked -Fabric tear -Riser-S/L joint fail
	Category IV - Minor	**Category III - Marginal**	**Category II - Critical**	**Category I - Catastrophic**

(Low)

Severity classification
(Level of severity --->)

Figure 6.3: Hazard risk assessment matrix for main parachute

6.4 Accident Scenario of Parachutes

6.4.1 TCS Chute

6.4.1.1 Forward Heat Shield Cover Not Open

The most important aspect of the recovery process is the removing of the forward heat shield from the module. It is operated using an altitude sensor during descent. Forward heat shield is fitted with the crew module through pyro-thrusters. The moment pyro-thrusters release the heat shield, the mortar-fire will deploy the chutes to carry away the forward heat shield from the module. The likely risks associated with not opening of the heat shield and its possible effects on the mission are shown in Figure 6.4.

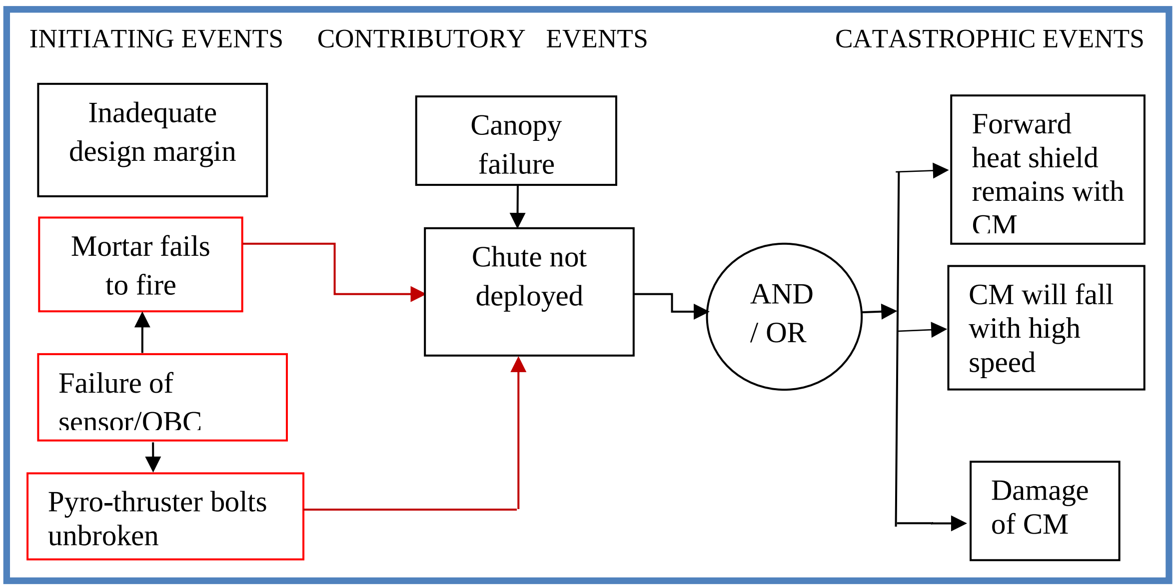

Figure 6.4: Accident scenario when forward heat shield is not opened

Figure 6.4 also shows the sequence of events that could cause an accident when the forward heat shield is not detached from CM. Initiating events are the main or basic causes of contributory hazards. These initiating events occur due to inadequate design or error in process. In this case, there are many initiating events, such as, OBC failure, failure of mortars, pyro-thrusters, etc. Contributing hazards are the main hazards which finally lead to the catastrophic results. For example, no separation of forward heat shield leads to loss of mission and or loss of life. Catastrophic events have high severity but low frequency of occurrence. To avoid these failures, it is recommended to reduce the occurrence probability of initiating events by using rugged design, use of MiL-grade materials, and proper inspection and testing.

6.4.1.2 Collision of Forward Heat Shield with CM

Collision of forward heat shield with CM has very high severity but is a low frequency event. Occurrence of initiating event of such a scenario is due to the same descent velocity of forward heat shield and CM. To avoid this initiating event, the velocity of CM should be much more than that of TCS chutes. From the trajectory analysis, it is found that the minimum differential velocity has to be more than 30m/s in between. The mass of forward heat shield is 130 kg, and its collision will damage the CM and loss of mission. The investigated possible hazard initiating events, intermediate and accident outcomes are shown in Figure 6.5.

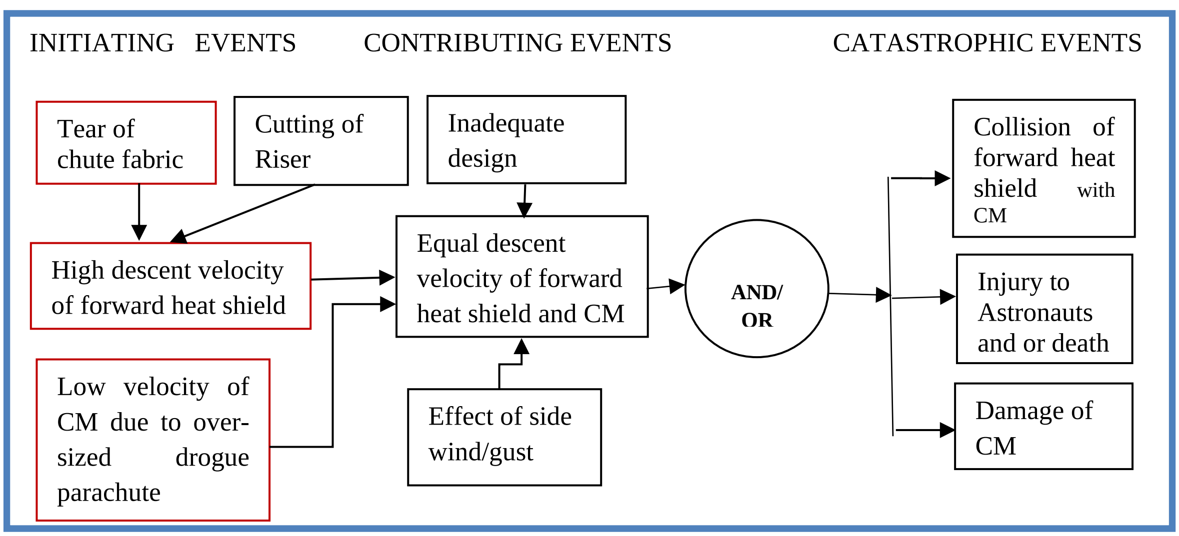

Figure 6.5: Accident scenario in case of collision of forward heat shield with CM

6.4.1.3 TCS Chute Malfunction

As discussed in Chapter 3, a cluster of two chutes are chosen for the separation of forward heat shield. Immediately after the jettisoning of the forward shield through command signal, the mortar fires to deploy the TCS chute to take away the forward heat shield from CM. TCS chute must operate in the sequence of the order for the success of the mission. Failure of the chute means that subsequent operation will not occur and CM will fall free from a very high altitude. The investigated accident scenario pertaining to chute malfunction is shown in Figure 6.6.

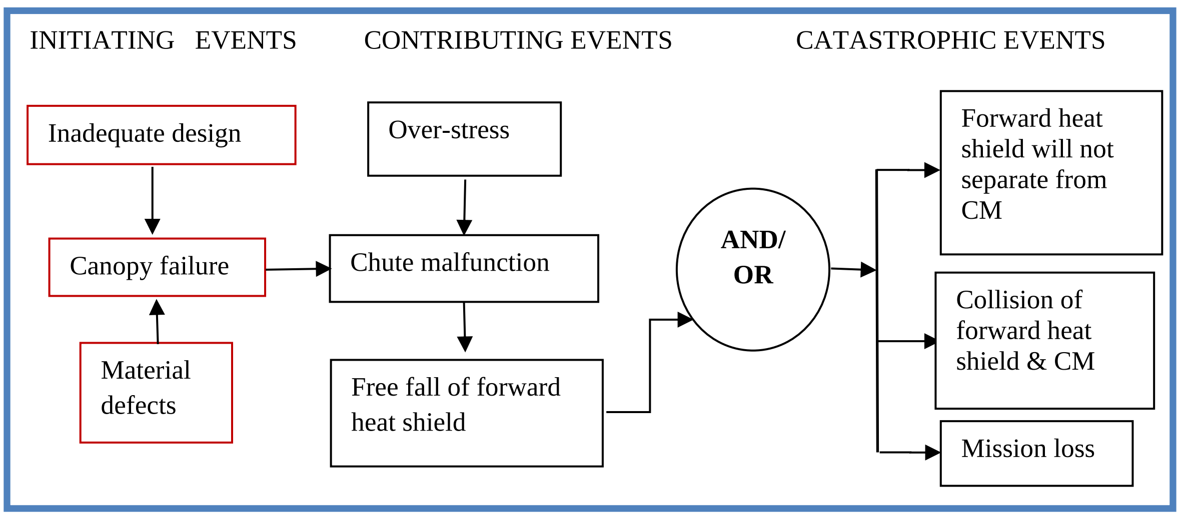

Figure 6.6: Accident scenario when TCS chute malfunction

There are many causes of chute malfunction, such as, material failure, inappropriate testing, obsolete materials used, improper packing of chute, etc. The following suggestions are to be followed to avoid such accidents.

(i) Use of proper materials after testing

(ii) Proper packing

(iii) Joint testing and Proper qualification tests

6.4.2 Pilot Chute

The sizes of pilot and TCS chutes are the same and, hence, all the tests were conducted on a single chute or in a cluster of two chutes for validation trials. In one of the dynamic test, the Vent lines and Vent band damaged as shown in Figure 6.7.

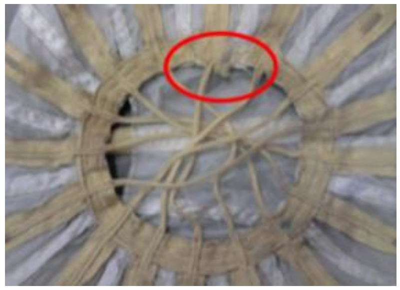

Figure 6.7: Vent-lines broken from vent band

The possible hazard investigation was carried out on malfunction of the pilot chute. Various initiating and contributory causes are listed in Figure 6.8.

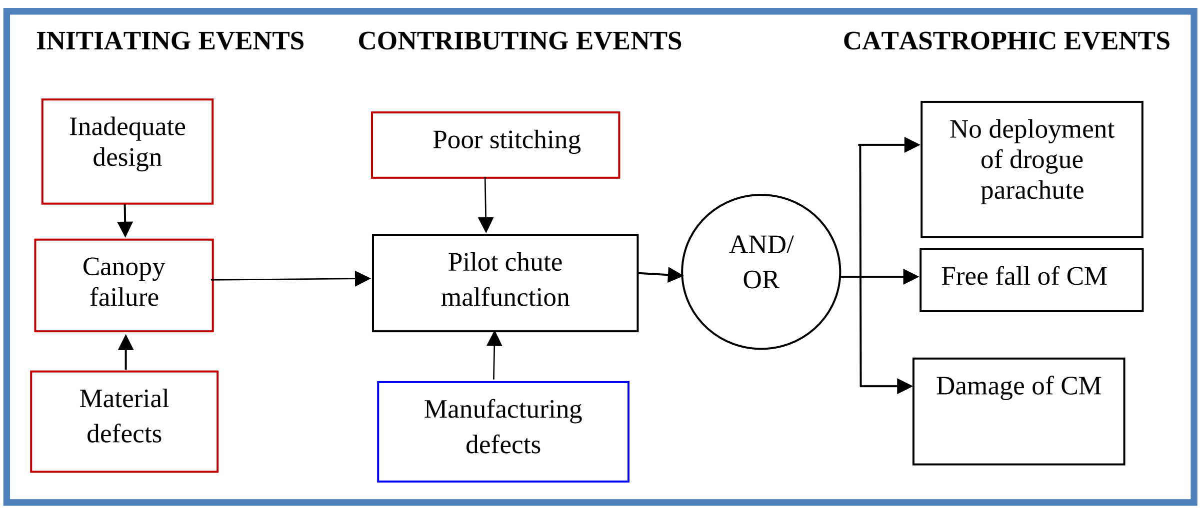

Figure 6.8: Accident scenario related to pilot chute malfunctions

The following remedies are recommended to overcome the malfunctioning of the chute.

(i) Material test before fabrication

(ii) Over-load test to check the uncertainty in design

(iii) Avoidance of tight packing

(iv) Critical joint test before fabrication

6.4.3 Drogue Parachute

6.4.3.1 Parachute Malfunction

The success of the main parachute solely depends upon successful function of the drogue parachute. Therefore, the design of drogue parachute must have high reliability and it must be well tested in a controlled environment. Joints, stitching and material quality must be ensured before the packing.

During the dynamic test, the suspension-lines broke near the skirt-band as shown in Figure 6.9.

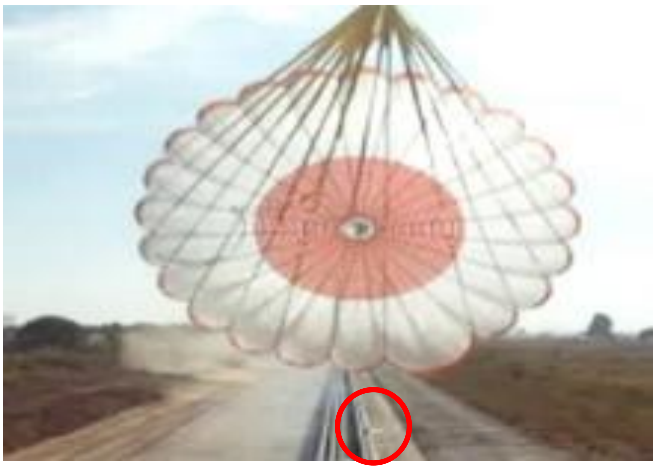

Figure 6.9: Suspension-lines broken near skirt band

The sequence of events that could cause an accident due to malfunction of the drogue parachutes is evaluated. It is found that the pilot chute failure and /or entanglement of parachutes are most critical. The possible causes of parachute malfunction are shown in Figure 6.10.

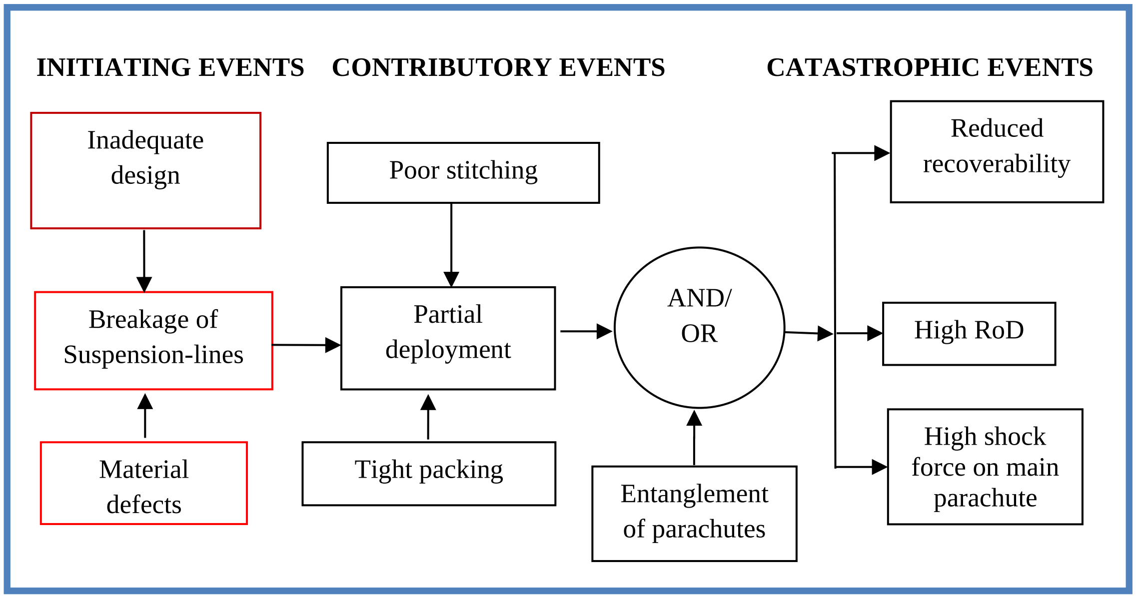

Figure 6.10: Accident scenario when drogue parachute malfunction

The flexible parachute is made of degradable fabrics, tapes, webbings. These are the causes or initiating events for parachutes malfunction. Cuts, tear and holes on fabric are the basic cause of contributory hazard. Initiating events may also be inadequate pack-cover design, degraded materials, deployment angles, tumbling of CM, turbulence air, gust, collision with foreign object, etc. There are many other reasons causing contributory hazards that lead to catastrophic results (viz., loss of missions, loss of life). It is found from the analysis that catastrophic events have high severity but low frequency of occurrence. To avoid these events, proper quality checks at each level of process, and also testing and packing should be adopted.

6.4.4 Main Parachute

6.4.4.1 Main Parachutes Malfunction Scenario

The main parachute has low risk factor compared to drogue parachute but is critical for crew safe landing. The main parachute opens at low subsonic speed and at a lower altitude.

The overall risk factor is product of risk factors associated with TCS chute, drogue and main parachutes. Any failure under this chain would lead to catastrophic disaster. The investigated hazard scenario related to the main parachute is shown in Figure 6.11.

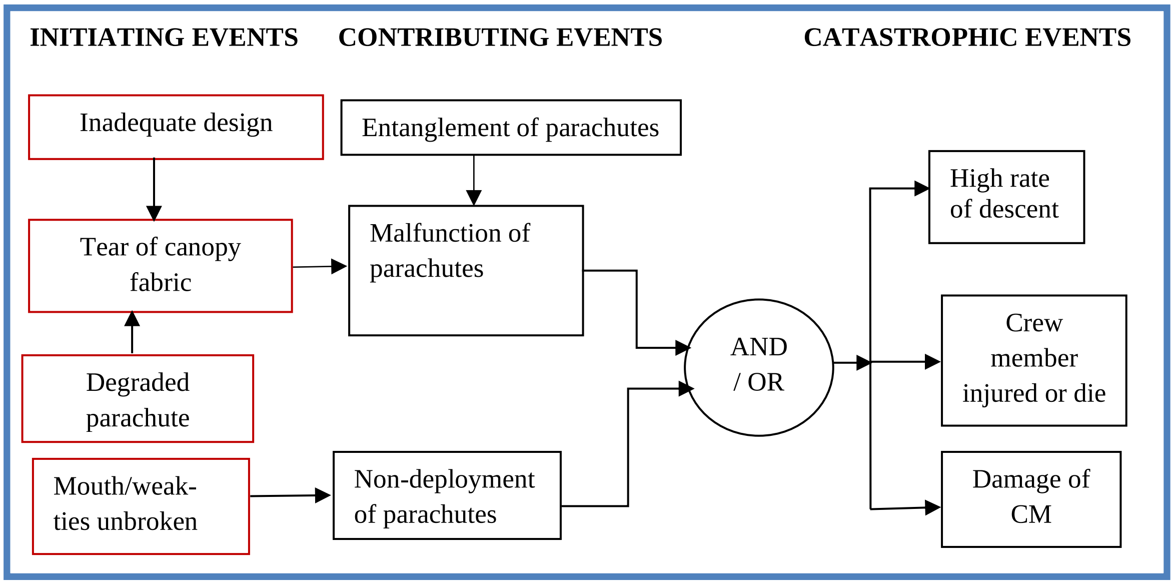

Figure 6.11: Probable causes of malfunction of main parachute

The main parachute's malfunction is due to the poor materials, insufficient qualification testing, faulty packing, failure of drogue parachute, failure of knotting, or parachute's opening at a high speed and altitude, etc. The malfunction will result in mission loss or damage of CM. If drogue's PRU remains inactive, then the main parachute will not separate from CM. Therefore, this initiating event will lead to high severity catastrophic events.

6.5 Mitigation of Risk-Hazard Events

Different possible risks and hazard events related to inflatable aerodynamic parachutes, detailed in the sections above, are identified from joint tests, bench test, screening test, overload tests of integrated system. Design margin also helps in identifying the scope for risk and hazard. A low margin is bound to yield poor reliability. These are also identified from various processes adopted for quality control. The malfunctioning of parachute system is mostly due to the wrong selection of materials, inappropriate testing, use of degraded materials, improper packing, failure of weak-ties, or parachute's opening at a high speed and altitude, etc. In order to curb these and to minimize the associated risks, the following are recommended:

(i) adequate design and high reliability of pyro release unit,

(ii) provision of override switch in crew cabin,

(iii) Automatic Activation Device (AAD) to be additionally installed for automatic detachment of parachute, and

(iv) use of a cluster of two drogues, and two main parachutes where one is sufficient to help in safe recovery of the crew module, the other will help in having an active redundancy.

6.6 Summary

This chapter covers all-possible risks-hazards associated with all the four parachutes for various accident scenarios along with strategies for their mitigation. Anything, including external sources, that can potentially generate adverse events will consequently cause damage to the subsequent decelerators. Considering the internal and external sources, the severity level and frequency of occurrence have been investigated for the four parachutes. The sequence of events that could cause an accident has been identified for all the stages of parachutes. It is observed that initiating events are the main causes in contributing to the hazards. These initiating events occur due to the inadequate design or error in the design process. There are many initiating events, such as, OBC failure, failure of mortars, pyro-thrusters, failure of leading parachutes, etc. Contributing hazards are the secondary hazards which finally lead to the catastrophic failure, such as, loss of mission and/or loss of life due to no separation of forward heat shield. Catastrophic events have high severity but low frequency of occurrence. To avoid these failures, it is recommended to reduce the probability of occurrence of initiating events by the use of rugged design and MiL-grade materials, and also by proper inspection and testing.