Design, development and flight performances of deceleration system

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Human Spaceflight Programme (HSP) of Indian Space Research Organisation is proposed with the objective of carrying two crew members to low Earth orbit and bring them back safely to a predetermined location on Earth. The deceleration system for the programme has been designed for a 4-tonne class payload and shall cater to the requirements of nominal as well as abort missions. In order to finalize the parachute configurations and deployment sequence, detailed studies and development tests, starting from wind tunnel tests to full-scale air-drop tests were carried out. After successful structural and functional qualification of the parachutes and the various subsystems, the system was used to safely recover the module in the Crew Module Atmospheric Re-entry Experiment, the first unmanned spaceflight of HSP. This article provides details on the system configurations, deployment sequence and numerous tests that have been carried out till now in order to make the system worthy of manned flights in future.

Keywords: Abort missions, deceleration system, deployment sequence parachutes, manned flights.

Introduction

THE Human Spaceflight Programme (HSP) of Indian Space Research Organisation (ISRO) is proposed with the objective of carrying two crew members to Low Earth Orbit (LEO) and bringing them back safely to a predetermined location on Earth. The same system shall also cater for safe landing of the module during various abort missions. The deceleration system developed is parachute-based, which has been designed for the safe recovery of a 4-tonne class Crew Module (CM) after its re-entry from space.

The system comprises three types of parachutes which differ in their construction, size and performance. The selection and design of the parachutes was based on extensive literature surveys and the experience of the teams in the field of parachute design. In addition, the system consists of pyro devices for ejection, release and disreefing of the parachutes.

CM is a part of the Orbital Vehicle (OV) which provides a safe habitat for the crew during all phases of the mission from launch to landing. The Module has a spherical nose at the fore end (end facing the re-entry flow) and a truncated conical portion at the aft end. All the elements of the deceleration system are positioned in the parachute compartment, provided at the aft end of CM around the docking tunnel. The deceleration system initiation takes place at an altitude of 7 km with the module velocity being nearly 137 m/sec.

This article presents the overall configuration of the system with emphasis on the development and qualification tests carried out at subsystem and system level in order to qualify and prove the flight worthiness of the system.

System configuration

The CM deceleration system consists of eight parachutes and 15 pyro devices, in addition to other hardware for stowing and connecting the parachutes and their risers. The elements of the deceleration system are housed in the parachute compartment located at the aft end of the crew module. The parachute compartment is divided into six sectors. The system elements are positioned in the compartments in such a way that safe and entanglement-free extraction and deployment of parachutes are assured. The entire parachute compartment is covered by an Apex Cover, which is made from carbon fibre reinforced polymer. The Apex Cover is bonded with ablative tiles for protecting the parachutes from re-entry heating, and is ejected at the time of deceleration system initiation using three pyro thrusters exposing the parachute compartment for parachute deployment. In order to prevent re-contact of the apex cover with CM due to the reverse airflow, two Apex Cover Separation (ACS) parachutes are used.

The system consists of two identical parachute chains, each consisting of one pilot, one drogue and one main parachute. It is designed to meet the functional requirements with single chain and the alternate chain is redundant. The main parachute has one stage reefing, for which

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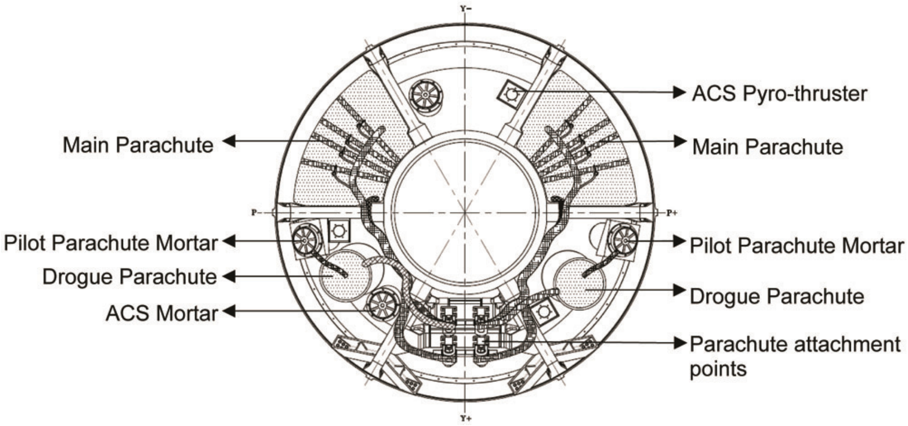


Figure 1. Configuration and layout of deceleration system in the parachute compartment.

Table 1. Geometry type and size of various parachute systems

Parachute	Type	Nominal diameter (m)	Quantity
Apex cover separation parachutes	Ring-slot parachute	2.5	2
Pilot parachutes	Ring-slot parachute	2.5	2
Drogue parachutes	Conical ribbon parachute	6.3	2
Main parachutes	Slotted circular parachute	31	2

two reefing line cutters are provided in each parachute. ACS system consists of two ACS parachutes for avoiding re-contact of the Cover with CM after separation. The functioning of any one ACS parachute will meet the functional requirements and second parachute is redundant. Table 1 lists the various parachutes in the system and their specifications.

The conical ribbon first-stage parachute is selected based on its capability to operate at high dynamic pressure and good stability characteristics, so that favourable conditions for deploying the main parachute are achieved. The slotted circular parachute is selected as the second-stage decelerator due to its high drag coefficient.

Figure 1 shows the layout of the deceleration system elements in the parachute compartment. As shown in the figure, the position of the parachutes is symmetrical with respect to the yaw axis. The ACS and pilot parachutes are housed inside the mortar tubes and the drogue parachute is housed inside the drogue container. The main parachute is packed in such a way that each parachute occupies the entire volume available in one sector of the compartment. The attachment of the drogue and main parachutes are provided on the two bridging members using Parachute Releaser Units (PRUs).

The configuration and layout of the compartment was finalized after a detailed study so as to accommodate all the elements without compromising their functionality. Special care was taken while routing the risers from the parachute location to the respective attachment points to ensure safe and entanglement-free extraction. The CM structure was smoothened at appropriate locations and cotton ties provided to secure the risers with the structure. Details of design constraints and challenges faced during the system configuration process are discussed in Aggarwal *et al.*[1].

Sequence of operations

The deceleration system initiation takes place at an altitude of 7 km by ejecting and deploying two ACS Parachutes. The velocity of the Module expected at this time is nearly 137 m/sec. The ACS parachutes along with three pyro thrusters effectuate the separation and safe jettisoning of the Apex Cover. After a short time interval of nearly 1.85 sec, which is enough to ensure sufficient clearance between the Module and the jettisoned Apex Cover, the two pilot parachutes are deployed. The ejection of ACS and pilot parachutes is achieved by firing mortars, a gas generator-based pyro device, which houses the parachutes. Upon full stretch, the pilot parachutes extract the two drogue parachutes from their respective containers, since the risers of the pilot parachutes are connected directly to the drogue pack covers. The risers of the two drogue parachutes are connected to the CM structure through PRUs, which are pyro-based pin-pullers used to disconnect the parachutes from the structure at the required time by issuing command. The descent of the Module under two drogue parachutes is the first stage of deceleration where the velocity of the module reduces to nearly 55 m/sec and its stabilization is achieved within allowable limit. When the Module reaches nearly 3 km altitude, command is issued for disconnecting the drogue parachutes by actuating the PRUs. On their way out, the drogue parachutes extract and deploy the two main parachutes.

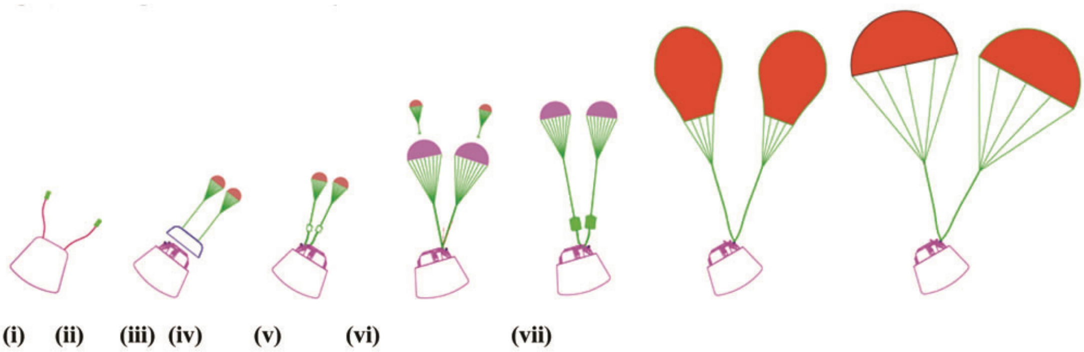


Figure 2. Deceleration system deployment sequence: (i) ACS mortar firing, (ii) Apex Cover separation, (iii) pilot parachutes extracting the drogue parachutes, (iv) deployed drogue parachutes, (v) drogue parachutes extracting the main parachutes, (vi) reefed main parachutes and (vii) fully inflated main parachutes.

The deployment method implemented by providing cotton ties in the parachute pack cover ensures proper extraction and deployment of the main parachutes with low levels of snatch load. A reefing ratio of 0.08 was chosen so as to achieve minimum reefing and full opening peaks. After an interval of 7 sec, during which the Module reaches a reefed terminal velocity of 20 m/sec, actuation of the reefing line cutters takes place which severs the reefing line in the skirt and allows full inflation of the canopies. Each main canopy is provided with two reefing line cutters. They are actuated by mechanically removing the puller causing the spring loaded striker to ignite the percussion charge, which in turn initiates the burning of delay cartridge and main charges of cutter.

The fully inflated main parachutes, which form the third and final stage of deceleration, reduce the terminal velocity of CM to nearly 8 m/sec. The final descent velocity with a single main parachute (in case of one chain failure) is close to 11 m/sec. Upon detecting impact in water, the main parachute risers are disconnected from the Module actuating the parachute releaser units. Figure 2 shows a schematic of the deceleration system deployment sequences.

Development programme

To meet the system requirements specified by the project team, several new technologies had to be developed. The system configuration, staging requirement, selection of parachutes, their construction and the test plan were finalized after different levels of review by appropriate committees. These are discussed in the following sections.

Configuration and layout

The configuration of the deceleration system (Figure 1) and the deployment sequence was arrived at after studying different configurations and considering factors like redundancy at each stage, oscillations induced in the case of asynchronous deployment of parachutes, method of parachute extraction, etc. Points considered while finalizing the layout of the deceleration system are listed below.

(i) Attachment point shall be along the yaw axis of the Module so that peak deceleration and oscillations induced at the time of parachute deployment would be along the direction of crew orientation.
(ii) Both chains of the parachute system are positioned symmetrical to the yaw axis to have minimum shift in the CM Centre of gravity (CG) about the pitch plane during deployment of parachutes.
(iii) Independent single-point attachment of drogue and main parachutes is made to limit the load on the parachute releaser units and also to avoid any single failure point in the system. The attachments are located close to each other to limit the oscillation level in case of asynchronous deployment of parachutes.
(iv) The attachment point is offset from the pitch axis to have a favourable input angle.
(v) The drogue parachute is housed in a special container to ensure safe and abrasion-free extraction of the drogue parachute.
(vi) Orientation of the pilot parachute ejection mortars was such that the parachutes are ejected away from each other for entanglement-free deployment. They were also located near the drogue container to have minimum routing of the pilot parachute riser.
(vii) Routing scheme of the drogue riser, main riser and extraction bridle is made to have entanglement and abrasion-free extraction. For this, the risers are tied to the structure using temporary cotton ties which break-off sequentially during extraction.
(viii) The drogue parachute retention system consists of an arrangement of nylon loops which close the mouth of the container. The pilot parachute, upon deployment, breaks these retention loops before extracting the drogue parachute from the container.

(ix) The main parachute retention system is designed to ensure sufficient gap between the main parachute pack and the Apex Cover during assembly as well as in flight.

(x) Orientation and location of ACS mortars on the Apex Cover are such that there is minimum shift in CG while ensuring adequate clearances during assembly.

Pyro devices

In order to meet the system requirements, the following pyro technologies and devices are developed.

(a) Mortar for ejection and deployment of ACS and pilot parachutes.

(b) PRUs for disconnecting the parachutes from the structure.

(c) Reefing line cutter for dis-reefing of the main parachute.

(d) Pyro thruster for separation and jettisoning of Apex Cover.

Redundancies were incorporated and device-level tests were carried out to achieve the required reliability of the subsystem and meet the requirements of human rating.

Parachutes

The selection of parachutes was based on different criteria like opening time, stability, drag coefficient, etc. The experience gained by the design teams during ISRO's Space Capsule Recovery Experiment and the heritage of use in various military applications further helped finalize the system configuration. Wind-tunnel tests were carried out for a scaled-down versions of the parachutes to determine their drag coefficients and stability characteristics.

The parachutes were packed in specially designed pack covers taking into account the available volume in parachute compartment and its location. The packing procedure for each parachute was finalized after conducting bench trials and drop tests to identify the possible failure modes. Several anomalies and inadequacies in the packing process were found in these tests. Few such anomalies and corrective actions implemented during the system development are given below.

(i) In one of the air-drop tests, the main parachute canopy and rigging line came out as a bunch from the pack due to lower strength of the mouth weak tie. This resulted in canopy inflation before full stretch and subsequent failure of the parachute. Several modifications to the packing procedure were made after this failure. The number of weak ties between canopy to pack cover was increased and separate flap was provided in the pack cover at the end of the canopy skirt location and these flaps were closed using rigging lines. This ensured opening of the canopy only after full stretching of the rigging lines and riser.

(ii) In another air-drop test of the main parachute, it was observed that the riser and rigging lines came out of the pack cover as a bunch rather than in a sequential manner. This was due to the absence of cotton ties between the riser/suspension lines and the pack cover. Thus, loops were introduced in the pockets and cotton ties provided to prevent premature extraction of the riser or suspension lines.

(iii) In yet another air drop test, the cotton loops were not found broken; instead the interface stitching of loop to pack cover was broken. This was due to inadequate strength of interface stitching. Stitches in the area were strengthened and load tests were done to ensure adequate strength.

Pressure packing scheme was adopted for the pilot parachute, whereas the drogue and parachutes main were packed manually. Care was also taken to ensure that no damage occurred to the fabric of the parachute due to the presence of an interface adaptor in the main parachute pack which connects 84 rigging lines to a single riser. All sharp edges of the adaptor were removed and smooth surfaces were ensured. Additionally, the adaptor was placed inside a nylon thimble to prevent contact of fabric with metal. Integration trials were carried out with a dummy parachute compartment to estimate the length of the risers to be kept out of the pack cover according to the riser routing.

A critical operation at the time of the main parachute packing was the attachment of pull cords for reefing line cutter actuation. A mechanical actuation system was adopted where a pull cord, attached to the rigging line, would remove the puller from the cutter assembly at the time of full stretch. This scheme was tested and improved upon by conducting bench trials and air-drop tests. Several anomalies and inadequacies in the reefing system were discovered in the main parachute drop tests which were corrected by implementing the required modifications and conducting confirmatory tests. Such examples are given below.

(iv) In a structural qualification test of the main parachute done by dropping a dummy payload of mass 5000 kg from an IL-76 aircraft, the main parachute canopy collapsed soon after inflation (Figure 3) and got detached from the platform resulting in the total test failure. The reason for this, as discussed in detail in Aggarwal *et al.*[1], was concluded to be high snatch force experienced by the reefing line cutter due to its heavy mass (0.9 kg). Several design changes were made and the mass was brought down to 0.4 kg, significantly reducing the snatch force.

(v) In one of the qualification tests, it was observed that the knot in the reefing line loosened as soon as the parachute inflated up to the reefed stage. This resulted in the immediate disreefing of the canopy. For subsequent tests, a stitched configuration of the reefing line was implemented rather than the knotted one (Figure 4).

(vi) Another anomaly observed was the bending of the puller of the reefing line cutter. Introduction of a metallic sleeve at the end of the cutter solved this problem, as the possibility of a lateral pull load was eliminated.

Auxiliary hardware

In addition to the above-mentioned pyro devices and parachutes, the system also consists of several interface adaptors used for connecting parachutes with CM, interfacing rigging lines with the riser, connection of pack cover with the riser/extraction bridle, brackets for main parachute retention system, etc. Special care was taken to ensure proper locking of the connecting pins. Freedom along two mutually perpendicular planes was provided for the adaptor used to connect the parachute risers with CM to account for the module oscillations. Static load tests up to the qualification level were carried out to verify the design. Other hardware include container for drogue parachute, brackets for mounting mortars and ACS pyro thrusters, etc.

Tests

A detailed development and qualification test plan was generated for the system after reviews involving system designers, project teams and quality teams. Due to the budget and schedule constraints, limited number of tests was planned so as to qualify the system within the timeframe specified for the Crew Module Atmospheric Re-entry Experiment (CARE) scheduled in December 2014, followed by Pad Abort Test (PAT-01) in July 2018. Details of these tests are given below.

Wind tunnel tests

Wind tunnel tests were carried out at the National Wind Tunnel Facility of the Indian Institute of Technology, Kanpur. These tests were done for scaled-down versions of the parachutes to determine the drag coefficient, parachute opening force coefficient, and to the opening behaviour and oscillations of the parachute (Figure 5). Data from the tests helped finalize the construction/type suitable for drogue and main parachutes. The drag coefficient obtained from the wind tunnel tests closely matched with those in the literature for similar types of parachutes[2].

Ground tests

As part of the development plan, ground-firing tests were done for the mortar ejected pilot/ACS parachutes. These tests were aimed at determining the optimum charge quantity, ejection velocity and reaction load measurements. Ground-firing tests for the ACS Mortar (Figure 6) were also done by simulating the thermal protection system over the lid of the mortar, while ensuring sufficient ejection velocity (Figure 6). Similar ground firing tests were done for the other pyro devices also.

Rail track rocket sled tests

A series of tests were done in the Rail Track Rocket Sled (RTRS) test facility, where the parachutes were deployed behind a horizontally moving sled. Due to the facility constraints, the tests were limited to ACS, pilot and drogue parachutes (Figure 7).

Figure 3. Main parachute failure due to high snatch force.

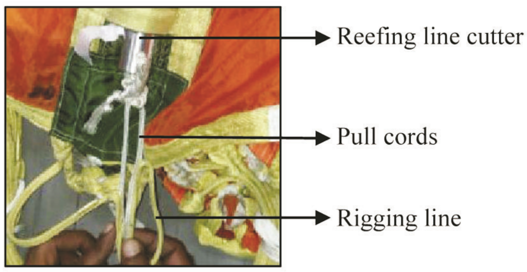


Figure 4. Reefing line cutter actuation scheme.

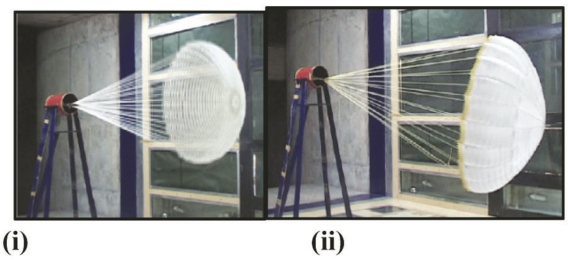


Figure 5. Wind tunnel models of (i) drogue parachute and (ii) main parachute.

The objectives of RTRS tests were to prove the structural integrity of the parachutes by subjecting them to qualification load level, verify ejection, stretching and deployment of parachutes and measure the parachute opening forces. Due to the external forces acting on the sled (drag and friction) and lesser payload mass, the pilot parachutes were deployed at a higher dynamic pressure (12.0 kPa) for the deployment of drogue parachute. The sled velocity required at the time of parachute deployment was 143 m/sec.

The tests were conducted in different configurations, viz. single pilot parachute deployed using mortar, two pilot parachutes in cluster using mortars, two ACS parachutes in cluster simulating the thermal protection system on the Mortar lid and single drogue parachute using mortar deployed pilot parachute. After initial failures like vent band failure in both pilot and drogue parachutes, drogue suspension line failure, etc. design modifications were done and the tests were repeated. The parachutes load levels achieved in the final tests were high enough to qualify the parachutes for the CARE Mission. Further tests need to be carried out to qualify the parachutes for the actual manned mission.

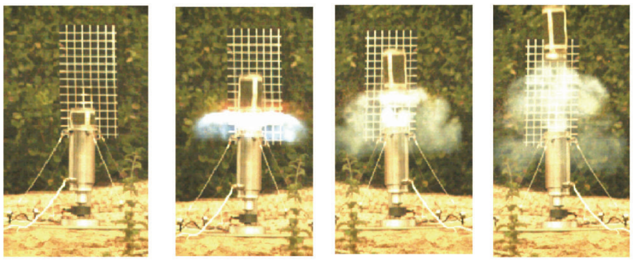
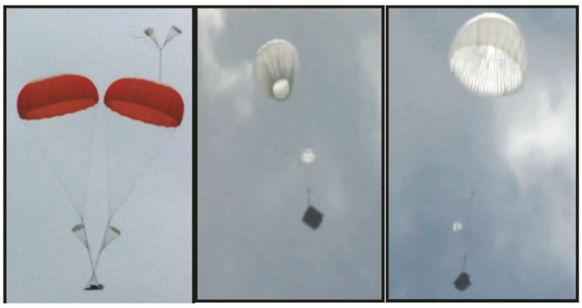


Figure 6. Mortar firing test.

Figure 7. Rail track rocket sled tests for pilot and drogue parachutes.



(i) (ii) (iii)

Figure 8. Air-drop tests for main parachutes: (i) clustered configuration, (ii) reefed opening, and (iii) fully inflated parachute.

Air-drop tests

Since the beginning of the HSP programme, a large number of drop tests were envisaged at subsystem level, primarily to validate the design and proceed with the development.

The initial drop tests for drogue and main parachutes were conducted using AN-32 aircraft of Indian Air Force (Figure 8). The major objectives of these tests are as follows:

- Finalize the parachute packing procedure.
- Estimate drag coefficient of the main parachute by measuring terminal velocity of the test platform.
- Test the main parachute reefing system with emphasis on mounting and actuation scheme of reefing line cutters.
- Measure the snatch force, parachute opening force and inflation time for the main parachute.
- Verify deployment of the main parachutes in clustered configuration.

Due to limitation of the AN-32 aircraft, the mass of the test platform was limited to 3000 kg. In order to structurally qualify the main parachute and its reefing system, a higher payload mass and drop altitude are required. Therefore, in addition, four tests were done using IL-76 aircraft where platforms of mass 4000–5000 kg were used.

The primary objective of the tests using IL-76 aircraft was to subject the main parachute to qualification load. The test configuration, altitude, aircraft velocity, etc. were finalized to meet this objective. However, the first two tests resulted in failures due to problems with the reefing system. A detailed post-test analysis was carried and further tests were done with several design modifications like introduction of a sleeve in the reefing line cutter assembly, reduction in mass of reefing line cutter, repositioning of the cutter and addition of four more rigging lines, strengthening of rigging line loops, etc. The subsequent tests were successful and a maximum load of 163 kN was simulated, thus qualifying the main parachute and the reefing system for the CARE Mission load of 107 kN.

Integrated air drop test

For the full-scale functional qualification of the deceleration system, an integrated air-drop test (IADT) was carried out by dropping a dummy module in the Bay of Bengal, off the coast of Satish Dhawan Space Centre, Sriharikota. In this test, the deceleration system was integrated with an air-drop test module (ADTM) which was dropped using Mi-17 V5 helicopter. The drop parameters like altitude, velocity and the deployment sequence were finalized after numerous computer simulations, taking into account different failure scenarios.

The ADTM was dropped from an altitude of 3750 m. A stabilizer parachute was used in this test to prevent the tumbling of the ADTM due to its forward velocity after separation from the helicopter. Once the stabilizer parachute was released, the sequence of deceleration system was initiated by firing of ACS mortars and ACS. The primary concern was safe extraction of the main parachute using the drogue parachute which occurred flawlessly and the Module was safely recovered from the sea. Figure 9 shows the deceleration system deployment sequence as captured in the test.

CARE

CM was flown as the payload in one of ISRO's launch vehicles as part the CARE mission. After separation from the launch vehicle at 126 km, the Module made a re-entry and was safely recovered with the help of the deceleration system (Figure 10). The deceleration system was initiated at a Mach number of 0.75 and an altitude of 15 km with the firing of the ACS mortars and the separation of the Apex Cover. The Module then descended under drogue parachutes up to 4.6 km, at which the main parachutes were deployed.

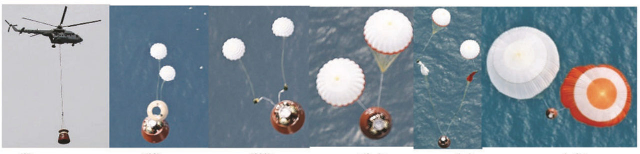


Figure 9. Integrated air-drop test sequence of events: (i) module with helicopter, (ii) Apex Cover separation, (iii) pilot parachutes extracting the drogue parachutes, (iv) deployed drogue parachutes, (v) drogues extracting the main parachutes, and (vi) fully inflated main parachutes.

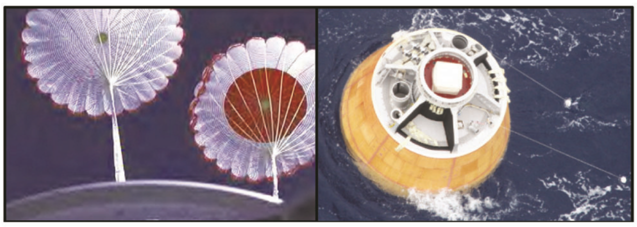


Figure 10. (i) Deployed drogue parachute as captured from the onboard camera. (ii) Crew Module after splash down in the sea.

Pad Abort Test

Pad Abort Test (PAT) of the HSP was successfully completed. In this test, CM was taken to an altitude of 3 km using the Crew Escape Motor. Then CM was separated from the tower. After a predefined interval of separation, the deceleration system was initiated. All system elements functioned well and the Module achieved a terminal velocity of 7.2 m/s with two main parachutes.

Conclusion

A deceleration system to cater to the safe recovery of a 4-tonne class payload is being developed as part of technology development for ISRO's HSP. The system was subjected to minimum number of qualification tests prior to the first successful unmanned (CARE) mission and PAT as part of HSP. The qualification of the system to meet manned mission requirements subjecting it to all extreme design conditions and failure modes is in progress.

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