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**APOLLO EXPERIENCE REPORT -
EARTH LANDING SYSTEM**

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16. Abstract A brief discussion of the development of the Apollo earth landing system and a functional description of the system are presented in this report. The more significant problems that were encountered during the program, the solutions, and, in general, the knowledge that was gained are discussed in detail. Two appendixes presenting a detailed description of the various system components and a summary of the development and the qualification test programs are included.			
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APOLLO EXPERIENCE REPORT

EARTH LANDING SYSTEM

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SUMMARY

The Apollo earth landing system operational requirements were defined through detailed reviews of the total-mission environments associated with both normal atmospheric entry and the various abort contingencies. These operational requirements and the necessity for compatible interface with the command module dictated the basic design and performance requirements of the earth landing system. For example, the high recovery weight of the command module ruled out the use of a single main-parachute system because of the lack of experience with single parachutes in a size needed to recover the spacecraft within the limitations placed on the rate of descent. In addition, the Apollo upper-deck structure presented formidable problems for packing and installing a single parachute of the required size.

Although much was known relative to the system requirements during the initial phases of the program, considerably more knowledge was gained during the course of the development program. The more significant problems encountered during the development of the Apollo earth landing system, the solutions, and the general knowledge gained from having encountered these problems are discussed. A brief description of the Block I, Block II, and Increased Capability Block II systems and a summary of the test programs that were conducted are included.

INTRODUCTION

In January 1962, the original specifications were released for a parachute recovery system to be incorporated on the Apollo command module (CM). The original program to develop and to provide this system was anticipated to extend over a period of 13 months; however, the final Apollo earth landing system (ELS) qualification test was not completed until July 1968. Then the system was considered suitable for manned lunar missions.

Early in the Apollo Program, the fact was recognized that, to accomplish the lunar-landing mission, certain major changes would have to be made to the initial CM design. In consideration of program cost and schedule, a decision was made to continue the original CM configuration (then designated as Block I) through the initial

earth-orbital system-verification flights. At the same time, a Block II program was initiated to implement the changes to the CM that were needed to accomplish the lunar-landing mission.

The major differences between the Blocks I and II spacecraft affecting the ELS were as follows.

1. The docking tunnel was shortened and the tunnel wall was tapered slightly inward. This modification significantly changed the shape of the main-parachute stowage compartment and necessitated complete redesign of the main-parachute deployment bag and the retention system.

2. A single structural assembly (called the flowerpot) was incorporated to attach the two drogue risers and the three main-parachute risers to the CM at a single location. This attachment fitting also served as the housing for the riser disconnects.

3. The pilot-parachute mortar mounts were moved from the deck of the forward compartment and relocated on the side of the gussets.

4. The CM uprighting bags were removed from the gusset-mounted containers and relocated under the main-parachute packs on the deck.

The drogue, pilot, and main parachutes remained essentially unchanged from the Block I configuration except for a length of steel riser incorporated in the lower end of the main-parachute riser for protection from abrasion. After the spacecraft 012 fire, many modifications were made to the Block II CM, resulting in a significant increase in vehicle weight. Analysis indicated that the projected weight increase would result in parachute loads greater than those that either the ELS or the CM structure was capable of withstanding safely. Therefore, in mid-1967, a program was initiated to increase the capability of the ELS and to reduce the main-parachute loads to acceptable levels with the greater CM weight. The major changes made to the ELS during this program were as follows.

1. The main-parachute reefing system was modified to incorporate an additional stage in the inflation process to reduce the peak opening loads.

2. The diameter of the drogue parachutes was increased to reduce the dynamic-pressure conditions and to provide a more stable vehicle at the time of main-parachute deployment.

3. The size of the drogue-parachute mortar was increased to provide the additional volume required by the larger drogue parachute.

4. The parachute reefing-line-cutter time-delay was modified to obtain delay times of 6 and 10 seconds for the two-stage main-parachute reefing system.

The various components of the Block I, Block II, and Increased Capability Block II systems are discussed in detail in appendix A. In appendix B the test programs that were conducted to develop and to qualify the ELS are outlined.

FUNCTIONAL DESCRIPTION

The ELS consists of the various parachutes and related components necessary to stabilize and to decelerate the CM to conditions that are safe for landing. The ELS was designed to recover the CM after either a normal entry or a launch abort. Nine parachutes are installed on the CM all of which function during the recovery sequence. Three main parachutes, three pilot parachutes, two drogue parachutes, and a forward-heat-shield-separation-augmentation parachute are included.

The recovery sequence is initiated automatically through the closure of barometric switches or through the function of time-delay relays. A logic diagram illustrating each of the ELS functions is presented in figure 1. A normal-entry or high-altitude-abort recovery sequence begins with the jettisoning of the forward heat shield at a nominal altitude of 24 000 feet (fig. 2). Immediately after separation of the

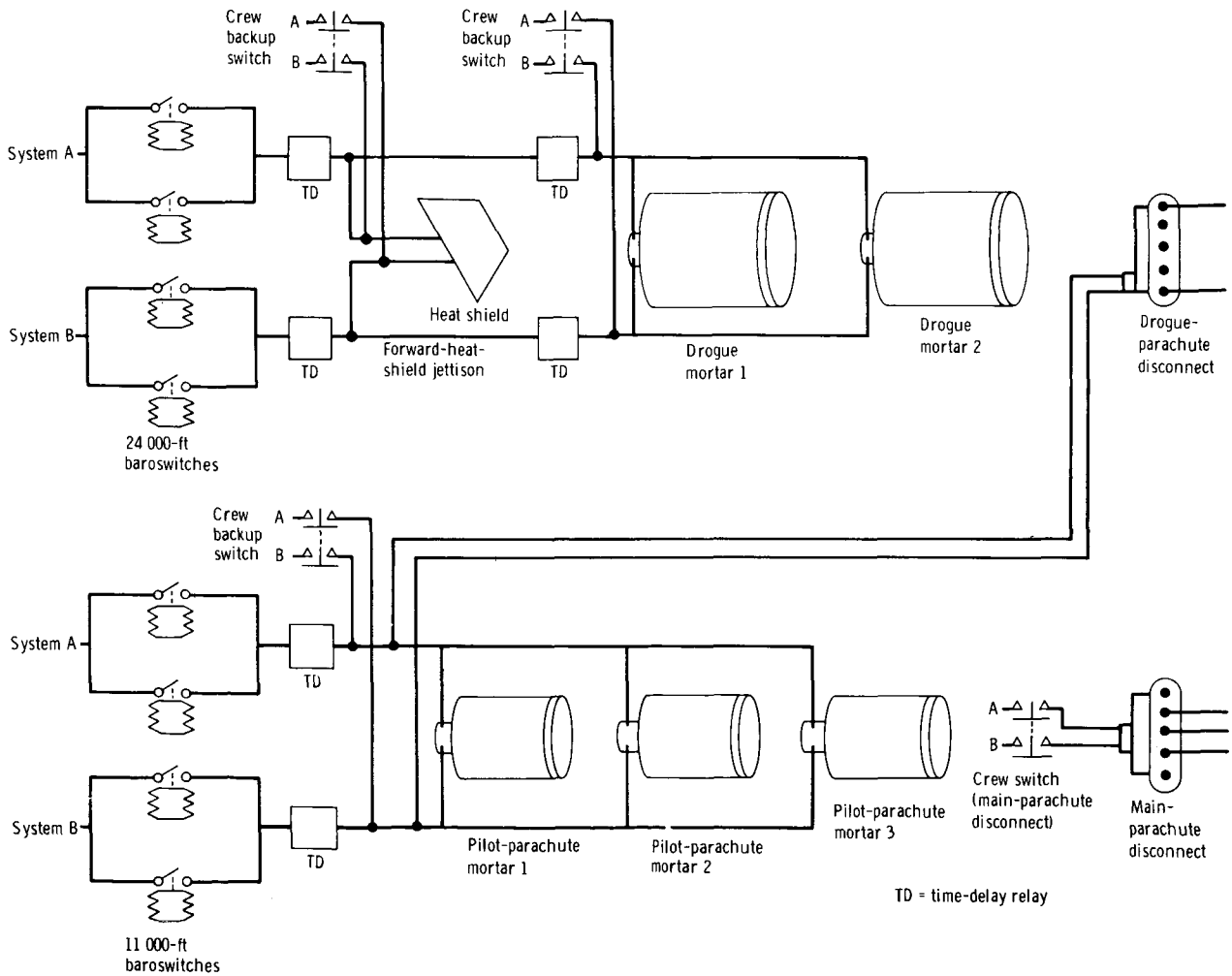


Figure 1. - Logic and redundancy in the ELS.

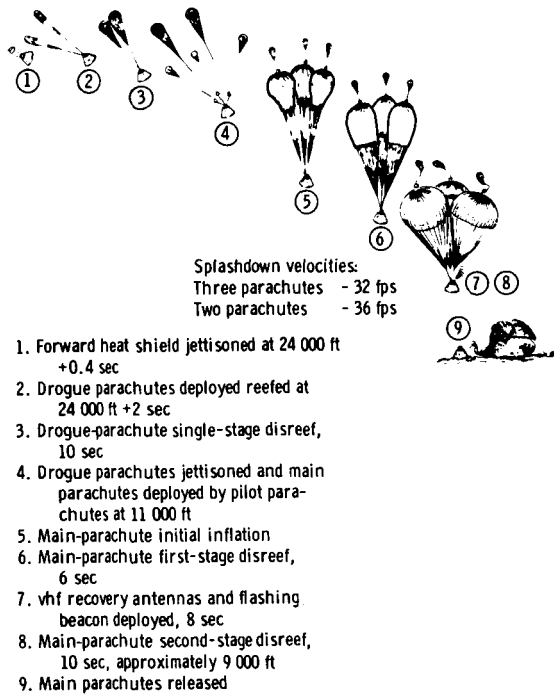


Figure 2.- Normal recovery sequence.

If a launch abort should occur and conditions are such that the maximum altitude attained is below the opening altitude of the baroswitches, forward-heat-shield jettison and deployment of the drogue and pilot parachutes occur on a timed sequence, controlled by the time-delay relays. The events that occur during a launch abort are illustrated in figure 3.

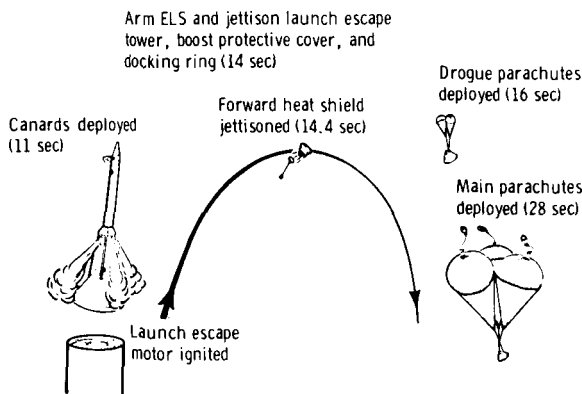


Figure 3.- Pad- and low-altitude-abort sequence.

heat shield from the CM, a small, 7.2-foot-diameter parachute is mortar-deployed from the forward heat shield. This parachute exerts a force to extract the jettisoned heat shield from the wake of the CM. Two 16.5-foot-diameter conical ribbon drogue parachutes are mortar-deployed 1.6 seconds after forward-heat-shield jettison. The drogue parachutes undergo a 10-second reefed interval before disreefing to full open, and remain attached to the CM to an altitude of approximately 11 000 feet. At drogue disconnect, three 7.2-foot-diameter ringslot pilot parachutes are mortar-deployed. The pilot parachutes then provide the force necessary to release the main-parachute retention system and to extract the main-parachute pack assemblies. The main-parachute packs are then pulled away from the CM and the three 83.5-foot-diameter main parachutes are extracted from the deployment bags. Each main parachute then inflates through two reefing stages to a full-open condition.

If a launch abort should occur and conditions are such that the maximum alti-

tude attained is below the opening altitude of the baroswitches, forward-heat-shield jettison and deployment of the drogue and pilot parachutes occur on a timed sequence, controlled by the time-delay relays. The events that occur during a launch abort are illustrated in figure 3.

SIGNIFICANT PROBLEMS

Throughout the ELS developmental program, emphasis was placed on providing a CM recovery system capable of functioning properly under extremely severe flight conditions. At the same time, the demands placed on the system in terms of vehicle recovery weight, component stowage, and vehicle interface requirements continued to grow. During the program, extreme measures appeared to be necessary in terms of system or spacecraft redesign to satisfy the requirements imposed on the recovery

system. Through the applied efforts of the various groups and agencies associated with the system, these problems were resolved with minimum design changes and with the least impact on the Apollo Program.

In addition to resolving difficult design problems, devising and optimizing component manufacturing and assembling techniques were also necessary to ensure that each part would function properly once it was assembled and installed on the spacecraft. On none of the previous space programs was it necessary to contain the parachutes in the limited volumes and in the irregular shapes necessary in the Apollo Program. This requirement necessitated the development of precise techniques for packing the parachutes at very high densities without inflicting damage that could propagate during deployment. The incorporation of steel cable as an integral part of the parachute risers required the development of stowage techniques that would provide assurance that the cable deployed consistently and safely.

In addition to stringent program requirements, several specific technical problems, the solution of which required the development of innovative methods and techniques, were encountered. In the following section, the more significant problems encountered, their solutions, and the knowledge gained are discussed.

Command Module Weight Increase

The most significant problem of the ELS was the continual increase in CM weight. This condition resulted in a major program of redesign and requalification of the Block II ELS. A plot of the total load of the main parachutes as a function of vehicle weight illustrates the effect of CM weight on parachute loads (fig. 4). The individual parachute loads are significant in terms of the structural capability of the parachutes; whereas the total cluster loads are significant in terms of the capability of the CM supporting structure. During the Apollo Program, the weight increase necessitated corrective action for the parachutes and the supporting CM structure. The modifications made to the parachutes increased the capability of the parachutes to withstand higher loads or changed the inflation characteristics of the parachute to reduce the peak opening loads.

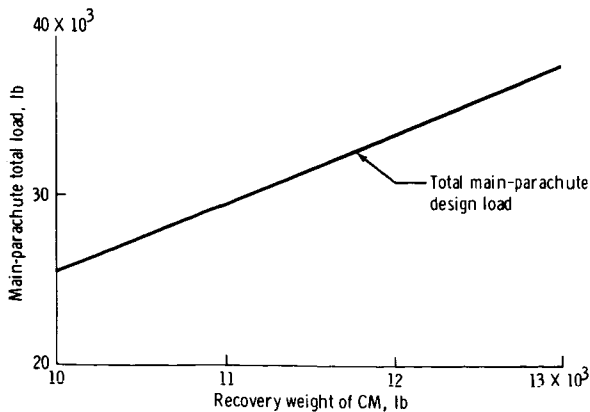


Figure 4. - Total main-parachute load compared with CM weight.

The CM weight growth and certain significant program events are depicted in figure 5. The first three Block I developmental aerial drop tests were conducted with a parachute design of lightweight material and with a minimum of reinforcing tapes. Because major damage was sustained on two of the three tests and because of the first announcement of a CM weight increase, the first modification was made to strengthen and to improve the main-parachute design. The initial changes increased the strength of the structural members of the parachute. These changes caused a significant increase in weight and

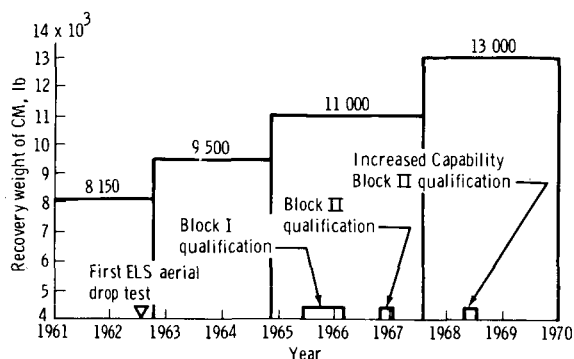


Figure 5. - Increases in CM recovery weight.

condition was not sufficient to justify major design changes in the ELS. Therefore, the Block II program was pursued as a minimum-change effort.

During the months immediately following the spacecraft 012 accident, numerous modifications were made to the CM. By mid-April 1967, weight estimates indicated that the projected weight of the spacecraft had increased to a value greater than that at which the ELS could recover the CM with an acceptable safety margin. The CM recovery weight possibly could increase to as much as 13 000 pounds, which, in turn, would increase the parachute loads to levels unacceptable for the parachutes and the CM structure.

The implemented solution consisted of increasing the size of the drogue parachutes and of providing the existing main parachutes with an additional reefing stage. The larger drogue parachutes and the additional main-parachute reefing stage were necessary to ensure adequate safety factors for the parachutes and the CM structure at the 13 000-pound recovery weight. Larger drogue parachutes on the heavier CM reduced the dynamic pressure at drogue disconnect/pilot mortar fire to a level near that of the smaller drogue parachutes on the lighter spacecraft. The additional reefing stage in the main parachutes reduced the individual and total main-parachute loads to values no greater than the design loads for an 11 000-pound CM.

On July 31, 1967, a program was approved to implement these changes to the ELS to become effective on the first Block II spacecraft (CSM 101). At the beginning of the improvement program, very few data were available to provide a basis for a detailed analysis of two-stage main-parachute reefing. Therefore, aerial drop tests had to be conducted early in the program. These tests generated the preliminary performance data that were used to establish reefing parameters and to support an evaluation of the adequacy of the existing main-parachute design. From these initial tests, two-stage reefing was proved feasible and the existing main-parachute design was proved structurally adequate with the higher CM weight. Reefed intervals of 6 seconds in the first stage and an additional 4 seconds in the second stage of inflation were selected. These reefed intervals provided nearly uniform loading in each stage and added only 2 seconds to the total inflation time of the earlier single-stage reefing system. The new reefing-time-delay requirement was then factored into the development of a

created new problems because of limited stowage volume. Shortly after the start of main-parachute-cluster tests, modifications had to be made to the main parachutes to change their opening characteristics to achieve more evenly balanced load sharing among the parachutes, thereby reducing the peak opening loads.

By the time the Block I ELS had completed qualification, each system of the spacecraft had progressed to the point at which accurate total-weight estimates were available. Although the maximum projected weight for a Block II spacecraft was above the specification values, the overweight

reefing cutter. In conjunction with the main-parachute-design changes, definition of the maximum volume available for larger drogue-parachute mortars became necessary because the size of the drogue parachute was limited primarily by the size of the mortar tubes that could be fitted to the spacecraft. Volume was made available for mortars accommodating 16.5-foot-diameter drogue parachutes.

Because the Block II schedule required delivery of parachutes for installation on spacecraft 101 (Apollo 7 mission) by mid-November 1967, the Increased Capability Block II program was recognized as a high-risk effort in terms of potentially delaying the first Block II flight. Therefore, the total effort was afforded a high priority and received the utmost support at all levels. Considering the schedule requirements, the plan was to deliver the first production system for installation on spacecraft 101; the followup system, which would be identical in configuration, was scheduled to support the system-qualification aerial drop test. Satisfactory completion of the total system-qualification effort was placed as a constraint on the Apollo 7 mission.

The main-parachute design-limit loads defined for the Block II 11 000-pound CM and the design-limit loads for the final Block II main parachutes with the 13 000-pound CM are presented in table I. These load values provide an indication of the effectiveness of the changes made to the Block II system. This table should not be used as a direct comparative evaluation of the changes, because data obtained during the Increased Capability Block II program allowed for considerable refinement of the parameters used in establishing the design-load values. The changes that were made to the ELS effectively counteracted the increase in CM weight and accomplished the required reduction in main-parachute loads.

TABLE I. - MAIN-PARACHUTE DESIGN LOADS

Parachute configurations	Design loads, lb (a)	
	Original Block II ELS with 11 000-lb CM	Final Block II ELS with 13 000-lb CM
Individual		
First stage	21 800	22 000
Second stage	--	23 800
Full open	24 700	22 900
Total cluster	39 000	37 500

^aThese values should not be used for direct comparison.

Main-Parachute-Cluster Interference

On November 27, 1962, the first aerial drop test was made using a parachute test vehicle (PTV) to investigate the performance characteristics of a cluster of three independently deployed 88.1-foot-diameter ringsail main parachutes. For the initial test, the vehicle was ballasted to only 4750 pounds, one-half the weight of the CM. The configuration of the parachute test specimens and the related components represented the then-current spacecraft design. Deployment of the main parachutes was achieved by simultaneously mortar-deployed pilot parachutes.

The results of this test indicated a significant problem relative to the deployment behavior of clustered ringsail parachutes and eventually led to some unique design features in the main parachutes. The three ringsail parachutes inflated in a nonsynchronous manner, that is, one canopy inflated rapidly and inhibited the filling of the lagging parachutes. This behavior was most pronounced during the inflation following disreef. This crowding effect and nonsynchronous inflation, often referred to as cluster interference, was not a new phenomenon but was unusually pronounced with the ringsail design. This uneven load sharing resulted in abnormally high opening loads on the leading parachute in the cluster.

The approach taken to correct this condition was to explore modifications that would reduce the rate of inflation of the parachute. Much of this rapid inflation of the ringsail parachute was attributed to a characteristic of the canopy to continue to fill during the reefed interval and thus produce a large reefed shape with internal pressures throughout a large portion of the canopy. This characteristic, in turn, contributed to a rapid full-open inflation following disreef. The flow of air around the large bulbous shape of a rapidly developed leading parachute was also noted to have a distorting effect on the adjacent lagging parachutes and to greatly inhibit the inflation in the reefed condition.

The modification demonstrating the most favorable effect in reducing the cluster interference was the removal of 75 percent of the material from the fifth ring of the canopy, thereby forming an open ring around the periphery of the crown. This open ring limited canopy growth in the reefed condition to a more cigar-like profile and produced near-uniform growth of each of the three main parachutes during reefed and disreefed inflation. A second change, greatly improving the shape of the lower skirt area and allowing a more efficient inflow of air into all three parachutes, was the relocation of the reefing rings on the skirt band from the radial seam-attachment point to a point on the skirt band in the middle of the gore (referred to as midgore reefing).

Based on test results obtained during this same effort, a decision was also made to remove four complete gores from the main-parachute canopy to reduce weight. This modification produced the basic 68-gore-configuration main parachute that would eventually be flown on Apollo spacecraft.

The combination of reduced peak opening loads and the removal of material resulted in a net allowable weight saving of approximately 45 pounds in the main parachute and harness assembly without exceeding the specified maximum rate of descent of 33 fps at 5000-foot pressure altitude. The open-ring-configuration main parachutes also reduced the system oscillations of the two-parachute cluster configuration from approximately $\pm 20^\circ$ to $\pm 6^\circ$, causing a reduction in landing hazards.

Parachute Riser Abrasion

On September 6, 1962, during the fifth total-system developmental test, using the boilerplate (BP) 3 test vehicle, a series of events occurred that resulted in separation of the main parachutes and loss of the vehicle. The BP failed to stabilize during the drogue-parachute interval, and the pilot mortars fired with the vehicle in an apex-forward (approximately 60°) flight attitude. The existing main-parachute risers, which were joined at a confluence above the vehicle, hung under the airlock with the vehicle in this flight attitude. This anomaly prevented full deployment of the harness until the vehicle rotated to a more favorable attitude. The parachute opening loads were transmitted through the unprotected textile harness legs directly into the gussets and the airlock structure, promptly severing the harness legs.

After this test, the main-parachute harness assembly was completely redesigned to preclude the possibility of its hanging during deployment. The test also made evident the fact that the parachute system had to be capable of deployment from an unstable or oscillating CM. To provide this capability, steps were taken to minimize the number of areas on the vehicle that could cause cutting and abrasion to the parachute risers. Because of requirements external to the ELS, relocation of certain items of spacecraft equipment or provision of a surrounding structure that would not cause damage to the fabric risers was not possible. It was necessary to provide risers with a high degree of abrasive resistance.

Investigation of various types of protective sleeving resulted in the selection of Dacron felt with wire-braid covering and resin impregnation for the Block I main-parachute attachment harness. The required degree of protection and the required flexibility for stowage and deployment ruled out this approach for the drogue- and pilot-parachute risers. Thus, the decision was made to pursue the development of steel cable risers to provide the necessary abrasion resistance in the lower portion of the risers where there was high probability of contact with the CM structure.

The incorporation of the flowerpot parachute attachment and the disconnect fitting on the Block II spacecraft made redesigning the main-parachute risers necessary (fig. 6). The flowerpot concept brought the two drogue-parachute risers and the three main-parachute risers into a common fitting. This concept reduced the available volume and eliminated the possibility of using the bulky Block I-type protected-fabric riser on the Block II spacecraft. Stowage tests on a Block II upper-deck mockup indicated that steel-cable main-parachute risers could be incorporated and stowed in a manner assuring orderly deployment. Because the steel-cable main-parachute riser provided a solution to the Block II volume problem and afforded the necessary resistance to abrasion, the decision was made to incorporate it in the Block II system.

Developmental tests on the drogue- and pilot-parachute systems incorporating steel-riser segments demonstrated that the cable risers could be stowed with the parachute in the mortar tube. A major problem in using steel cable was the possibility of kinks developing during deployment and seriously degrading the strength of the riser. Some kinking was experienced in early developmental mortar firings; however, reverse twisting of the cable while it was being stowed and a modification to the cable-end fitting eliminated the problem.

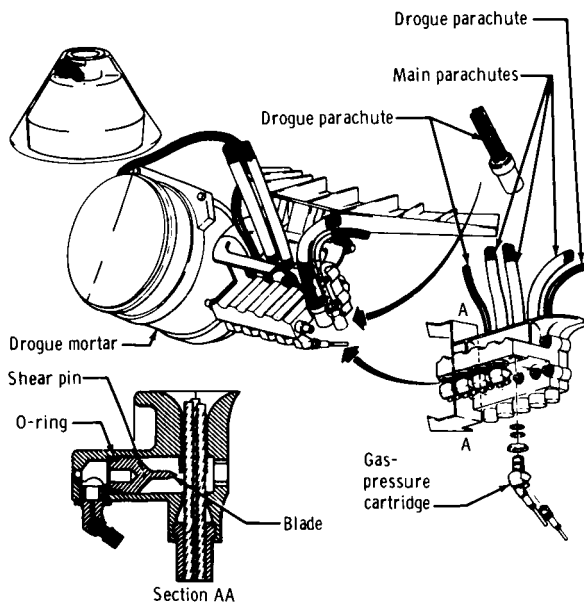


Figure 6.- Parachute attachment and disconnect fitting.

In several of the Block II aerial drop tests incorporating the flowerpot parachute attachment fitting, numerous cable strands were damaged on the drogue risers. This damage occurred in the portion of the cable riser that contacted the lip of the flowerpot fitting while the vehicle was oscillating and the parachute loads were high.

Laboratory tests were conducted to simulate the dynamics between the drogue steel-cable riser and the flowerpot fitting with loads applied to the riser. As the parachute loads were applied through the riser over the lip of the flowerpot, these tests revealed sufficient deflection in the flowerpot lip to cause a local misalignment between the two halves, resulting in a slight ridge over which the cable was abraded. Abrasion was also caused when the four strands of cable in a riser arranged themselves such that one cable would be loaded across another while bent over the lip of the flowerpot.

A 4-inch-wide band of lead tape, wrapped around each of the drogue riser cables where they crossed the lip of the flowerpot, provided excellent protection from abrasion and proved to be a simple and an effective solution to the problem. In the Blocks I and II systems, the steel-cable parachute risers proved an acceptable design and functioned correctly on all tests and flights.

Main-Parachute Canopy Strength Increase

During the second aerial drop test in the original Block II developmental test series, a significant deficiency was found in the structural capability of the main-parachute canopy. The test was established to demonstrate the deployment characteristics of the main parachute at a full-open limit-load condition following deployment from the Block II deployment bag. The main-parachute design remained unchanged between Blocks I and II; there was little concern about the structural capability of the main parachute because it had been demonstrated at ultimate-load conditions in excess of 33 000 pounds during the Block I qualification program. During this test, however, a complete gore was split from the skirt band to the vent band of the main parachute under an axial load between 20 000 and 23 000 pounds while inflating from disreef to full open. Although the parachute design previously had been subjected to significantly higher loads following disreef, a post-test investigation revealed that it had never been exposed to the conditions of this particular test.

Because of the inherent inflation characteristics of the main parachute, the conditions of this test produced much higher local-stress levels in the canopy skirt than were experienced with conditions at a much higher axial load on previous tests. This

deficiency was corrected by the addition of circumferential reinforcing tapes to strengthen the canopy (fig. 7). This test failure clearly illustrated the necessity for demonstrating the inflation characteristics and the strength of the parachutes over the entire range of possible operating conditions.

High-Density Parachute Packing

During the Blocks I and II ELS developmental programs, many modifications involving added material were made to the parachutes. However, increase in available stowage volume for the parachutes on the spacecraft was minimal. Early in the Block I program, the more conventional hand-packing techniques had to be replaced by machine-assisted pressure packing to stow the parachutes in the available volumes. The volumetric requirements for the Blocks I and II main parachutes are depicted in table II. As the density of the parachute packs increased, the amount of damage to the parachutes also increased.

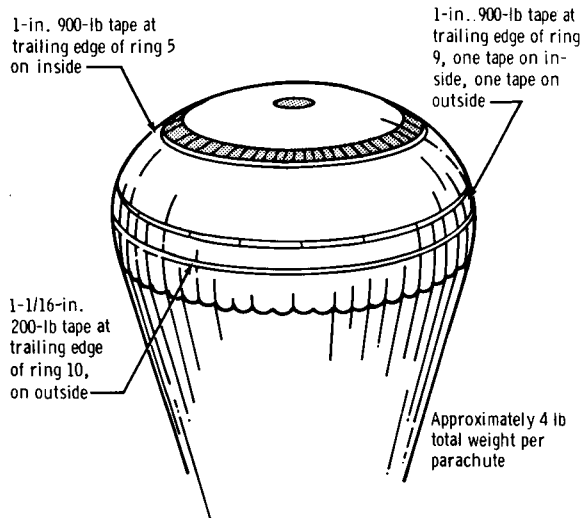


Figure 7. - Main-parachute reinforcement.

The general procedure followed in packing the parachutes involved supporting the parachute deployment bag in a rigid metal container and progressively folding

first the canopy and then the suspension lines into the deployment bag. In pressure packing the parachutes, a ram force was applied to the partially stowed parachute to press it into the deployment bag. Because a high percentage of the main parachute is fabricated from lightweight (1.1 ounce) nylon cloth and because the parachute also contains numerous metal reefing-line cutters and reefing rings, it was particularly susceptible to damage by pressure packing. Layers of cloth would tend to be pinched between metal parts, causing cuts and tears, and the pressure applied to the cloth would cause strained seams, friction burns, and weave separations.

TABLE II. - VOLUMETRIC REQUIREMENTS OF MAIN-PARACHUTE PACK

ELS test programs	Volume of main-parachute pack assembly, cu in.	Net usable volume, cu in.	Volumetric efficiency of parachute pack, percent	Main-parachute pack density, lb/cu in.
Block I	5089	6808	74.8	0.0239
Block II	5500	6925	79.4	.0241
Increased Capability Block II	5500	6925	79.4	.0247

Because of the damage being sustained, a concerted effort was made to design handling equipment and to establish procedures minimizing packing damage. During this effort, approximately 70 trial parachute-packing operations were performed, in addition to the parachute packing that was being accomplished to support the developmental aerial drop tests. Steps taken to correct this problem were as follows.

1. Several basic deployment-bag designs were tried with many modifications to each design. A Teflon-impregnated cloth liner was used in the deployment bag to reduce friction between the parachute and the bag.
2. A high-pressure packing ram was developed with rotating pressure feet, swivel-mounted hydraulic cylinders, and other special features designed to aid packing.
3. The design of the packing pressure feet and protective pads was modified many times.
4. A high-capacity vacuum system was used as an integral part of the packing container to evacuate air from the folds of cloth during packing.
5. Several packing-container designs were tried with many modifications to each design.
6. Packing-container inserts were designed to gain subtle changes in pack contours.
7. Various lubricants (Teflon spray, Teflon-coated cloth, et cetera) were used on the walls of the packing container to aid in packing under pressure.
8. Variations in packing pressure and in soak times were introduced at various stages in the packing process.
9. Combinations of high and low packing pressures were introduced at various stages during the packing process.
10. Changes were made in the design of the reefing rings and in the method of placing them in the deployment bag.
11. Padded reefing-cutter packets were developed and incorporated into the parachutes.

Because of the high densities achieved and because of the tendency for the parachute packs to expand when removed from the packing container, form blocks and vacuum packaging were necessary for storage of the parachute packs to ensure a proper fit of the parachute pack during installation on the spacecraft.

The high-density parachute-packing equipment and the procedures developed and refined throughout the program allowed for maximum use of the available stowage volume on the spacecraft. Although minor packing damage (small cuts and burns) is still present, it is reduced to a level no longer considered to be a hazard or problem to the parachutes.

Forward-Heat-Shield Recontact

During the recovery sequence for spacecraft 009 (Apollo-Saturn (AS) 201), a data-acquisition camera mounted in the CM disclosed a potentially hazardous condition that could have had an adverse effect on successful operation of the parachute recovery system. Immediately following the jettison of the forward heat shield, the cover separated from the vehicle and then returned toward the upper deck at a relatively high rate. Further aerodynamic studies revealed that the forward heat shield jettison system did not provide sufficient energy to thrust the heat shield through the strong reverse flow present in the wake of a stable CM. To ensure separation of the forward heat shield, a conventional pilot-parachute mortar assembly was mounted in the apex of the cover, oriented to fire straight up from the vehicle, and initiated by the same signal that initiated thruster firing of the forward heat shield. This modification was never tested in the Block I BP aerial drop tests (they were already completed), but was tested in a series of ground firings and was incorporated successfully on each of the remaining Block I spacecraft.

Because of the Block I recontact problem, consideration was given to the possibility that this condition existed on the Block II vehicle. Analysis indicated that recontact would not occur because of a 30-percent reduction in the weight of the forward heat shield and because of an increase in thruster output; they combined to provide a separation velocity of 45 fps as compared to the Block I value of 24 fps. However, during the final BP aerial drop test in the original Block II ELS qualification program, onboard cameras revealed that the same condition previously encountered on the Block I AS 201 flight was again present in the Block II system.

The Block II forward heat shield was captured in the wake of the vehicle, and the reverse flow, which was stronger than anticipated, forced it back toward the parachute compartment. Because this condition represented a serious hazard to the ELS, appropriate corrective action was again taken through the addition of a Block II forward-heat-shield-separation-augmentation parachute system (fig. 8).

Because this condition was observed on the final qualification drop test for the original Block II system, and because no unmanned Block II flights were scheduled, concern was focused on a method to demonstrate the fix. This problem was resolved when the Increased Capability ELS program provided a means of evaluating the performance of the forward-heat-shield-separation-augmentation system during total-system aerial drop tests.

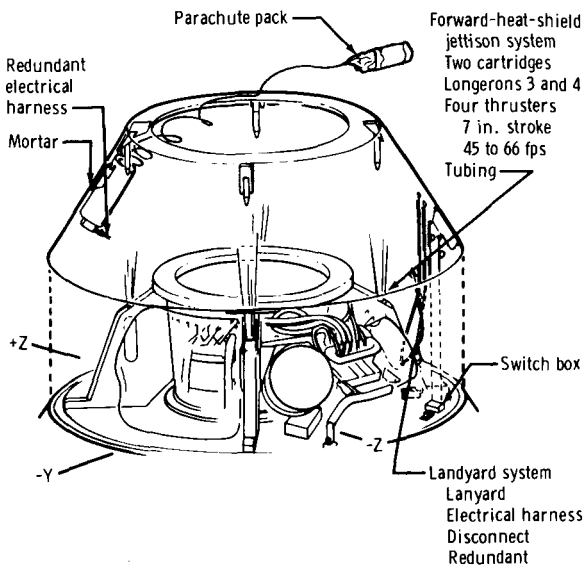


Figure 8. - Block II forward-heat-shield parachute system.

Main-Parachute Oxidizer Burn Damage

One Block I AS 202 main parachute, retrieved following the spacecraft landing, revealed many small burn holes throughout the canopy and suspension lines. Laboratory analysis revealed that the parachute had been damaged by nitrogen tetroxide (N_2O_4) expelled from the CM reaction control system (RCS). The postflight investigation disclosed that the ratio of fuel and oxidizer carried in the CM was such that, during the burn and dump modes (used to purge the RCS after main-parachute deployment), the fuel was depleted before the oxidizer, causing raw oxidizer to be dumped into the air stream. The N_2O_4 , which is very damaging to nylon parachute material, was then sufficiently concentrated on the parachute to burn many small holes. This

condition was corrected on subsequent missions by controlling the ratio of fuel and oxidizer loaded on the CM to ensure that the oxidizer would be depleted before the fuel during the burn mode. Thus, only the fuel remained, and it does not react chemically so as to degrade the strength of the nylon.

An anomaly occurring during the recovery of the Apollo 15 CM caused one of the three main parachutes to collapse during the final descent. The postflight investigation revealed three potential causes for the anomaly: (1) a possible collision of the jettisoned forward heat shield with the main parachute, (2) a failure of the suspension line to the riser connector links, and (3) RCS fuel burning the fabric riser or suspension lines. This investigation was seriously hampered because only one of the three main parachutes was recovered following the landing, and the recovered parachute was not the parachute that collapsed. Secondly, an onboard camera that clearly showed the sequence of the parachute deployment was turned off just before the failure occurred. After a thorough analysis of the existing data, and after considerable testing, the following conclusions were reached.

1. Although it passed very close to the descending spacecraft, the forward heat shield did not contact the Apollo 15 main parachute.
2. Although faulty connector links were found in the recovered main parachute, failure of connector links did not cause the main parachute to collapse.
3. The most probable cause of the anomaly was burning monomethyl hydrazine (expelled from the CM RCS) coming in contact with the main-parachute fabric riser. A complete description of this anomaly and the subsequent findings and corrective actions are presented as appendix C.

CONCLUDING REMARKS

The performance of the ELS during many rigorous tests, and the performance of each component of the ELS during the spacecraft flights proved that the program objectives had been met. A parachute-recovery system was provided that satisfied the mission requirements, was compatible with the physical characteristics of the vehicle, and had a high degree of reliability. The increasingly severe demands placed on the ELS in terms of recovery weight, limited stowage volume, and a wide range of initial conditions were met and resolved without undue impact on the overall Apollo Program.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, July 2, 1973
914-11-00-00-72

APPENDIX A

DESCRIPTION OF ELS COMPONENTS

The basic system concept of the ELS changed little throughout the program from that described in the original statement of work. However, the individual components of the system underwent numerous changes as the program progressed through the Block I and II phases. The following is a brief description of the major components of the Block I, Block II, and Increased Capability Block II ELS.

BLOCK I ELS

The original parachute system consisted of a single, mortar-deployed, 13.7-foot-diameter, 25° conical-ribbon drogue parachute which was attached to the CM in the -Z quadrant of the forward compartment by a 56.75-foot fabric riser and three mortar-deployed, 10-foot-diameter, ringslot-type pilot parachutes, used to extract and deploy three 88.1-foot-diameter ringsail main parachutes. The main parachutes were joined at a confluence fitting 62 inches above the CM. This fitting was attached to the CM by four harness legs that suspended the spacecraft from points located at the top of the forward-compartment gussets. Originally, a main-parachute disconnect was to be contained in this confluence fitting.

Problems such as vehicle weight increase, main-parachute inflation anomalies, and riser abrasion resulted in many modifications to components of the Block I ELS. The Block I system flown on the first Apollo spacecraft is illustrated in figure A-1. This system used two mortar-deployed drogue parachutes, attached by steel-cable risers to a single disconnect fitting. Three mortar-deployed pilot parachutes extracted

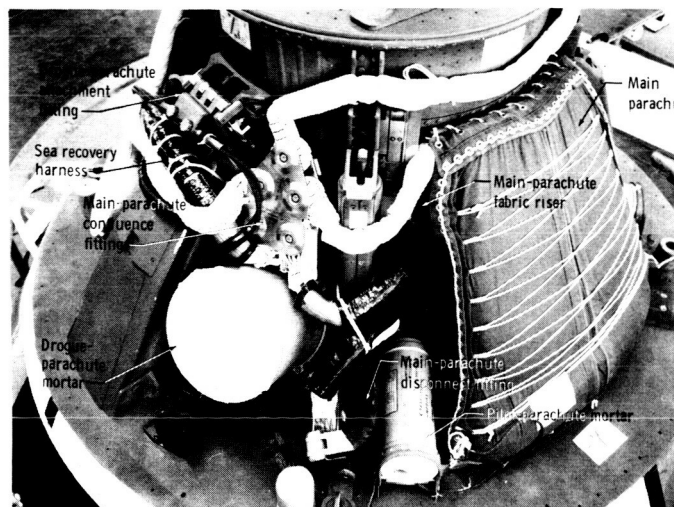


Figure A-1. - Block I ELS installation.

the three main parachutes that were connected by fabric risers to a single confluence fitting. Two harness legs extended from the confluence fitting down to two upper-deck-mounted, main-parachute disconnects.

Drogue-Parachute Systems

The drogue parachute, a 13.7-foot-diameter conical ribbon type, was actively reefed to 39.3 percent of its nominal diameter by redundant reefing lines with two 8-second reefing cutters per line. This parachute is illustrated in figure A-2. The drogue-parachute mortar assembly is illustrated in figure A-3. An electric current first initiates burning of pyrotechnics in the pressure cartridges. Expanding gases then flow from the breech assembly through a restrictor and into the drogue mortar tube. As the gas pressure increases in the tube, the sabot assembly, acting as a piston, ejects the drogue-parachute pack assembly into the airstream. The inertia in the system, and the airloads, cause the drogue parachute to be extracted from the deployment bag; the steel-cable portion of the riser, contained in a polyurethane foam ring, breaks out of the foamed ring and uncoils. The parachute then goes through a normal inflation process.

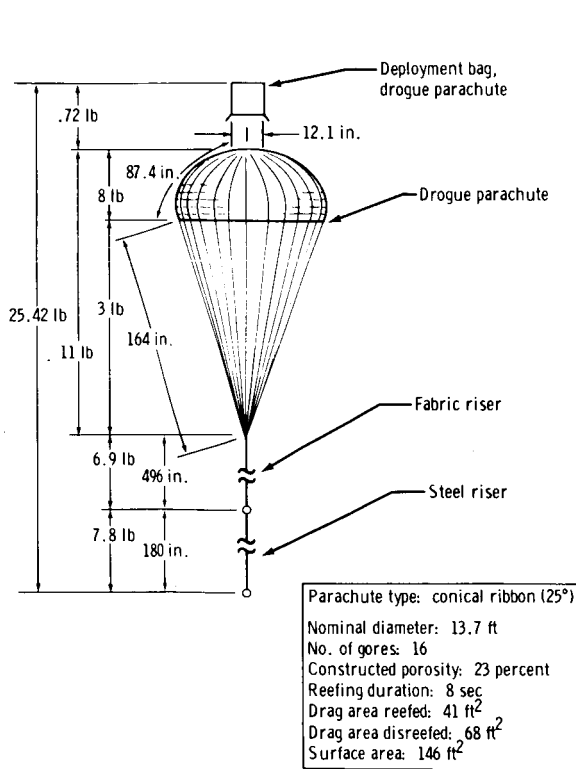


Figure A-2. - Block I drogue parachute.

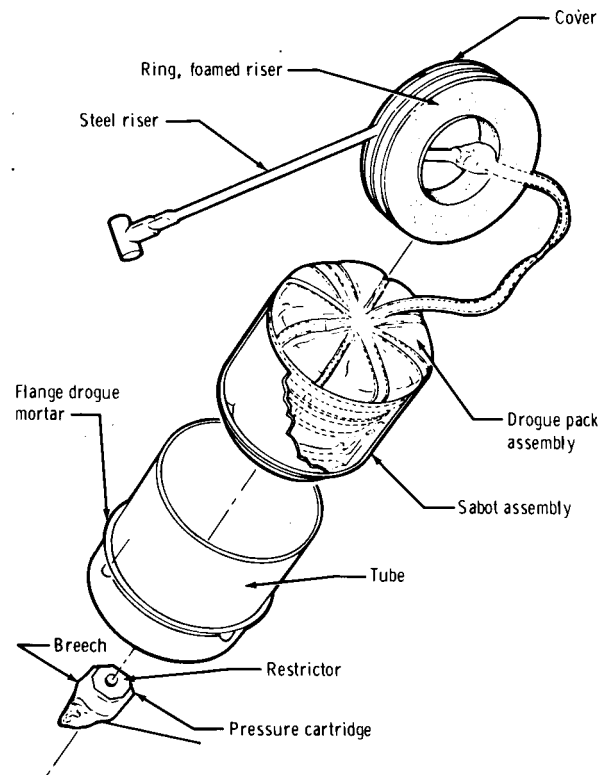


Figure A-3. - Block I drogue-parachute mortar assembly.

Pilot-Parachute System

The pilot parachute, which extracts and deploys the main parachute, is illustrated in figure A-4. This was a 7.2-foot-diameter ringslot design permanently attached to the main parachute and main-parachute deployment bag. The pilot-parachute mortar, pack assembly, and related components are illustrated in figure A-5. As with the drogue system, the pilot parachute was deployed through the action of expanding gas in the mortar tube. The pilot parachute then provided the force required to release the main-parachute retention system and extract the main-parachute pack from the CM.

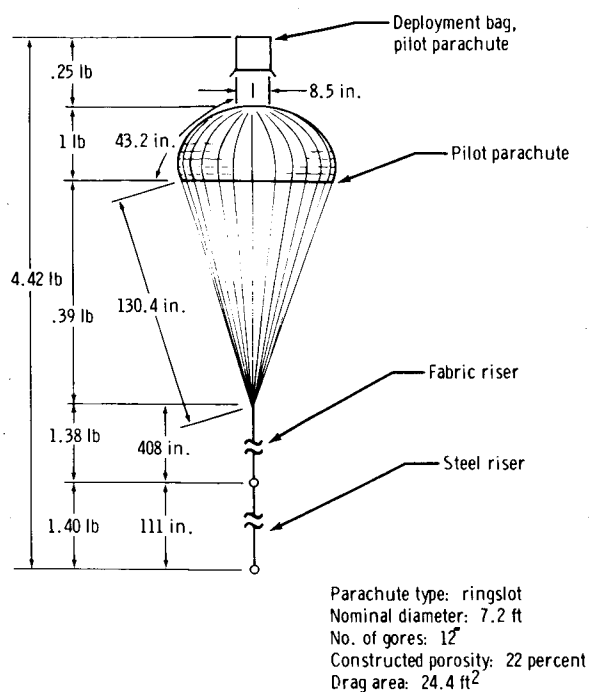


Figure A-4. - Block I pilot parachute.

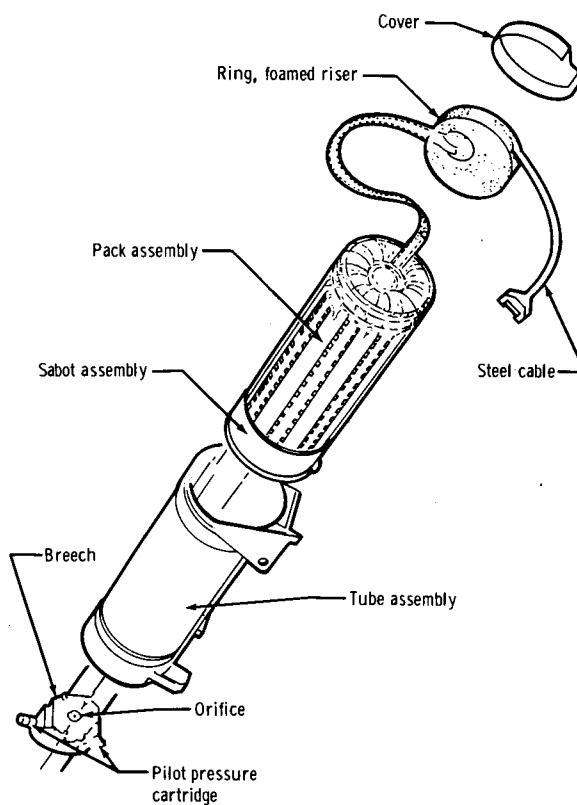
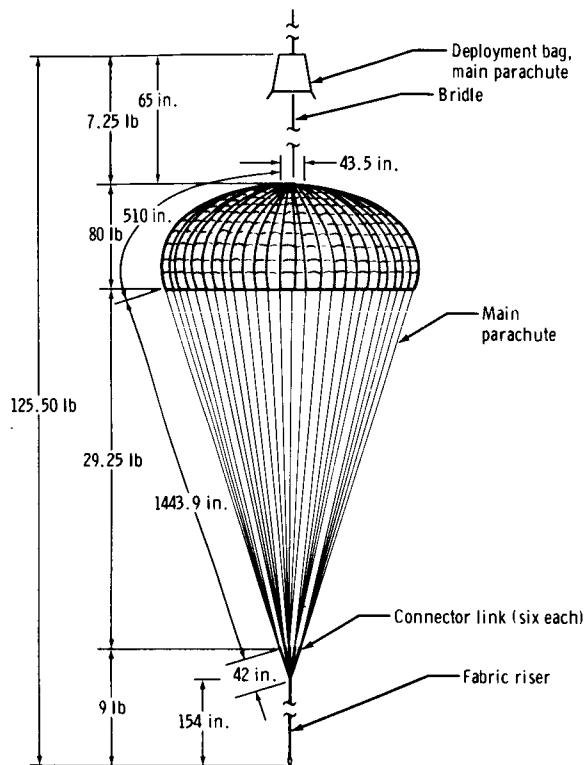


Figure A-5. - Block I pilot-parachute mortar assembly.

Main-Parachute System

The main-parachute system consisted of the three main parachutes, three main-parachute retention assemblies, a main-parachute harness assembly, and two main-parachute attachment fittings. The Block I main parachute was an 83.5-foot-diameter ringsail design, actively reefed to 9.5 percent of its nominal diameter by redundant reefing lines with three 8-second reefing cutters per line. The final Block I main parachute is illustrated in figure A-6 (D_R = diameter reefed). The main parachute was packed in a deployment bag retained on the upper deck of the CM against the airlock wall by the main-parachute retention-flaps assembly (fig. A-7). Force exerted by the pilot



Nominal diameter: 83.5 ft
No. of gores: 68
Calculated total porosity: 12 percent
Reefing: 7.9 ft D_R (9.5 percent midgore)
Reefing duration: 8 sec
Drag area reefed: 353 ft ²
Drag area disreefed: 4000 ft ²

Figure A-6. - Block I main parachute.

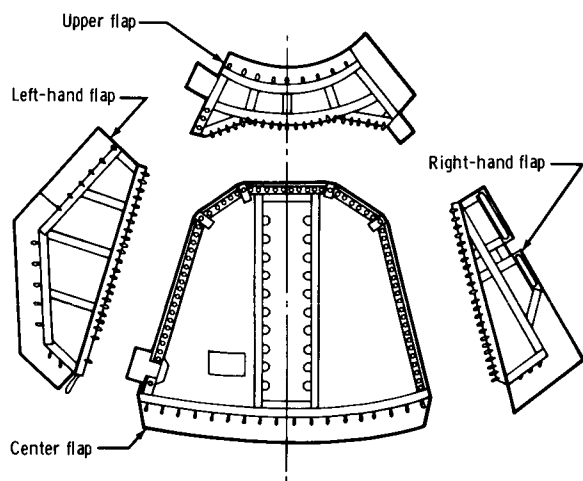


Figure A-7. - Block I main-parachute retention assembly.

parachute released a chain lace securing the retention-assembly center panel to the two side flaps and to the upper flap. Release of the chain lace allowed the center flap to open outward and release the main-parachute pack. As the pilot parachute lifted the main-parachute pack away from the vehicle, the main parachute was extracted from the deployment bag in an orderly manner beginning with the connector links, followed by the suspension lines, and finally by the canopy.

Main-Parachute Harness Assembly

Two harness legs and a confluence fitting constituted the main-parachute harness assembly. The harness assembly served as a bridge between the three main-parachute risers and the harness-attachment fittings of the vehicle. The main-parachute harness assembly is illustrated in figure A-8.

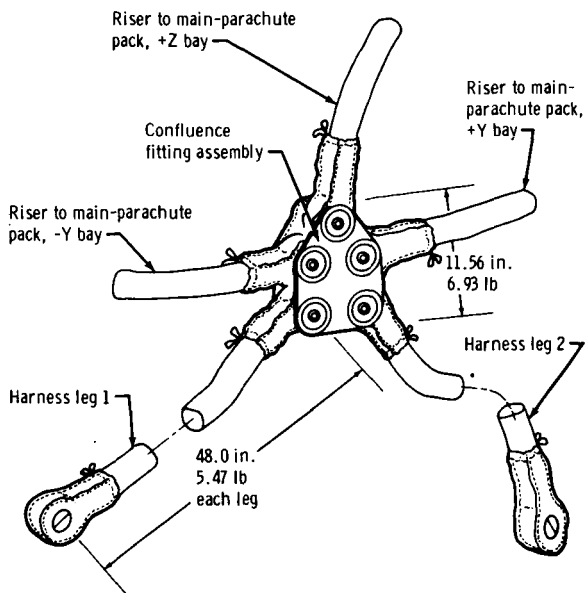


Figure A-8. - Block I main-parachute harness assembly.

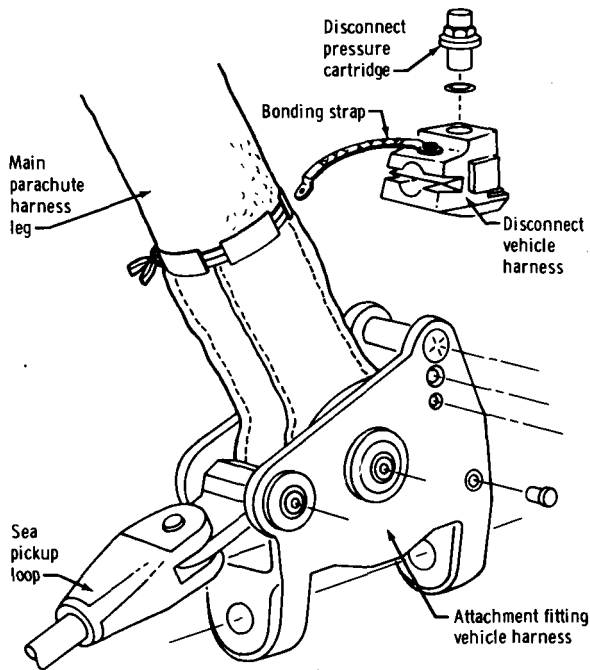


Figure A-9. - Block I main-parachute attachment and disconnect fitting.

Main-Parachute Attachment Fitting

The two main-parachute attachment fittings were located on the upper deck of the CM at the base of longerons 3 and 4. Each of the two fittings was capable of withstanding the total opening loads generated by the three main parachutes. A main-parachute-harness disconnect was incorporated into each of these attachment fittings. This unit included a pyrotechnic pressure cartridge which, when initiated, drove a sharp blade into the harness retaining pin, severing that leg of the harness and releasing it from the vehicle. The main-parachute attachment fitting and harness disconnect are illustrated in figure A-9. As a safety feature, the two disconnects received their current from two separate electrical sources; thus, an inadvertent premature signal would disconnect only one leg of the harness, and the main parachutes would remain attached to the CM through the other leg.

Reefing Cutters

The 8-second reefing-line cutters used in the Block I drogue and main parachutes were identical and interchangeable. The reefing cutters were used to sever the reefing line, which limited the inflated diameter of the parachute for a predetermined time, thus reducing the parachute opening loads.

The reefing cutters (fig. A-10) were contained in cutter pockets sewed to the skirt of the parachute. A lanyard was then attached from the reefing-cutter shear pin to a suspension line on the parachute. Tension in the suspension line caused the lanyard to extract the cutter shear pin, cocking and releasing the cutter firing pin. The firing pin then struck and detonated a primer that ignited an 8-second pyrotechnic time-delay element in the cutter. At the

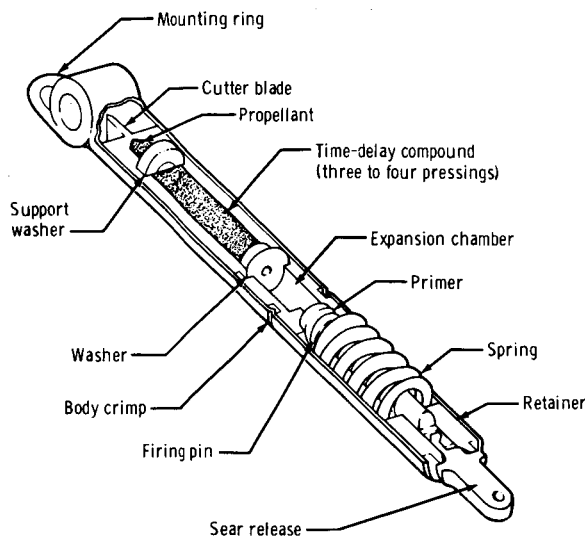


Figure A-10. - Reefing-line cutter.

ated to replace the drogue-parachute attachment fitting and the two main-parachute deck-mounted attachment fittings. The ELS components affected by these changes included: (1) the main-parachute deployment bag and retention system, (2) the main-parachute riser assembly, (3) the drogue-parachute cable-riser assembly, and (4) the pilot-parachute mortar tube and breech assembly.

The general arrangement of the Block II ELS installed on the upper deck is depicted in figure A-11. The Block II installation used the available volume in the forward compartment more efficiently than did the Block I system. The incorporation of the flowerpot parachute attachment fitting eliminated the large, bulky, two-leg, main-parachute harness assembly and the confluence fitting and provided for much better stowage of both the main- and drogue-parachute risers.

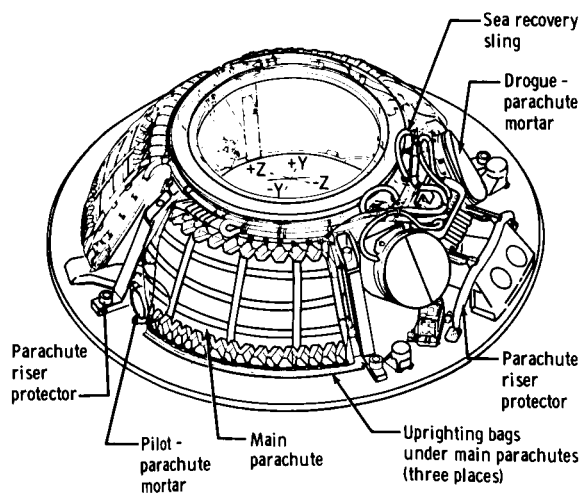


Figure A-11. - Block II ELS general arrangement.

end of the time-delay burn, a pyrotechnic charge ignited and caused a cutter blade to sever the reefing line. This same type of reefing-line cutter was also used to release the VHF recovery antennas and the flashing light, allowing them to deploy 8 seconds after the main parachutes were deployed.

BLOCK II ELS

Changes made to the spacecraft upper deck between Blocks I and II necessitated modification of certain components of the ELS. The docking tunnel was shortened and the tunnel wall was tapered, significantly altering the shape of the main-parachute stowage compartment. A single flowerpot parachute attachment fitting was incorporated

Main-Parachute Deployment Bag and Retention System

The main-parachute deployment bag was generally reconfigured to fit the shape of the Block II stowage compartment. The net result was a Block II bag that was shorter and wider than the Block I configuration. This change in shape resulted in the incorporation of a side-opening bag instead of the Block I bottom-opening deployment bag.

The Block I main-parachute retention flaps were replaced by a series of fabric-covered, spring steel straps attached to the upper-deck structure. These straps were then chain-laced by an interlocking length of cord to loops sewed to the face of the main-parachute deployment bag (fig. A-12). Because the Block I retention flaps also provided environmental/thermal protection for the main parachutes, eliminating these flaps necessitated the incorporation of these protective features into the Block II deployment bag. This task was accomplished by adding a layer of 1/4-inch Dacron felt to the walls of the deployment bag.

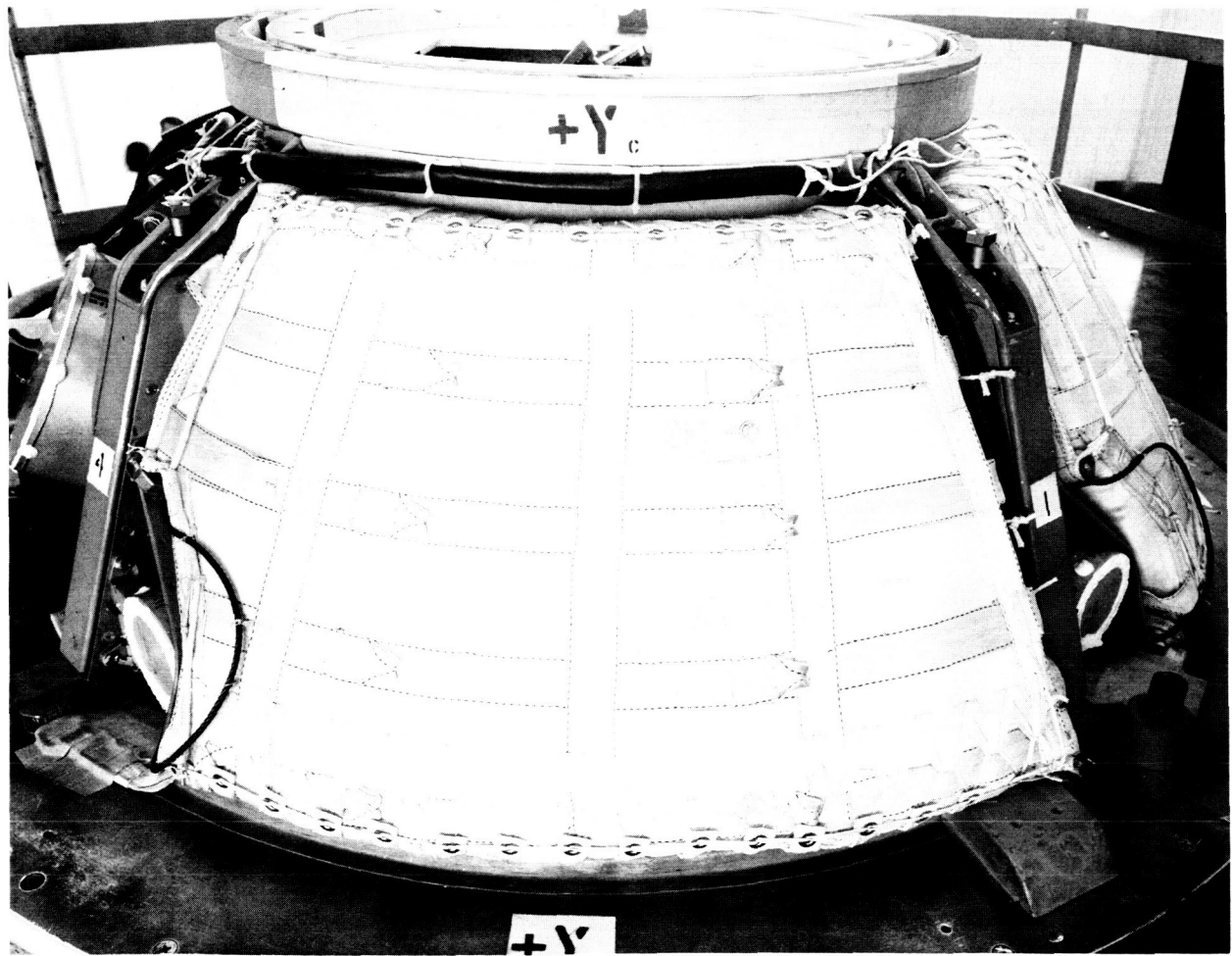


Figure A-12. - Block II main-parachute deployment bag and retention system.

The Block II main-parachute deployment bag was a significant improvement over the Block I configuration. Because the new end-opening bag provided a constant cross section area as viewed through the open end, it was superior for packing the parachute at a high density with minimal packing damage. The elimination of retention flaps reduced the amount of retention lacing and provided a much more efficient installation in terms of material required to retain the main-parachute packs on the spacecraft.

Block II Parachute Riser Assemblies

The Block II main parachutes incorporated riser assemblies composed of steel cable and fabric that attached each of the three parachutes directly to the CM. The steel-cable portion was 80 inches long and was composed of six 0.28-inch-diameter cables, assembled with swaged-steel end fittings. These end fittings were designed to attach one end of the cable riser to the flowerpot fitting on the CM and to attach the other end to the main-parachute fabric riser. The entire cable riser, except the end fittings, was encased in a thermally fitted, polyolefin sleeve to maintain the six individual wire cables in their relative positions during stowage and deployment. The fabric portion of the main-parachute riser assembly remained generally the same as in the Block I configuration, except for a slight reduction in length.

The drogue-parachute steel riser consisted of three 0.28-inch-diameter cables with swaged-steel end fittings. With two exceptions, the basic cable configuration remained the same for Blocks I and II. The lower end fitting was redesigned on the Block II version for compatibility with the CM flowerpot attachment fitting, and the basic cable strength was slightly upgraded through selection control to satisfy the Block II abrasion criteria.

Pilot-Parachute Mortar Assembly

The Block II pilot-parachute assembly, thermally insulated deployment bag, fabric riser, and steel riser were identical to the Block I version. The changes incorporated into the Block II pilot-parachute mortar assembly included the following.

1. The opposing-cartridge breech configuration was replaced by a side-by-side cartridge arrangement and an eroding-type orifice to obtain the required muzzle velocity within the allowable reaction-load limits.
2. As opposed to the deck-rail installation used on Block I, the mortar-mounting provisions were changed to install the pilot mortars on the forward-compartment long-rons. This change allowed for more efficient use of the available volume and provided added volume for the main-parachute pack assemblies.

INCREASED CAPABILITY BLOCK II ELS

Because of the increase in CM weight, which occurred after completion of qualification of the original Block II ELS, modification of the parachute system was necessary to increase its capability to recover the heavier CM. The major changes were associated with a redesign of the main-parachute reefing system to achieve a second reefing stage and with an increase in the size of the drogue parachutes. A modification was also made to the pilot-parachute assembly to assure adequate strength in the riser.

Although the incorporation of the Block II forward-heat-shield-separation-augmentation system was not directly associated with the CM weight increase, it was also developed and qualified during the Increased Capability Block II program.

Two-Stage Main-Parachute Reefing

The significant difference between the original Block II main parachute and the Increased Capability Block II main parachute was the incorporation of two-stage reefing. The two-stage reefing system, illustrated in figure A-13, reduced the peak opening loads generated by each of the main parachutes. The incorporation of the additional reefing stage reduced the initial drag area present at high-dynamic pressures and then allowed the parachute to inflate to a larger intermediate drag area before inflating to a full-open condition. The first- and second-stage disreefings were timed to occur as the dynamic pressure decreased to near-minimum levels. These times were established at 6 and 10 seconds after initial parachute deployment, or 6 and 10 seconds after line stretch.

The two-stage reefing system incorporated dual reefing rings mounted on the skirt of the parachute canopy. The reefing-cutter mounting provisions and midgore reefing concept remained essentially unchanged from the Blocks I and II configurations. Redundant reefing lines were used for the first stage because analysis showed that bypassing this stage of inflation could generate loads that would destroy the parachute. This redundancy was not needed for the second stage; therefore, only a single reefing line was incorporated.

A typical reefing-line installation at a first-stage cutter position is illustrated in figure A-14. The first-stage reefing lines are threaded through the lower holes of the reefing rings. One of these lines passes through the 6-second cutter in the conventional manner; the other line bypasses this cutter and passes through identical 6-second cutters located on other gores. The second-stage reefing line is routed through the upper holes of the reefing rings, bypassing the 6-second cutters and passing through 10-second cutters mounted in the same manner on other gores.

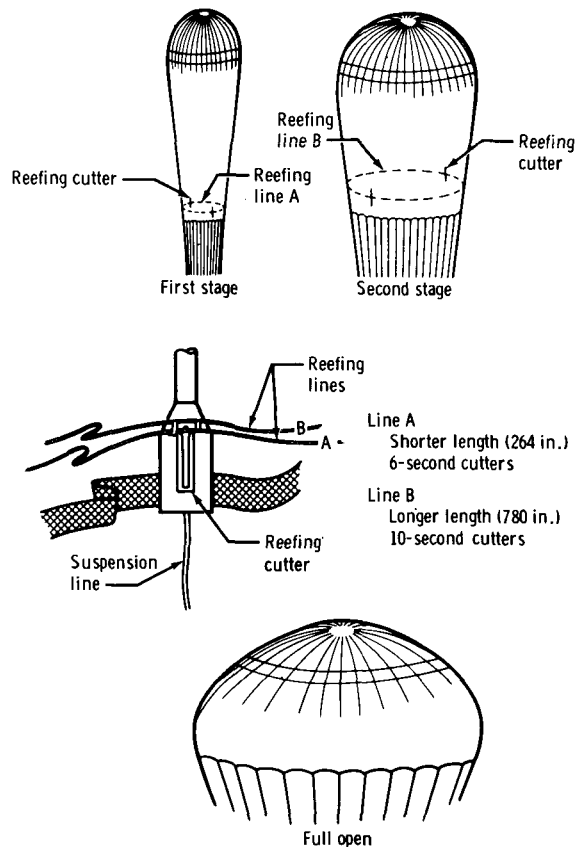


Figure A-13. - Main-parachute two-stage reefing.

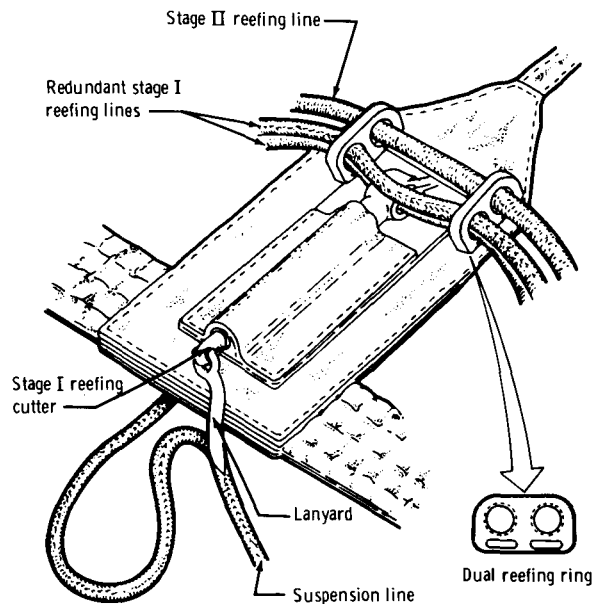
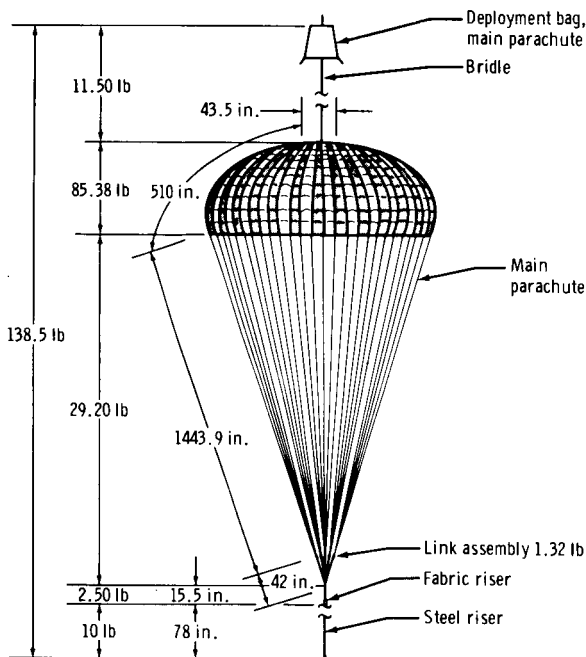


Figure A-14. - Reefing-line installation for two-stage reefing.

Although single-stage reefing of parachutes has become a rather common practice for reducing opening loads, the use of two-stage reefing was virtually untried before its incorporation in the Block II system. This system proved to be effective and reliable in reducing the parachute opening load below what otherwise would have been encountered because of the increased weight of the CM. The final Block II main-parachute configuration is illustrated in figure A-15.



Nominal diameter:	83.5 ft
No. of gores:	68
Calculated total porosity:	12 percent
Reefing	
First stage:	7.0 ft D_{R1} (8.4 percent midgore)
Second stage:	20.7 ft D_{R2} (24.8 percent midgore)
Drag area (average)	
First stage:	285 ft ²
Second stage:	1080 ft ²
Full open:	4200 ft ²

Figure A-15. - Final Block II main parachute.

geometric differences in the canopy from the original Block II design were minimal. A comparative summary of the original Block II and the Increased Capability Block II drogue-parachute design is presented in table A-I.

Several significant departures from Block II construction methods were used to reduce weight, to minimize volume requirements, and to improve certain design features of the parachute. A substantial saving of weight and volume was accomplished by using continuous horizontal-ribbon construction in much of the canopy. The use of

Reefing-Cutter Modifications

The time intervals of 6 seconds for the first stage and 4 additional seconds for the second stage were selected for the reefing of the main parachute. Because the reliability of the mechanical functions of the 8-second reefing cutters was amply demonstrated on the Blocks I and II systems, only the burning rates of the pyrotechnic delay elements were modified.

Because two different time-delay reefing cutters were used in each of the main parachutes and because both had an identical physical appearance, the possibility of inadvertent interchange of the cutters existed. To minimize this possibility, a black oxide was applied to the body of the 6-second first-stage reefing cutters, which, in turn, were installed in olive-drab cutter pockets of the parachute. The 10-second reefing cutters retained the untreated finish and were used in natural-colored cotton-duck cutter pockets on the parachutes.

Drogue-Parachute Modifications

The drogue-parachute design for the Increased Capability ELS is a 16.5-foot-diameter, 25° conical-ribbon parachute illustrated in figure A-16. Except for the increase in size and subsequent drag area,

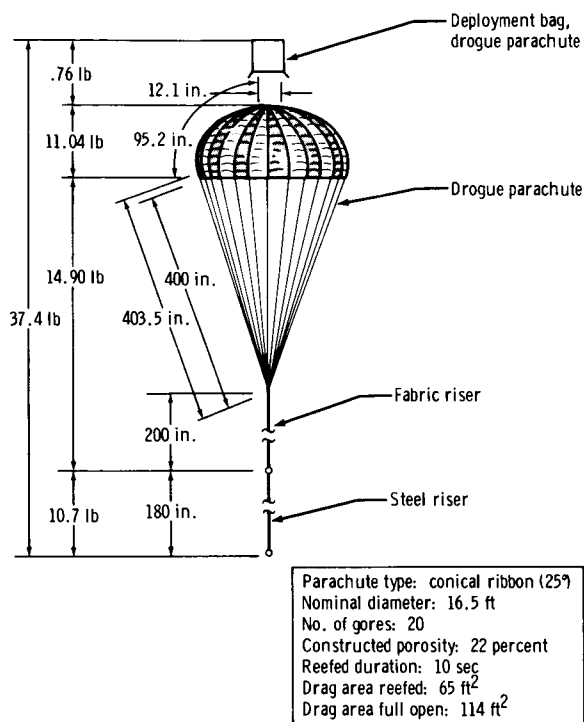


Figure A-16. - Final Block II drogue parachute.

continuous ribbons with a single-lap splice eliminated the added material previously required to make multiple-gore splices.

A second significant departure from the original Block II configuration was the incorporation of an integrated suspension-line/riser design, with an extension of the suspension lines forming the riser. The elimination of the suspension-line-to-riser connection and the use of multiple strands of braided cord instead of the webbing riser used in the Block II construction allowed a weight saving of approximately 1.5 pounds.

The 16.5-foot-diameter drogue parachutes were reefed at 42.8 percent of their nominal diameter for 10 seconds. The 10-second reefing cutter used in the drogue parachutes was identical to the reefing cutter used in the main-parachute second-stage reefing system.

TABLE A-I. - COMPARATIVE CHARACTERISTICS OF ORIGINAL AND FINAL BLOCK II DROGUE PARACHUTES

Drogue-parachute characteristics	Block II	Increased Capability Block II
Nominal diameter, ft	13.7	16.5
Gores, number	16	20
Drag area, sq ft	68	114
Total porosity, percent	23	22.4
Gore construction	Spliced horizontals	Continuous horizontals
Riser material	Dacron webbing	Continuation of suspension lines
Suspension-line material	Nylon cord	Nylon cord
Rated strength, lb	1500	2500
Maximum design-limit load, lb	12 600	17 200
Parachute-assembly weight, lb	25.4	37.4

Because of an increase in the drogue-parachute design loads from 12 600 to 17 200 pounds, the steel-cable portion of the drogue riser had to be strengthened. This strengthening was accomplished by replacing the three strands of 0.28-inch cable by four strands of 0.25-inch cable, and by incorporating the necessary changes to the riser and fittings (fig. A-17). To reduce the abrasive action between the steel-cable riser and the spacecraft flowerpot fitting, a lead-tape wrapping was added to drogue cable risers where they contact the flowerpot fitting.

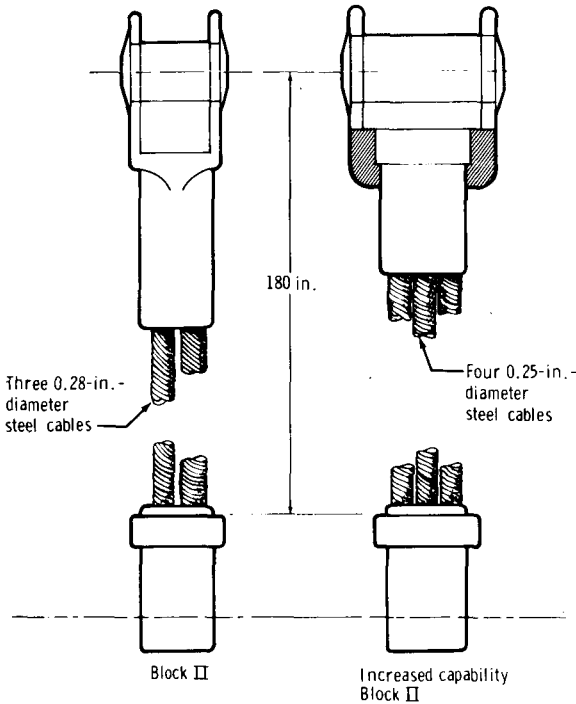


Figure A-17. - Drogue-parachute riser assembly.

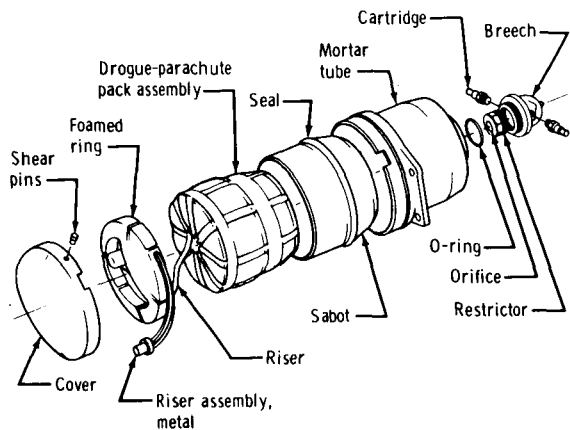


Figure A-18. - Increased Capability Block II drogue-parachute mortar assembly.

Drogue Mortar-Assembly Modifications

The drogue mortar function for the Increased Capability Block II system was identical to that of the Blocks I and II configurations. The major difference was that the new mortar assembly was designed to deploy a larger and a heavier drogue parachute (fig. A-18).

To acquire additional volume for the larger parachute, the drogue mortar was increased in diameter from 11.4 to 12.6 inches, and the face of the mortar was contoured to the inner radius of the forward heat shield. The increase in ejected weight presented a problem in attaining the necessary muzzle velocity with the new mortar without exceeding the maximum allowable reaction load. This task was accomplished by using an optimized erodible orifice to regulate the flow of gas from the breech assembly into the mortar tube.

The design, performance, and structural integrity of the new drogue mortar were demonstrated satisfactorily and were qualified on the basis of successful performance during the system-qualification aerial drop tests and in laboratory mission-environmental qualification tests. The mortar configuration remained unchanged throughout qualification testing.

Pilot-Parachute System

The pilot-parachute mortar remained unchanged from the earlier Block II design. The significant changes to the assembly

were modifications to strengthen the pilot parachute. The parachute (fig. A-19) was modified to increase the strength specification of the suspension lines from 400 to 600 pounds, and was changed from a multiple-ply-webbing riser to the integrated suspension-line and riser configuration similar to that used on the drogue parachute. The multiple-ply-webbing riser design was unsatisfactory because of susceptibility to improper manufacturing. In securing the plies of webbing, uneven gathering of a single ply of webbing often occurred. This condition was difficult to detect by visual inspection and resulted in uneven load distribution between the plies of webbing. Because of this condition, the riser assembly failed to satisfy the strength requirements. The design changes incorporated into the pilot-parachute suspension lines and riser resolved this deficiency.

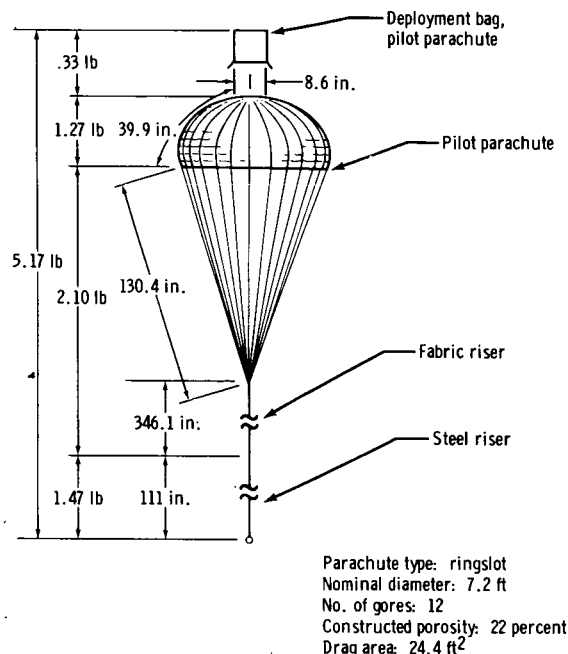


Figure A-19. - Final Block II pilot parachute.

Block II Forward-Heat-Shield-Separation-Augmentation System

The incorporation of a forward-heat-shield-separation-augmentation parachute system in the Block II heat shield was somewhat more complex than the same modification to the Block I system. The conical shape of the Block I forward heat shield allowed for installation of the parachute mortar assembly directly under the apex of the cover. With the Block II docking provisions, the forward heat shield assumed the shape of a frustum that required the separation-augmentation mortar assembly to be installed on the inner wall of the heat shield. This installation was further complicated by the requirement to delay the mortar firing until the forward heat shield had sufficiently separated from the CM to allow the parachute pack assembly to be ejected through the docking tunnel opening in the heat shield without impacting the top of the docking tunnel (fig. A-20). This requirement was met by incorporating a time-delay firing circuit, activated by lanyards attached to the forward heat shield. The firing current was transmitted from the CM to the forward-heat-shield mortar pyrotechnic initiators through an umbilical which was deployed from the heat shield as it separated from the CM. Because the mortar was mounted on the inner wall of the heat shield, the installation of a ramp above the mortar was necessary to deflect the parachute pack so that it would pass through the docking tunnel opening in the heat shield.

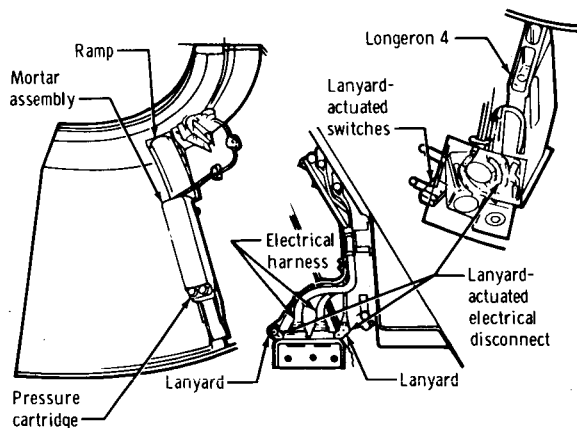


Figure A-20. - Block II forward-heat-shield mortar installation.

The parachute used was a conventional Apollo 7.2-foot-diameter ringslot parachute identical to that used to extract the main parachutes. To reduce the loads, the parachute incorporated fixed or permanent reefing to reduce its effective drag area. Because of volume limitation in the CM forward compartment, the conventional cylindrically-shaped pilot mortar could not be used. By relocating certain equipment in the forward compartment, it was possible to install the elliptically shaped forward-heat-shield mortar assembly illustrated in figure A-21. The Block II forward-heat-shield-separation-augmentation system was successfully demonstrated during the Increased Capability Block II test program.

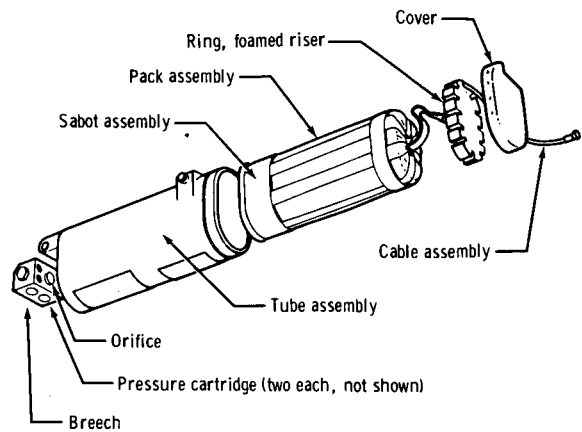


Figure A-21. - Block II forward-heat-shield mortar assembly.

APPENDIX B

SUMMARY OF TESTS

Each component of the Block I, Block II, and Increased Capability Block II ELS was subjected to extensive testing during the developmental and qualification phases of the programs. Considerably more developmental testing was associated with the Block I effort because this program established the basic designs from which the Block II and the Increased Capability Block II system evolved. However, the same general approach and testing techniques were applied during each of the three programs.

As the programs progressed, when defining the test requirements associated with the modifications made to the system, much consideration was given to test data generated during the preceding ELS programs. During each of the programs, before qualification testing, each component had to demonstrate a sufficiently high degree of performance and reliability during developmental or prequalification testing.

In defining the tests for the ELS, two basic requirements had to be satisfied. One requirement was to demonstrate that each component and subassembly of the total system was capable of withstanding the total-mission environment and functioning properly with adequate margins and within specified tolerances. The second requirement was to demonstrate that the total system would function properly in all potential flight modes and that a safe interface existed between the various components of the CM and the parachute recovery system.

The nature of the ELS made it impractical to combine these two requirements into a single test program where the parts could be subjected to mission environments in a laboratory and then to operating conditions in an aerial drop test. Considering also such factors as the amount of time and handling required between the laboratory and the test, this approach would not have been valid, nor would the results have been representative of conditions encountered in an actual mission. Therefore, two separate and somewhat independent test programs had to be conducted, that is, the aerial drop tests and the laboratory tests.

LABORATORY TEST PROGRAM

The laboratory testing conducted during the program was generally confined to individual component and lower assembly-level tests. Each component was evaluated in terms of potential loss of strength or performance (or both) resulting from exposure to the environments of the Apollo mission and the interface between that component and the spacecraft. In the laboratory, much effort was expended in testing various components to support the selection of the most promising designs, to support the failure analyses, and to obtain performance data on new designs. After each component had demonstrated the required level of performance, it was subjected to qualification testing. Each qualification test article was manufactured, inspected, and accepted as if it were spacecraft hardware. During the qualification tests, if any item failed to meet the

prescribed levels of performance, the failure was formally reported, and a thorough analysis was performed to determine the exact cause and the necessary corrective action.

The laboratory qualification tests performed on the various components of the Block I ELS are summarized in table B-I. Laboratory testing on the original Block II system was centered mainly around the changes made between Blocks I and II. This testing included the redesigned main-parachute deployment bag, the main-parachute steel-cable riser, and the redesigned pilot-parachute mortar.

TABLE B-I. - SUMMARY OF BLOCK I LABORATORY TESTING

Component	Test conditions
Textile materials	Temperature and vacuum
Suspension-line connector links	Structural
Pilot steel-cable riser	Structural and abrasion
Drogue steel-cable riser	Structural and abrasion
Main-parachute harness	Structural and abrasion
Vehicle harness-attachment fitting	Structural
Main-parachute riser	Structural and abrasion
Main-parachute retention assembly	Humidity, acceleration, vibration, thermal vacuum, high temperature
Reefing-line cutters	Humidity, acceleration, thermal vacuum, drop, high temperature, low temperature, physical strength
Pilot-mortar assembly	Humidity, vibration, thermal vacuum, high temperature, low temperature
Drogue-mortar assembly	Humidity, vibration, thermal vacuum, high temperature, low temperature
Main-parachute disconnect assembly	Humidity, vibration, thermal vacuum, high temperature, low temperature, immersion

During the original Block II program, emphasis was placed on ground testing to thoroughly evaluate the changes made from the Block I design. These ground tests were used extensively to obtain comparative performance data on several main-parachute-deployment-bag configurations being considered. The ground-test approach considerably reduced the number of required aerial drop tests and reduced the program cost.

Following the decision to modify the Block II ELS to increase its capability to recover the heavier CM, the establishment of ground-test requirements was necessary. Because each component of the ELS had been qualified previously for use on manned spacecraft, the extent to which retest was necessary was governed strictly by the nature and the extent of individual component redesign. For example, modifications were made to the reefing cutters to vary the delay time from 8 to 6 and 10 seconds. This change affected only the pyrotechnic time-delay element in the cutter, not the structure or actuating mechanism. Therefore, the redesign reefing cutters were subjected only to the mission-environmental test conditions that could influence the performance of the time-delay element, that is, acceleration, high and low temperature, and high humidity.

Those components requiring major redesign, such as the drogue-parachute mortar assembly, were subjected to extensive laboratory tests. In such cases, the verification of the structural adequacy, performance characteristics, and overall reliability of the redesigned components over a wide range of mission conditions was necessary. Much of this laboratory work had to be accomplished before integration of the particular components into the aerial drop tests.

AERIAL DROP TESTS

The aerial drop tests were conducted at the Air Force/Navy Joint Parachute Test Facility, El Centro, California. This facility was ideally equipped for Apollo-type drop testing because it provided a fully instrumental test range, an onsite shop, and administrative office space. Sources for data acquisition included ground-to-air and air-to-air photographic coverage, ground cine-theodolite tracking stations, and a telemetry ground station. In addition, the El Centro test facility provided many of the drop aircraft and the test-vehicle ground-handling equipment. All BP vehicle drop tests were made from a modified C-133A aircraft provided by NASA and manned by contractor personnel.

Three basic types of vehicles used in the aerial drop tests included an instrumented cylindrical test vehicle (ICTV), a parachute test vehicle (PTV), and the boiler-plate (BP) test vehicles. Often referred to as a bomb-drop vehicle, the ICTV was simple in concept, rugged in construction, and low in cost (fig. B-1). The ICTV was used on tests where the CM interface was not a consideration and where it provided simplicity; minimizing test-preparation time. These vehicles were usually equipped for telemetry and onboard photographic data acquisition.

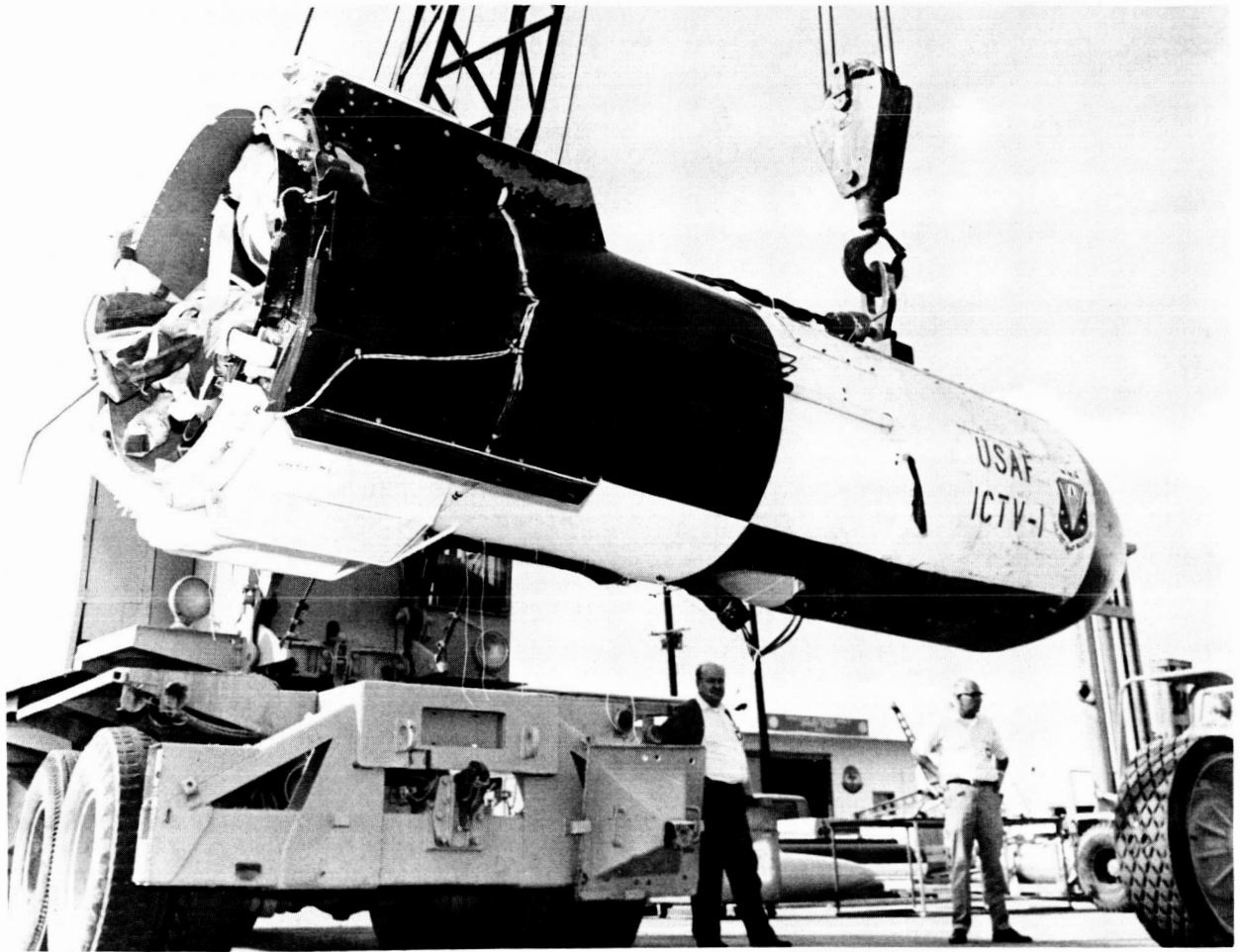


Figure B-1. - Instrumented cylindrical test vehicle.

Well suited for testing at the total-system level, the PTV was designed to simulate the major features of the spacecraft upper deck (fig. B-2). Below the deck level, the PTV was a simple cone shape of sturdy construction to eliminate impact damage. Because the total drag area of the PTV was much less than that of a CM, this vehicle was well suited for conducting system-level tests at dynamic pressure conditions above the limits for spacecraft.

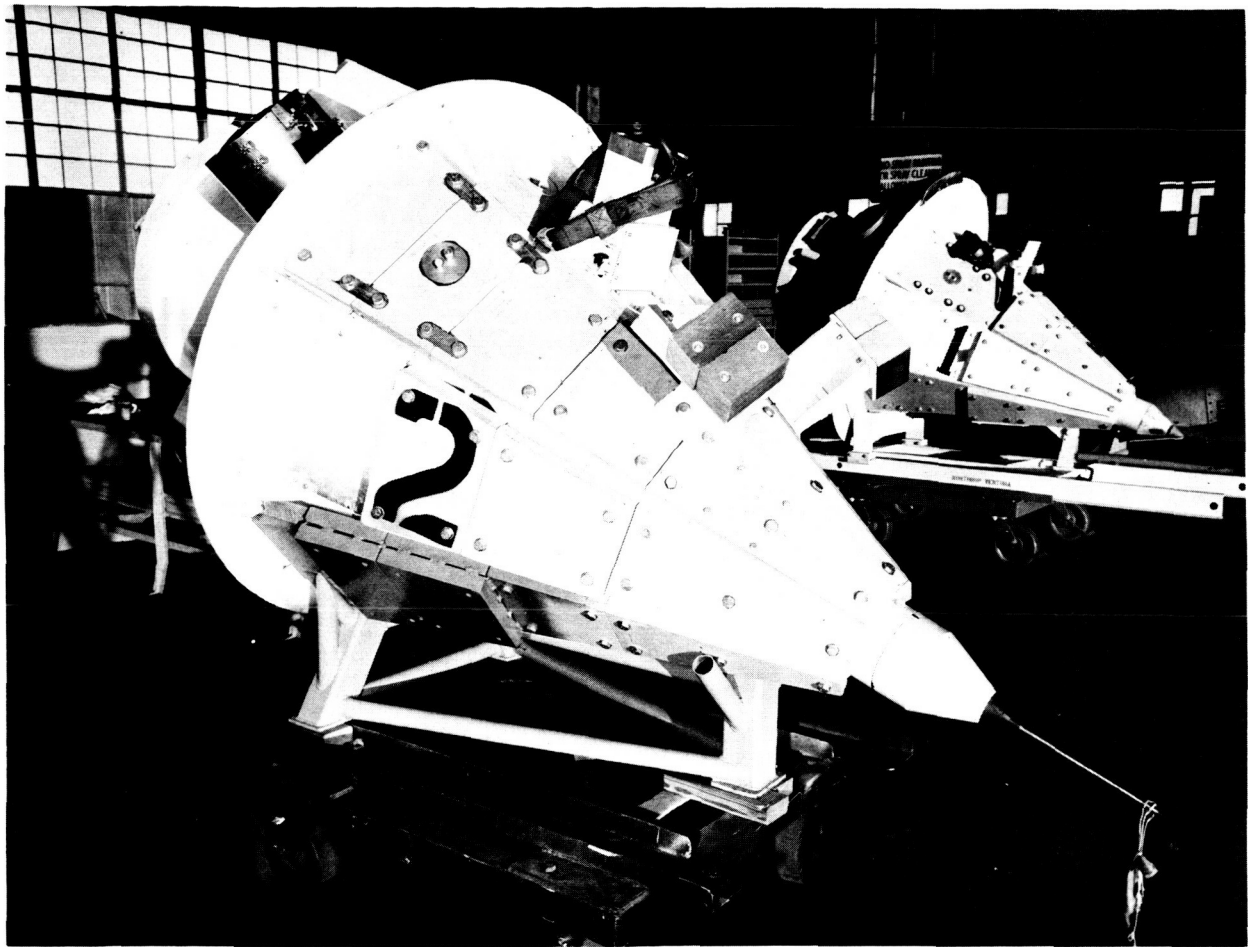


Figure B-2. - Parachute test vehicle.

The BP test vehicle was the most elaborate spacecraft-representative test vehicle used in the parachute drop tests (fig. B-3). The test accurately simulated the CM weight, the center of gravity, and the geometric profile. In addition to testing the total parachute recovery system, the test could incorporate the forward-heat-shield jettison. All the various components interfacing with the ELS (location aids, vehicle-uprighting bags, and other spacecraft components) that could affect, or be affected by, the parachutes were installed on the BP. The BP was the first vehicle in which the spacecraft-configuration ELS sequence controller performed the system-sequencing functions. Instrumentation in the BP was similar to that used on the PTV, consisting primarily of telemetry and onboard cameras.

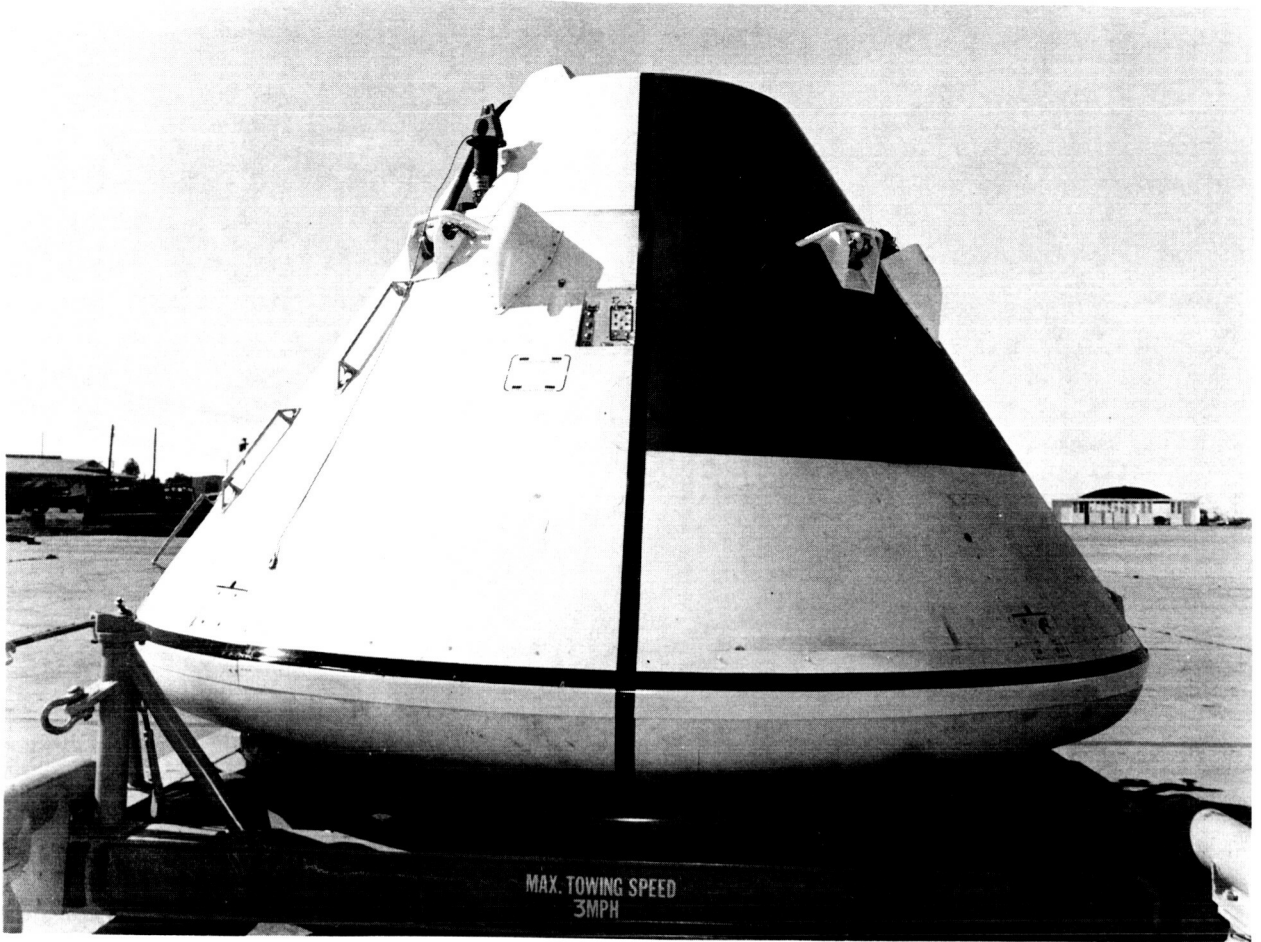


Figure B-3. - Boilerplate test vehicle.

BLOCK I DEVELOPMENTAL DROP TESTS

During the Blocks I and II programs, the aerial drop tests were classified as being either developmental tests or qualification tests. Developmental tests were further grouped into individual test series according to specific test objectives.

The aerial drop tests made during the Block I developmental program are illustrated in figure B-4. During the first year of the Block I developmental effort, many single-main-parachute ICTV drop tests were made to evaluate various main-parachute design concepts. In 1963, much of the developmental testing consisted of multiple

Series	Series objectives	1962					1963					1964					1965								
		J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
1	Preliminary developmental tests, one main parachute						▼																		
3	Developmental tests, one main parachute						▼▼▼▼																		
6	Developmental tests, one main parachute	▼▼▼▼▼▼▼▼						▼		▼▼▼▼															
7	Developmental tests, three main cluster						▼			▼▼															
13	Developmental tests, three main cluster									▼▼															
17	Drogué tests, one and two parachutes							▼	▼																
18	Drogué tests, one parachute									▼	▼▼														
24	Drogué tests, one and two parachutes										▼														
26	Modified main parachute in clusters							▼▼▼▼▼▼▼▼	▼		▼▼														
28	System test																								
29	Main-parachute design-verification tests																								
40	Main-parachute improvement tests																								
41	Main-parachute improvement tests																								
44	Main-parachute improvement tests																								
46	Main-parachute strength verification																								
48	Drogué-parachute design verification																								
50	BP total-system developmental tests																								

Figure B-4. - Block I developmental drop-test summary.

parachute (cluster) tests and the higher-level system tests. During these tests, the main-parachute-cluster interference problems became a concern. Several two-main-parachute ICTV drop tests were conducted during the first 6 months of 1964 to evaluate the main-parachute modifications incorporated to improve cluster inflation. Following a limited series of total-system verification tests, the Block I developmental drop test was concluded early in 1965 with drop tests to demonstrate the ultimate strength capability of the drogue- and main-parachute designs.

As the time approached for the qualification aerial drop tests to begin to support the spacecraft flights, certain qualifiable configuration components apparently were not going to be available for the initial tests. Problems encountered during the latter part of the developmental program required that some late changes be made to certain components; time was insufficient to incorporate all these changes in the initial system-qualification drop tests. Although a basic rule for qualification testing states that items subject to qualification be of the spacecraft configuration, compelling schedules necessitated initiation of total-system testing with certain items that were not yet in a qualifiable configuration. These items included the drogue and pilot mortar cartridges, the main-parachute disconnect and cartridge, and the reefing-line cutters. The use of these interim components was permitted on the basis of similarity to final design and on the fact that the flight items were to be subjected to laboratory qualification tests. The plan was to phase the final-design components into the qualification drop-test program at the earliest date.

BLOCK I SYSTEM-QUALIFICATION DROP TEST

From May 6, 1965, to February 24, 1966, 12 aerial drop tests were made to complete qualification of the Block I ELS and to rate the system suitable for manned flights. A summary of this program is presented in table B-II.

TABLE B-II. - SUMMARY OF BLOCK I QUALIFICATION DROP TESTS

Test number	Date	Simulation	Recovery weight, lb	Forward-heat-shield jettison	Parachute disconnect			Drogue mortar fire			Pilot mortar fire		
					Altitude, ft $\times 10^3$	q^a , lb/ft ²	Time, sec	Altitude, ft $\times 10^3$	q^a , lb/ft ²	Time, sec	Altitude, ft $\times 10^3$	q^a , lb/ft ²	Time, sec
60-1	5-6-65	Normal entry	11 000	No	28.4	33.7	14.9	24.9	88.1	24.9	10.9	49.1	74.3
62-1	6-3-65	High-altitude abort	11 000	No	27.5	32.5	15.1	19.9	147.0	35.2	10.9	46.4	64.9
^b 62-3	8-5-65	Pad abort	11 000	Yes	--	--	--	--	--	--	--	--	--
62-2	8-19-65	Medium-altitude abort	11 000	No	29.5	24.7	15.0	26.4	79.0	24.0	11.4	47.6	75.2
62-3A	9-23-65	Pad abort	11 000	Yes	11.0	28.0	29.6	10.4	48.5	31.7	7.1	56.6	43.9
^c 62-4	10-8-65	Normal entry	11 000	Yes	28.4	32.0	20.0	19.9	160.8	39.0	11.2	69.4	64.5
62-4A	11-29-65	Normal entry	11 300	Yes	27.3	25.0	20.0	23.4	91.9	32.1	10.7	49.6	76.1
62-7	12-2-65	High-altitude abort	11 000	No	29.0	32.5	15.1	18.2	175.8	40.0	11.3	46.9	60.7
62-8	1-28-66	Medium-altitude abort	11 000	No	23.8	36.5	25.1	22.9	56.2	27.2	18.9	67.1	39.1
62-5	2-3-66	Pad abort	11 000	No	13.0	28.5	34.7	9.4	48.0	36.8	6.2	56.6	49.0
62-6	2-17-66	Normal entry	11 000	No	27.1	24.0	20.0	22.9	116.9	32.1	10.7	49.5	73.7
62-9	2-24-66	High-altitude abort (one drogue)	11 000	No	27.9 ^a	31.0	15.0	19.7	149.7	34.9	10.1	77.0	60.9

^aDynamic pressure.

^bTest 62-3 programer parachute failed to disconnect.

^cTest 62-4 failed to meet required test conditions.

The drop-test conditions were established to demonstrate the system under as many operational flight conditions as possible. The following test conditions were selected for the qualification drop tests.

1. Normal-entry simulations - three tests
2. High-altitude-abort simulation - two tests
3. Medium-altitude-abort simulations - two tests
4. Pad-abort simulations - two tests
5. High-altitude-abort simulation with one drogue parachute - one test

Although 10 tests were planned in this series, 12 tests were actually conducted because of failure on two occasions to achieve the desired test conditions.

In these tests, the service ceiling of the C-133 drop-test aircraft (30 000-foot maximum altitude) and other limitations would not allow complete duplication of the operational flight modes. For example, in an operational normal entry or high-altitude abort, the drogue parachutes would normally be deployed by closure of the high-altitude baroswitches at approximately 24 000 feet. In a drop-test simulation of these operational modes, the BP test vehicle was released at 30 000 feet. To allow for a minimum auxiliary-brake parachute-stabilization interval and some finite free-fall interval to achieve the required dynamic pressure condition, drogue-parachute deployment (initiated by an auxiliary events controller) had to be delayed to altitudes moderately below the normal 24 000-foot level. As a result, two compromises were made in the total performance of the ELS, that is, recovery was not initiated by the sequence-controller barometric switches, and the normal drogue-parachute operating interval was reduced from a normal 50 to 55 seconds to approximately 25 seconds. The first compromise was reconciled by monitoring the sequence controllers for proper closure of the barometric switches, thus acquiring evidence of satisfactory performance. Analysis showed that the lack of the full drogue interval would not have a significant effect on the test conditions at the time of main-parachute deployment because there would be no substantial improvement in vehicle dynamic stability after the 25-second test interval. Secondly, the shorter drogue interval represented a more demanding condition pertaining to total-system operation than that which would be experienced in a comparable spacecraft operation.

Although desired dynamic pressure and vehicle attitude could be programed into the tests, a representative flight-path angle could not be achieved. Also, the marginal stability of the BP vehicles made the acquisition of desired initial attitudes and CM dynamics at the end of long free-fall intervals very difficult. At the end of the free-fall interval, these test limitations generally resulted in vehicle dynamics more severe than those predicted for an actual mission. Because the test conditions were more severe than those the spacecraft would experience, the tests were judged as a satisfactory demonstration of the systems capabilities.

With the exception of a minor modification in the main-parachute retention system incorporated in the last four tests, the remaining six qualification drop tests were conducted with the final Block I ELS configuration.

BLOCK II DEVELOPMENTAL DROP TESTS

The major changes from the Block I to the Block II ELS concerned the redesigned main-parachute deployment bag and retention system, the steel-cable main-parachute riser, the flowerpot parachute-attachment fitting, and the modified pilot-parachute mortar. The Block II developmental drop-test program was oriented to demonstrate that these modifications did not degrade the strength or the performance of the system in any way.

The developmental drop-test program was originally planned as a series of three, single, main-parachute PTV tests. However, during the second test of the series, a strength deficiency was found in the main-parachute canopy, and three interim tests were conducted to demonstrate the adequacy of the fix to the main parachute before conducting the final test of the developmental test series.

BLOCK II QUALIFICATION DROP TESTS

From October 19, 1966, to January 17, 1967, a series of four total-system aerial drop tests was conducted using the BP-6 vehicle, modified to the Block II configuration. This series of tests (table B-III) completed qualification on what was then believed to be the final ELS. Before entering this test series, a basic ground rule was established stating that only qualified or qualifiable parachute system components and installation specifications would be used in the test series. This policy was maintained throughout the test series; in contrast to the Block I test series, no configuration changes were made to the hardware during the Block II qualification drop-test program.

TABLE B-III - SUMMARY OF BLOCK II QUALIFICATION DROP TESTS

Test number	Date	Simulation	Recovery weight, lb	Forward-heat-shield jettison	Parachute disconnect			Drogue mortar fire			Pilot mortar fire		
					Altitude, ft $\times 10^3$	q^a , lb/ft ²	Time, sec	Altitude, ft $\times 10^3$	q^a , lb/ft ²	Time, sec	Altitude, ft $\times 10^3$	q^a , lb/ft ²	Time, sec
73-4	10-19-66	High-altitude abort	11 000	No	26.8	37.6	24.7	22.5	114.3	36.4	10.8	50.1	75.6
73-1	12-7-66	Pad abort with short drogue interval	11 785	Yes	8.9	46.4	73.08	8.5	58.8	74.8	7.9	68.4	76.8
73-3	12-20-66	Medium-altitude abort with extended drogue interval	11 785	Yes	19.2	46.7	49.7	18.7	53.2	51.5	4.4	49.7	107.8
73-5	1-17-67	Normal entry	11 785	Yes	25.0	70.1	29.5	24.4	76.7	31.3	10.6	51.6	80.4

^aDynamic pressure.

A second basic difference between the Blocks I and II test programs was an attempt in Block II to eliminate the off-limit and overtest conditions prevalent in the Block I series. Two of the Block I tests had to be repeated, and other tests were difficult to rationalize as fully valid because of their severity. In the Block I effort, long free-fall periods, used to obtain high dynamic pressures, often resulted in a very unstable vehicle and higher-than-desired dynamic pressures. In the Block II effort, smaller programer parachutes were used; they remained attached to the vehicle and remained operative until attaining the desired test conditions and attaining the initiation of the recovery sequence. This technique permitted control over the attitude of the vehicle and over body rates to the point where the ELS functions began. This technique resulted in near-nominal and sometimes below-nominal conditions for certain flight modes; however, the tests were far more representative of spacecraft conditions than were many of the Block I tests.

The Block II qualification drop tests were also characterized by two added operational simulations not demonstrated in Block I. The first simulation involved an early manual main-parachute deployment whereby the crew elects to override the automatic sequence. This operation results in a short drogue-parachute interval. The second simulation concerned the main-parachute inhibit mode whereby the crew elects to delay automatic main-parachute deployment and to extend the drogue interval. This technique could be used to avoid drifting back to a land landing in the event of a near-pad abort.

One aspect of the Block II qualification drop tests, which might be considered as being off-limit, concerned test-vehicle recovery weight. Although the specifications still reflected a maximum vehicle weight of 11 000 pounds at the time of the tests, the projected weight for Block II spacecraft had risen to 11 785 pounds. The three final tests were conducted with the vehicle at this increased weight.

The results obtained from the Block II qualification drop tests demonstrated the capability of the Block II ELS to land the CM safely under the conditions stipulated in the specifications.

INCREASED CAPABILITY BLOCK II DEVELOPMENTAL DROP TESTS

The aerial drop tests conducted in support of the Increased Capability Block II program began on July 10, 1967, and continued until July 17, 1968, when the final parachute drop test was completed at El Centro, California. The developmental and design-verification tests were established as five series, identified as 80, 81, 82, 83, and 84 (fig. B-5). The individual tests in each series were identified by dash numbers (80-1, 80-2, et cetera). A 99 series was later added to augment the drogue-parachute test.

Series	Series objectives	1967												1968											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
80	Reefing evaluation, single parachute						▼	▼	▼	▼	▼	▼													
81	Reefing evaluation, two-parachute cluster						▼			▼	▼												▼ ICTV		
82	Main-parachute strength verification																						▼	▼	
83	Main-parachute cluster test, missed second-stage reefing (one of three parachutes)																							▼	
84	Total-system test, two drogues, two and three main parachutes																							▼	
99	Drogue-parachute strength verification, two-parachute cluster																							▼	

Figure B-5. - Increased Capability Block II developmental drop-test summary.

The 80 and 81 series were quite similar in that both were aimed at developing the two-stage main-parachute reefing system. The 80 series was single main-parachute tests; on the other hand, the 81 series used clusters of two main parachutes. In the 80 series, seven single parachute tests were conducted with the primary objectives being to confirm the effective canopy drag areas and load estimates, to determine fill rates, to establish the time interval for the reefed stages, and to determine the second-stage reefing-line load. Four 81 series cluster tests were conducted to evaluate staged reefing with a cluster of two parachutes, representing the design condition, to establish reefed load sharing, to determine quantitatively the effect of nonsynchronous deployment and disreef, and to obtain further verification of selected reefing parameters.

Using single main parachutes and the ICTV, the 82 series were verification tests of canopy strength. This series consisted of four tests conducted to demonstrate the ultimate load-carrying capability of the main parachute in the first-stage reefed condition, the second-stage reefed condition, and the full-open condition.

The 83 and 84 series were similar because both were combined drogue and clustered main-parachute tests using the PTV. The 83 series was planned primarily as developmental type tests to establish drogue reefing parameters and to obtain additional performance data on main-parachute clusters. The planned 84 series was to have been conducted with final spacecraft-configuration hardware and was to have included drogue-parachute ultimate-strength verification tests. Because of delays in the test schedule, the unavailability of spacecraft-configuration hardware, and the close similarity between the objectives of the 83 and 84 series, only one of the 83-series tests was actually conducted to demonstrate the effect of a missed second-stage reefing in one of a cluster of three main parachutes. The test results supported an analysis showing that the total axial load generated by a single main parachute (in a three-parachute cluster) would not exceed the structural capability of the parachute if it prematurely disreefed from, or bypassed, the second-stage reefing.

The 83 and 84 series were followed by the 99 series of supplementary drogue-parachute-strength verification tests, which included one test to demonstrate drogue-parachute deployment at an altitude of 40 000 feet. This test simulated a condition wherein the astronauts would initiate an early drogue-parachute deployment to stabilize the CM.

INCREASED CAPABILITY BLOCK II QUALIFICATION TESTS

On April 4, 1968, the first of a series of seven qualification aerial drop tests was conducted on the final configuration of the ELS. This series was completed on July 3, 1968, approximately 1 year after formal approval of the ELS increased capability program and 3 months before the first flight of the system on a manned Apollo spacecraft.

During the qualification tests, each tested component was identical to the spacecraft production design with one minor exception. During the three final tests, strain-gage link assemblies were incorporated in the main-parachute riser to obtain parachute load data under simulated operational conditions of the spacecraft.

The Increased Capability Block II qualification program consisted of the following tests (table B-IV).

1. Two pad-abort simulations were conducted; one test demonstrated the bypassed drogue condition. One test included jettison of the forward heat shield.
2. The second test conditions pertained to high-altitude-abort simulations without the forward heat shield. Both tests used only one drogue parachute, and one test used only two main parachutes.
3. The third test conditions concerned three normal-entry simulations, all incorporating jettison of the forward heat shield. Two of these tests demonstrated single-drogue parachute conditions; one of these tests demonstrated the system with a 13 500-pound vehicle recovery weight. The apex-forward attitude of the vehicle, required to achieve the desired test conditions, prevented the use of the forward-heat-shield system during three of the tests.

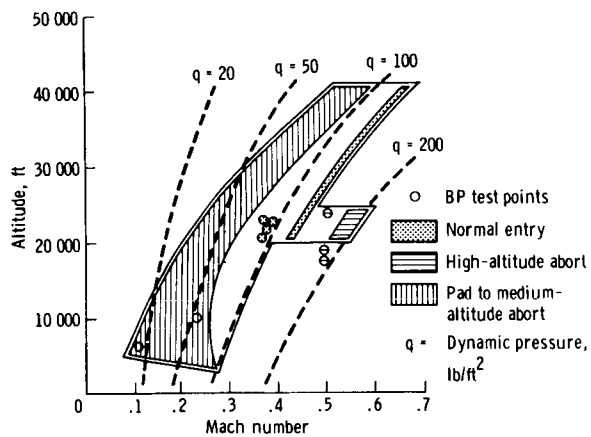
The drop tests made during the qualification series were dispersed as widely as possible over the potential operational envelopes for the drogue and main parachutes (figs. B-6(a) and B-6(b)). Included in figure B-6 are the test conditions at which the drogue and main parachutes have been demonstrated during the total system-level (BP vehicle) tests. Limitations imposed by the drop aircraft prevented drogue-parachute deployments at the higher altitudes; however, the high-dynamic-pressure conditions were well demonstrated. For each of the qualification tests, the conditions obtained were very close to desired values, and no discrepancies of sufficient magnitude were encountered to invalidate the test or to prevent fulfilling the test objectives.

On the basis of the performance of the parachute system during each of the qualification drop tests, and on successful completion of laboratory qualification at the component and lower-assembly level, the Increased Capability Block II ELS was verified for use on manned Apollo spacecraft.

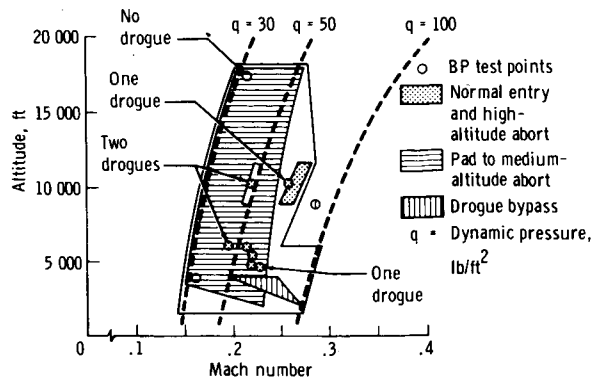
TABLE B-IV. - SUMMARY OF INCREASED CAPABILITY BLOCK II QUALIFICATION DROP TESTS

Test number	Date	Simulation	Recovery weight, lb	Forward-heat-shield jettison	Parachute disconnect			Drogue mortar fire			Pilot mortar fire		
					Altitude, ft × 10 ³	^a q, lb/ft ²	Time, sec	Altitude, ft × 10 ³	^a q, lb/ft ²	Time, sec	Altitude, ft × 10 ³	^a q, lb/ft ²	Time, sec
85-1	4-4-68	Normal entry	13 000	Yes	23.1	75.5	29.6	22.5	87.4	31.4	10.9	39.4	74.8
85-3	4-24-68	Normal entry (one drogue)	13 000	Yes	25.2	100.0	38.9	24.4	115.0	30.7	4.5	63.7	93.0
85-2	5-1-68	Pad abort	13 000	Yes	11.0	45.0	4.95	10.8	54.0	6.72	8.0	55.2	19.0
85-6	5-14-68	Pad abort (drogue bypass)	13 000	No	--	--	--	--	--	--	10.2	92.3	3.0
85-5	6-6-68	High altitude abort (one drogue)	13 000	Yes	29.0	42.7	15.0	19.6	170.5	36.5	4.2	63.5	84.8
85-4	6-17-68	Normal entry (one drogue)	13 500	Yes	25.6	79.6	29.1	24.9	92.5	30.9	4.3	65.1	96.5
85-7	7-3-68	High altitude abort (one drogue and two mains)	13 000	No	28.9	42.0	20.1	22.5	149.5	35.4	4.4	63.3	91.6

^aDynamic pressure.



(a) Drogue parachute.



(b) Main parachute.

Figure B-6. - Deployment envelope.

APPENDIX C

APOLLO 15 MISSION

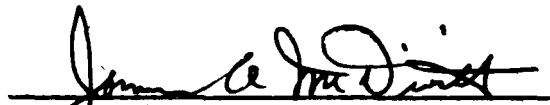
MAIN PARACHUTE FAILURE

Anomaly Report No. 1

PREPARED BY

Mission Evaluation Team

APPROVED BY



James A. McDivitt
Colonel, USAF
Manager, Apollo Spacecraft Program

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
December 1971

MAIN PARACHUTE FAILURE

The three main parachutes of the Apollo 15 spacecraft deployed and inflated properly at approximately 10 000 feet altitude. Films show that all three parachutes disreefed and opened fully in the proper sequence. The spacecraft and its parachutes were obscured by clouds at about 7000 feet altitude. Upon emerging from the clouds at about 6000 feet altitude, one of the three main parachutes was deflated as shown in figure 1. The spacecraft and parachute system descended in this configuration to water landing. The three parachutes were disconnected and one of the good main parachutes was recovered. The failure occurred abruptly. At about the altitude and time of the failure, the forward heat shield was in close proximity to the spacecraft and the reaction control system propellant depletion firing was about completed. An inspection of the recovered parachute showed one of the six riser links had a broken stud and three others had cracks. The investigation of the failure was, therefore, focused on the reaction control system propellant depletion firing, the forward heat shield, and the failed links.

DESCRIPTION AND SYSTEM OPERATION

The earth landing system decelerates and stabilizes the command module to safe conditions for landing. The landing sequence is initiated at a nominal altitude of 24 000 feet with jettisoning of the forward heat shield. Immediately after separation of the heat shield from the command module, a 7.2-foot-diameter parachute is mortar-deployed from the forward heat shield. This parachute prevents initial recontact between the heat shield and the command module.

Two 16.5-foot diameter conical ribbon-type drogue parachutes are mortar-deployed 1.6 seconds after forward heat shield jettison. The drogue parachutes are deployed in a reefed condition and, 10 seconds later, inflate to the fully open configuration. The drogue parachutes are released from the command module at an altitude of about 11 000 feet. At drogue parachute disconnect, three 7.2-foot diameter ring-slot pilot parachutes are mortar-deployed. The pilot parachutes provide the force necessary to release the main parachute retention system and pull the main parachute pack assemblies from the upper deck. As the main parachute packs are pulled away from the command module, the parachutes are extracted from their deployment bags. Each main parachute inflates through two reefing stages to the fully open configuration. The three main parachute assemblies (fig. 2) decelerate the command module to the final descent velocity.

Each main parachute canopy consists of twelve rings of sails with each ring divided into 68 gores. The canopy terminates in 68 suspension

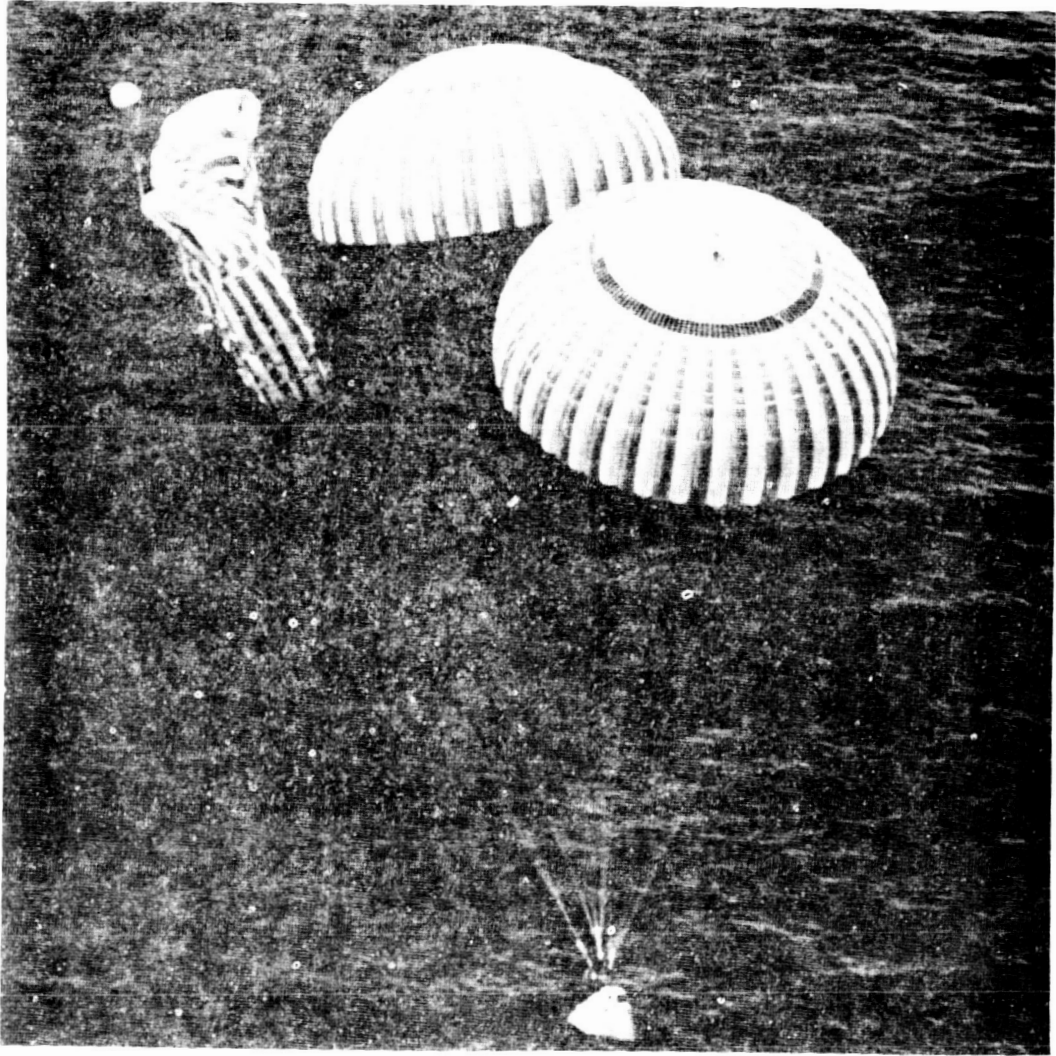


Figure 1.- Spacecraft descending with one main parachute failed.

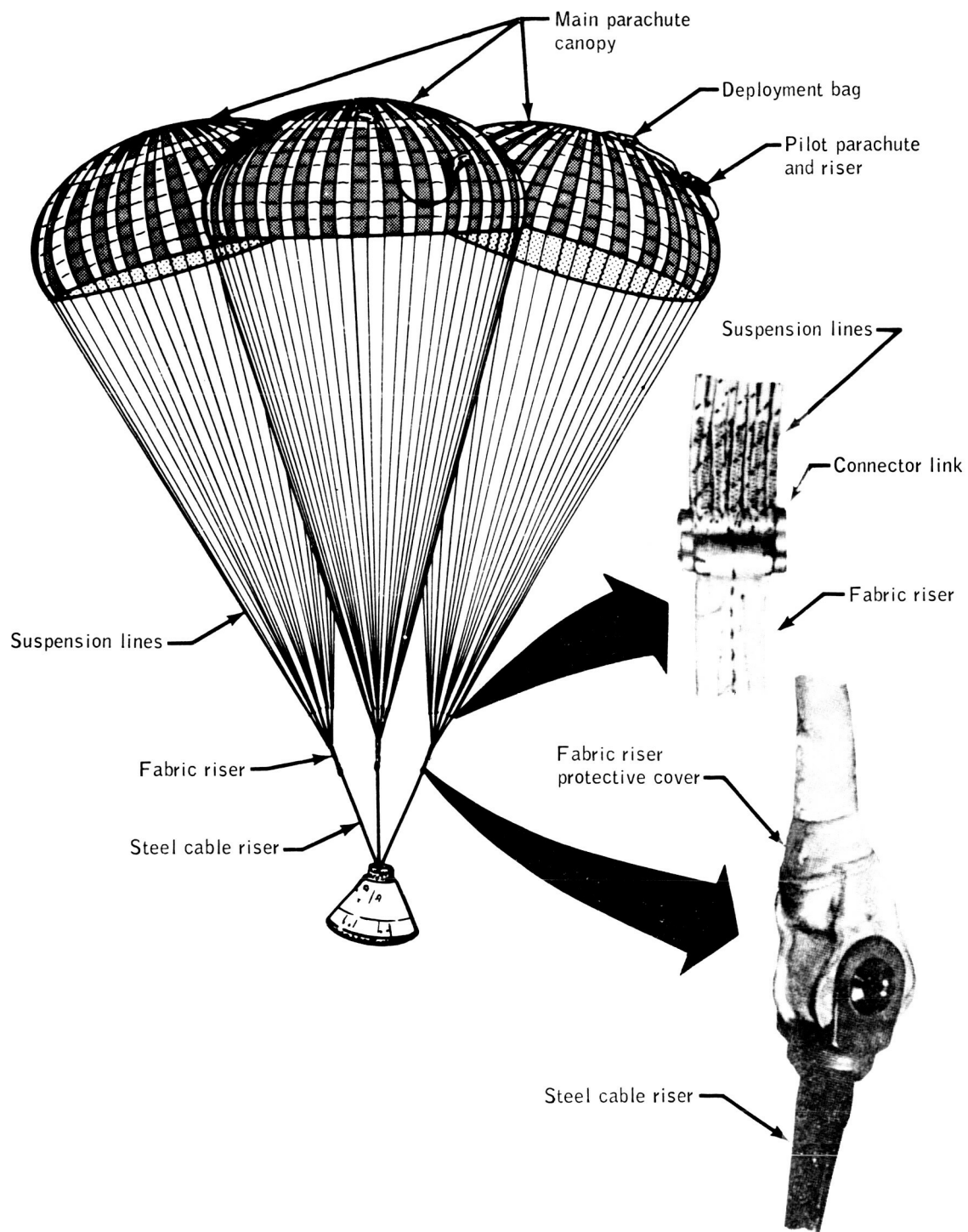


Figure 2.- Parachute system configuration.

lines which are attached by six steel connector links to six individual legs of a fabric riser. The six legs of the fabric riser converge into a single leg which connects to the end of a steel cable riser. The three steel cable risers of the parachute system converge and attach to the command module through the parachute attachment and disconnect assembly.

DISCUSSION

A discussion of the analysis, tests, conclusions, and corrective actions are contained in this report. All times shown in this report are elapsed time from range zero. Range zero is the nearest integral second prior to lift-off.

FLIGHT DATA

Pertinent data and the sequence of events are shown in figure 3. The data showed no abnormal conditions or events prior to the failure. About 3.5 seconds before the failure, the reaction control system manifold pressure abruptly increased to a new level, indicating the regulator had closed because all the oxidizer was expelled from the tanks. The fuel, however, was still being expelled and was calculated to have been depleted about 4.7 seconds after the oxidizer depletion. This was based on a determination of about 7 pounds of fuel remaining at oxidizer depletion. About 8 seconds after the failure, the reaction control system purge was initiated by the crew. (The crew was unaware of the failure until some time after the purge.) The time of the purge is indicated in figure 3 by the abrupt decrease in system pressure.

The forces acting upon the spacecraft at the time the parachute failed were determined from body-mounted accelerometer data. The force vector change at the parachute attach point was:

$$\underline{F} = -1379 \underline{X} + 356 \underline{Y} + 886 \underline{Z} \text{ pounds}$$

This resultant vector locates the failed parachute as shown in figure 4. The computed force vector was substantiated by body-mounted rate gyro data.

PHOTOGRAPHIC DATA

Figure 5 shows the spacecraft and lower parachute system when the spacecraft was relatively close to landing. The following observations resulted from study of this figure and other photographic data.

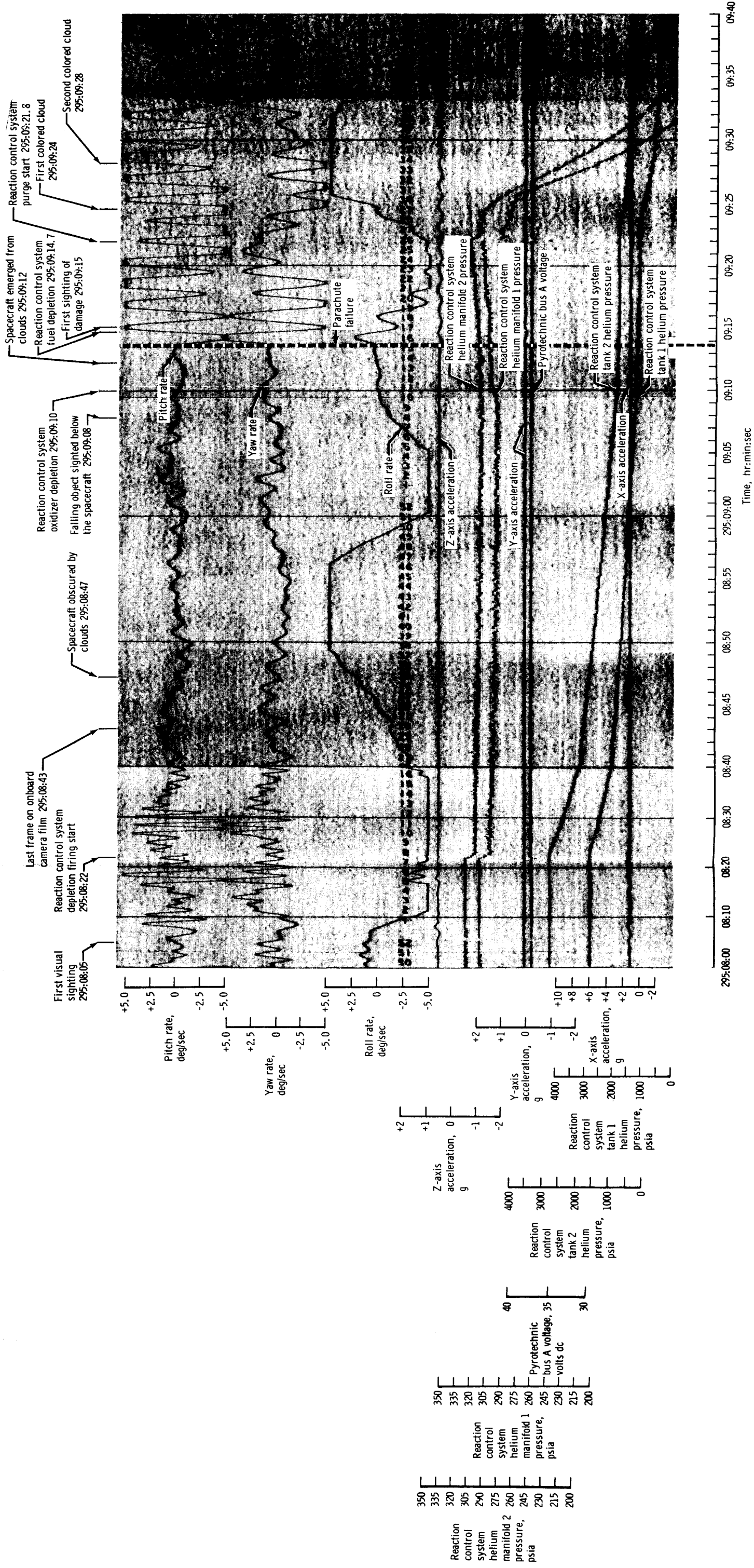


Figure 3. - Sequence of events during descent on the main parachutes.

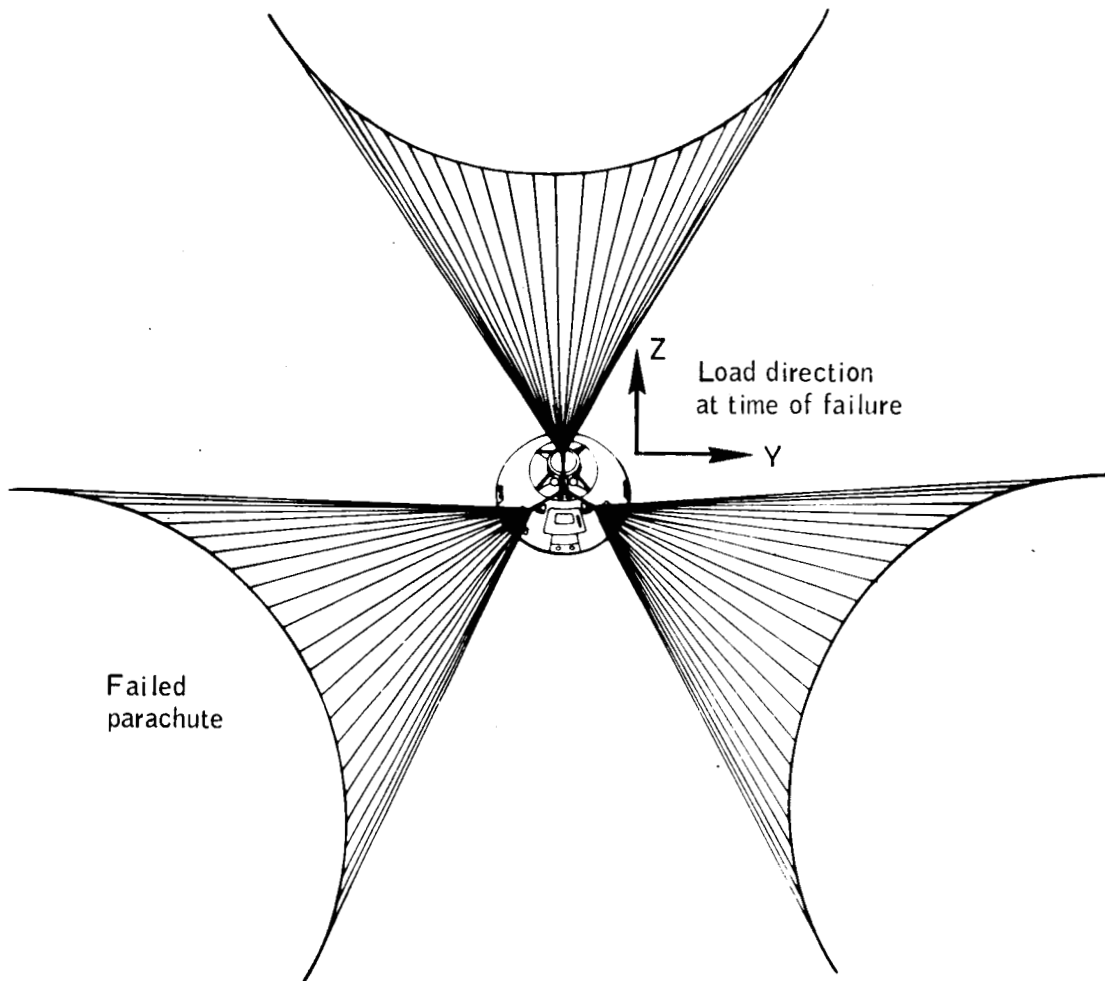


Figure 4.- Parachute location at time of failure.

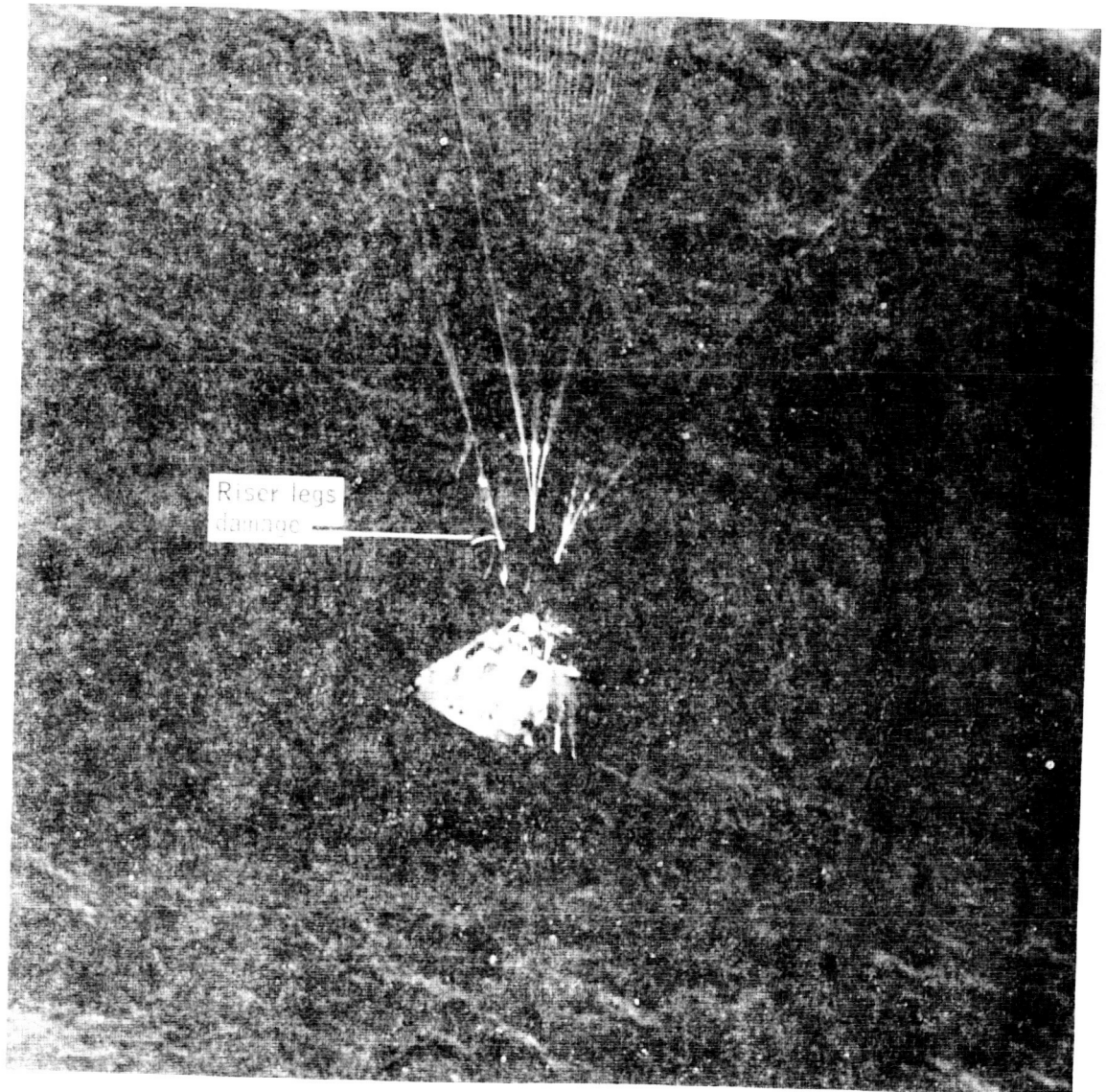


Figure 5.- Parachute riser damage during final descent.

- a. Apparently three of the six legs of the fabric riser were taking the load.
- b. There was no significant canopy damage observed.
- c. About two-thirds of the suspension lines appeared to be missing.

CREW OBSERVATIONS

The Command Module Pilot, while looking through the left-hand rendezvous window, witnessed the jettisoning of the heat shield and the deployment of the drogue parachutes; both functions appeared nominal. A few seconds after drogue parachute release, the Command Module Pilot observed the deployment of the main parachutes in the reefed condition. The parachutes maintained the reefed condition, after which disreefing occurred, and all three parachutes inflated normally. Following this event, the crewmen were performing various cockpit tasks which included the reaction control system depletion firing. After the completion of the firing, the Command Module Pilot observed that the parachute had failed. At the same time, he noticed the normal brown oxidizer cloud from the purge. Other functions through landing were nominal except that the landing was harder than normal.

RECOVERY FORCES OBSERVATIONS

The pilots and copilots of three of the recovery helicopters (Swim 2, Photo, and Relay) observed the spacecraft between main parachute opening and landing. The locations of the recovery forces at the time of the anomaly are shown in figure 6. The observations of the three helicopter crews show that the anomaly occurred at approximately 6000 feet and that the forward heat shield was falling in close proximity to the spacecraft, but slightly out of plane from the observer's viewpoint. The helicopter crews observed the brownish cloud and puffs of white smoke which normally occur during the reaction control system purge.

The swimmers successfully recovered one of the main parachutes and the forward heat shield, although the forward heat shield parachute was subsequently lost during the recovery operations. An experienced parachutist who was a member of the recovery team stated that the forward heat shield parachute appeared to be in good condition, with no tears in the canopy nor broken shroud lines.

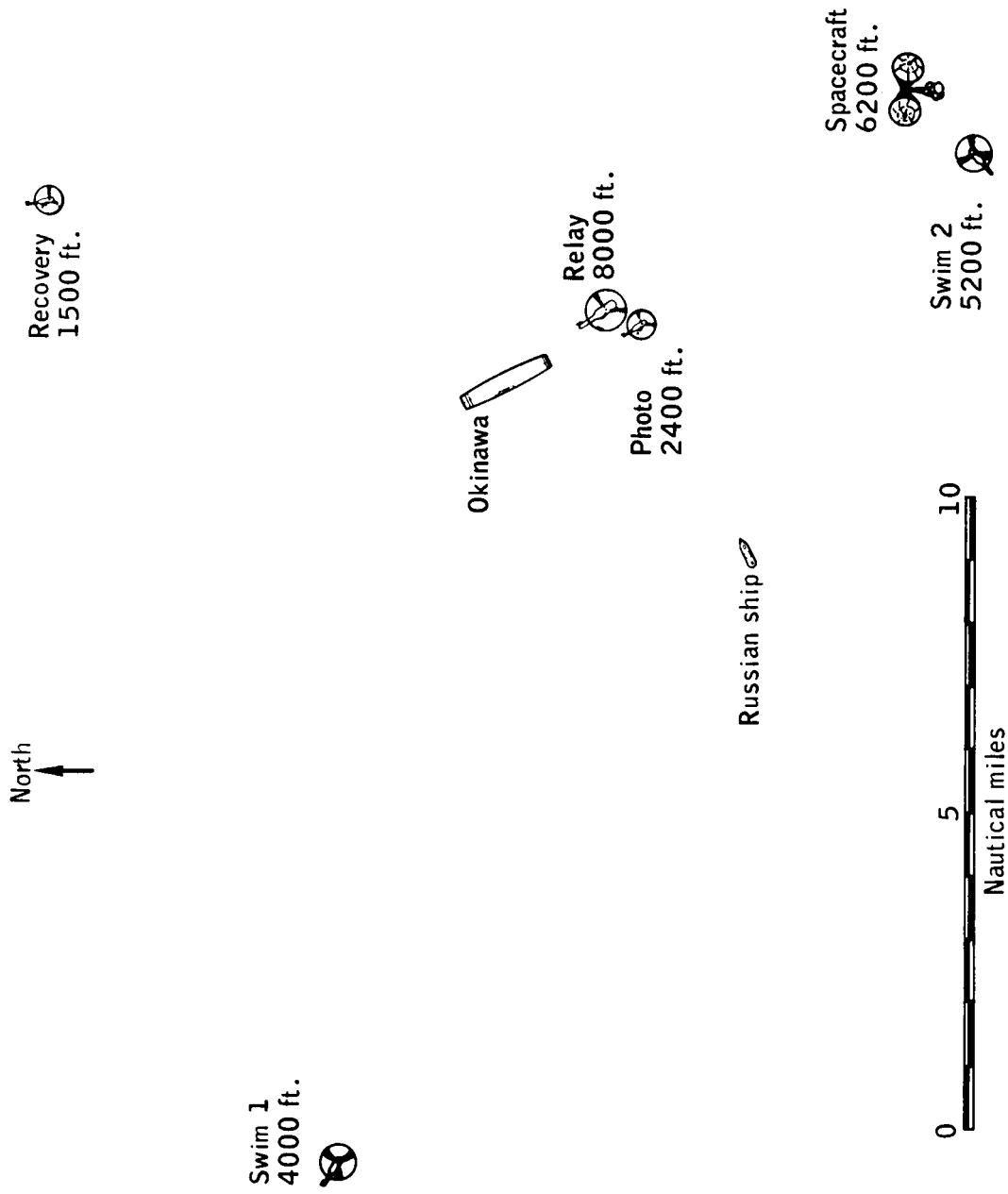


Figure 6.- Approximate location of recovery forces at 295 hours 9 minutes.

RECOVERED PARACHUTE INSPECTION

The recovered main parachute which had not failed was inspected and the results of the inspection were:

a. Nine consecutive suspension lines were cut approximately 19 feet above the riser/suspension-line connector link. Additionally, some 25 feet of line was missing from each of the cut suspension lines. (Lines were cut by Navy swimmers to free the parachute from the command module.)

b. Gore 11 of panel 9 had a tear approximately 12 inches by 12 inches which did not appear to have been caused by stress or friction burning, but probably occurred during retrieval.

c. Gore 55 of panel 5 had an 8-inch horizontal tear which also appeared to be the result of retrieval or postflight handling operations rather than that of flight damage.

d. There were numerous small (1/16-inch to 1/4-inch) holes in the canopy. (These were probably caused by postflight handling.)

e. The pilot parachute and riser were in excellent condition, and the main parachute deployment bag had only minimal (normal) damage.

f. The canopy was stained with oil and grease.

g. A broken riser/suspension-line connector link was found after the protective Dacron bootie had been removed (fig. 7).

h. Evidence of high temperature was noted on the Dacron riser protective cover (fig. 8) and the Dacron connector link bootie.

FORWARD HEAT SHIELD INSPECTION

The overall appearance of the forward heat shield was consistent with that of the forward heat shields previously recovered. The heat shield was examined for evidence of foreign material and none was found. The following specific points were noted:

a. The leading edge seal was not damaged.

b. Parachute cable riser marks were present on the outside of the forward heat shield. These marks occurred as a result of the normal forward heat shield parachute deployment.

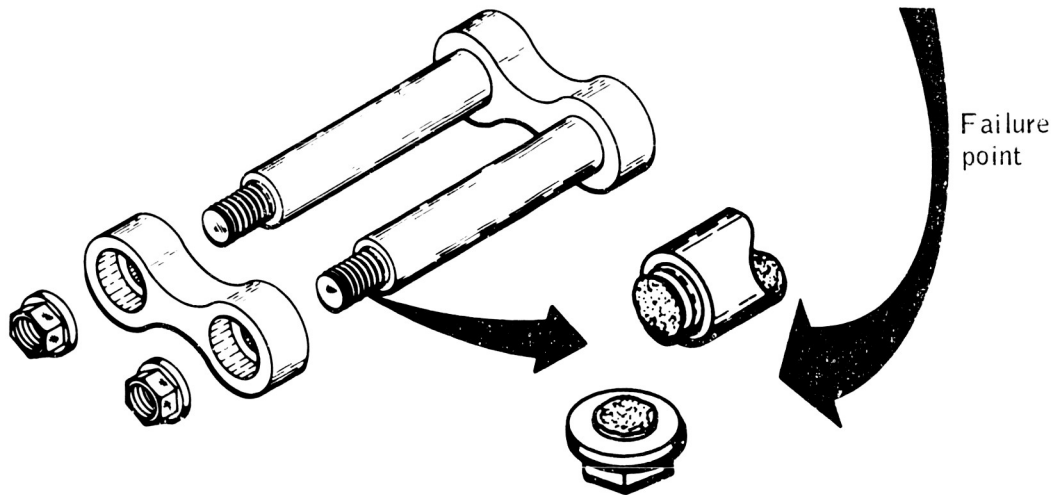
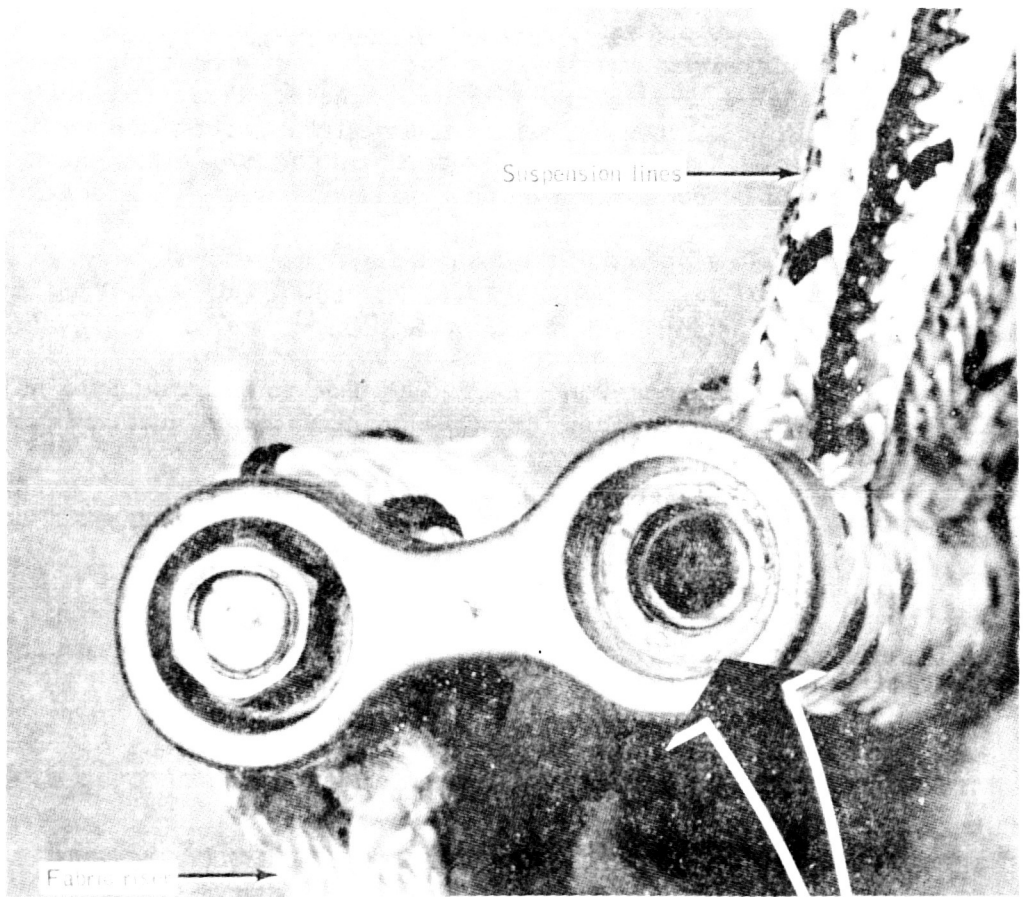


Figure 7.- Main parachute connector link failure.

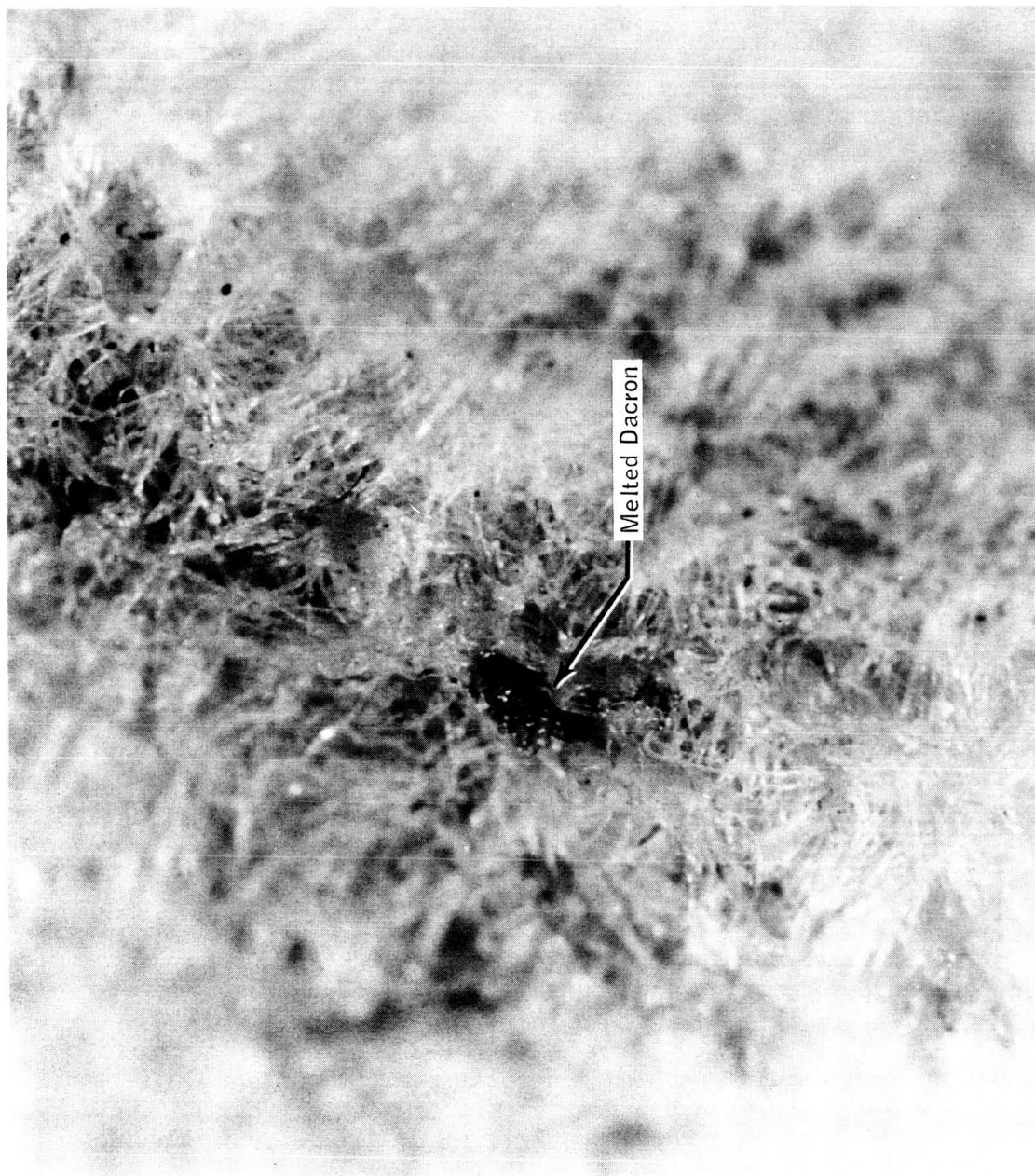


Figure 8. - Magnified view of Apollo 15 Dacron riser protective cover.

- c. The forward heat shield mortar had fired and the ramp had its normal scratches. One pyrotechnic connector was bent, probably as a result of ground handling.
- d. The handrail had been severely heated and approximately 7 inches of rail was missing. This condition was caused by reentry heating.
- e. The minus Z side was slightly flattened from impact with the water.
- f. The lanyards and pins from the forward heat shield switch appeared to be normal.
- g. The umbilicals appeared to be normal.
- h. A slice from the base of the ablator (7 inches by 1.5 inches by 0.75 inch) on the plus Z side was missing, but the room-temperature vulcanizing seal was undamaged. The damage to the ablator was probably caused by the recovery operation.
- i. All forward heat shield thrusters appeared to have functioned normally from the appearance of the area surrounding the piston rods.
- j. Approximately 50 inches of the fabric parachute riser were still attached to the steel riser. The fabric portion of the forward heat shield riser was cut by the swimmers.

FAILURE ASSESSMENT

The investigation was essentially divided into three areas which were likely suspects as to the cause of the parachute failure.

1. The forward heat shield was suspect because of the close proximity of the heat shield to the spacecraft flight path during the period when the failure occurred.

2. A broken riser/suspension-line connector link was found on the recovered parachute indicating the possibility of broken links in the failed parachute.

3. The command module reaction control system propellant depletion firing had just been completed and fuel expulsion was in progress at the time of the failure, indicating the possibility of damage from the propellants.

The analyses and tests performed to investigate each possibility are presented in the following paragraphs.

Forward Heat Shield

Trajectory analysis.- A trajectory analysis was performed using simulations to determine if the forward heat shield could have contacted the main parachutes. The simulations were based on the point-mass equations of motion, which used the known mass and aerodynamic characteristics of the forward heat shield and spacecraft parachute systems and the measured downrange and crossrange winds.

The simulations and analysis showed that, at approximately 150 seconds after the 24 000-foot altitude had been reached, the spacecraft and forward heat shield were at the same altitude of about 5700 feet with a miss distance of approximately 150 feet. This correlates with observations of the recovery personnel. Further, the analysis indicates that, at landing, the spacecraft and the forward heat shield were about 850 feet apart. This agrees with the estimated separation distance of 900 feet on the water.

Since the wind data were measured several minutes before landing, some deviations were expected. A wind profile within the expected deviation of ± 2 knots was constructed to determine if contact between the forward heat shield and command module parachute system was possible.

Based on the wind profile trajectory simulations, the forward heat shield could have contacted the spacecraft parachute system at an altitude near 6000 feet. The inaccuracies in the measured data and the simulations are such that it cannot be conclusively stated that the contact did or did not occur. It can only be stated that, in all probability, the miss distance was small.

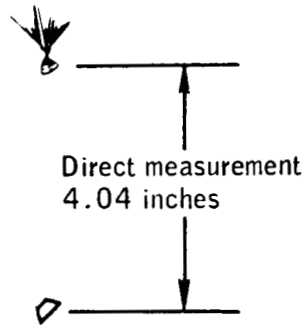
Photographic analysis.- A close examination of the television record of spacecraft descent on the main parachutes establishes that the forward heat shield was below the spacecraft at the time of the failure. Specifically, the forward heat shield is seen below the spacecraft in frame 588 (fig. 9) at 295:09:11.3, approximately 2 seconds before the anomaly occurred. By correlation with frame 775, which shows the parachute and forward heat shield in the same frame at 295:09:17.5, and by direct measurement of the separation distance between the two objects and measurement of the known parachute dimensions, the vertical separation distances between the forward heat shield and the spacecraft were 580 feet for frame 588 and 1020 feet for frame 775.

The position of the forward heat shield relative to the guidance-and-navigation-estimated trajectory is shown in figure 10. By extrapolating the forward heat shield trajectory, the forward heat shield would have intercepted the spacecraft at 295:09:03. This is 10.5 seconds before the spacecraft data indicate the anomaly occurred.

Television frame 588
 295:09:11.3 elapsed time

$$\Delta H = \frac{4.04}{7.11} (1020 \text{ ft.}) = 580 \text{ ft}$$

$$\Delta H = 580 \text{ ft}$$

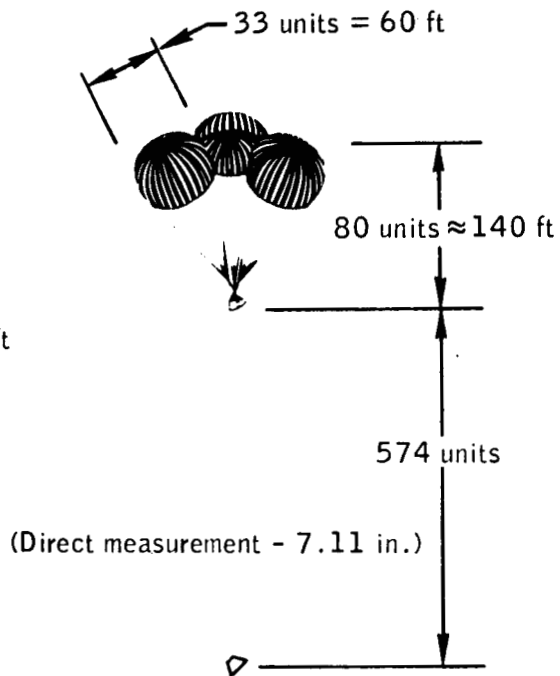


Television frame 775
 295:09:17.5 elapsed time

$$\Delta H = 574 (60/33) \text{ ft} = 1042 \text{ ft}$$

$$\text{or } 574 (140/80) \text{ ft} = 1004 \text{ ft}$$

$$\Delta H = 1020 \text{ ft}$$



$$\Delta V = \frac{1020 - 580}{17.5 - 11.3} \text{ ft/sec}$$

$$\Delta V = 71 \text{ ft/sec}$$

Figure 9.- Television frame and trajectory analysis.

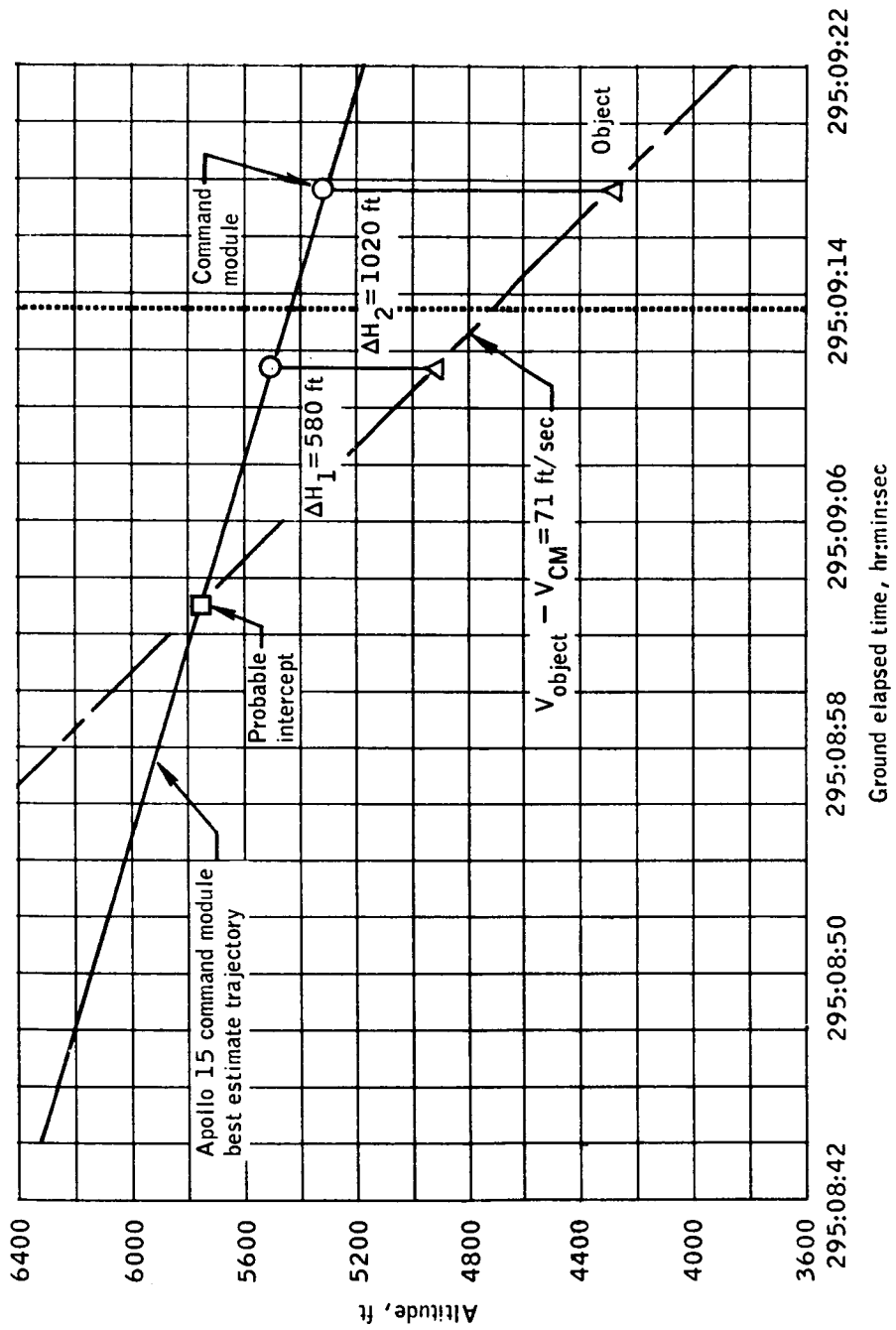


Figure 10. - Position of forward heat shield relative to spacecraft trajectory .

Assessment of probability of forward heat shield contacting spacecraft.- An assessment of the probability of the forward heat shield contacting the spacecraft was made to determine the hazard associated with contact. Actual wind data in the form of frequency of occurrence of winds as a function of altitude, wind velocity, and direction were used as a basis for the study. Wind data were applied to nominal trajectories of the spacecraft and forward heat shield in a planar (2 dimensional) analysis which yielded the frequency of occurrence of specific values of range separation between the two bodies at intercept altitude. Range separation values of less than 100 feet between the two vehicles were considered contact. The cumulative probability of contact is 0.093 percent. This analysis considered no trajectory dispersions. Subsequent refinement of the planar analysis to include effects of lateral dispersion (due to the moderate lift of the forward heat shield system and the spacecraft on the drogue parachute) provided a method which is much less sensitive to variation in initial conditions, principally in flight path angle. The refined analysis also yields a contact probability of about 0.1 percent.

The wind data are based on measurements during the month of August over a 13-year period for an area near the Apollo 15 recovery zone. Wind frequencies were concentrated in the east-northeast and west-southwest directions. These winds, and winds $\pm 22\text{-}1/2$ degrees from east-northeast and west-southwest, were used to provide a conservative planar wind profile which permitted the analysis.

The winds were used to modulate point mass, zero-lift nominal trajectories of the forward heat shield and spacecraft. Characteristics of the trajectories are shown in table I.

Forward heat shield/parachute suspension system impact tests.- Drop tests were conducted to determine the nature and extent of the damage to the main parachute suspension lines and fabric risers when impacted by a forward heat shield at simulated flight conditions. In tests of the parachute components, the risers and associated lines were mounted at the flight angle (38 degrees from vertical), with the lines correctly fanned and pre-tensioned (fig. 11). In the suspension line test, the forward heat shield impacted 5 feet above the connector links, striking all 22 of the lines used, breaking four, and damaging 10 others (fig. 11). The room-temperature vulcanizing material on the forward heat shield edge was cut and gouged where it struck the suspension lines.

Two riser tests were made. In the first, the forward heat shield impacted $1\text{-}3/4$ inches above the fabric confluence point, and in the second, the forward heat shield impacted near the center of the 42-inch riser legs. In both cases, the forward heat shield bounced off without damaging the risers. However, the room-temperature vulcanizing material on the leading edge of the forward heat shield was gouged (fig. 12).

TABLE I.- COMMAND MODULE/FORWARD HEAT SHIELD TRAJECTORY PARAMETERS

Initial Conditions

Forward heat shield jettison	
Altitude, ft	23 300
Flight path angle, deg	-73.1
Dynamic pressure, lb/ft ²	124
Spacecraft weight, lb	12 810

Forward Heat Shield

Weight, lb	310
Drag area, C _D S, ft ²	27.75
Lift coefficient, C _L	0

Spacecraft

Drag area, C _D S (Nominal history for two-drogue/ three-main-parachute operation)	
Lift coefficient, C _L	0
Altitude of initiation of main parachute deployment, ft	10 700

Forward Heat Shield Intercept

Altitude, ft	6 415
Time from forward heat shield jettison, sec	135.2
No-wind range separation, ft	^a -755

^aSpacecraft downrange of forward heat shield.

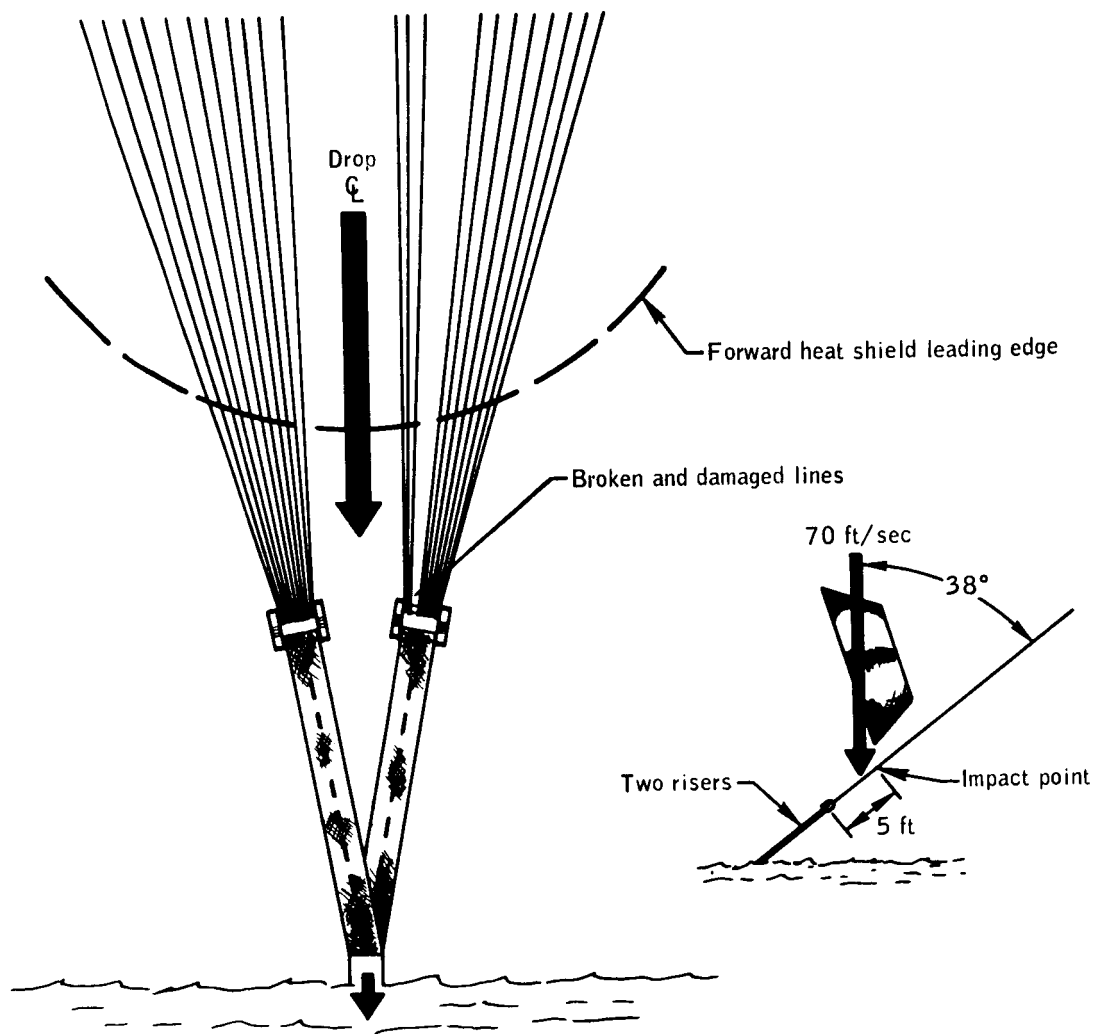


Figure 11.- Results of forward heat shield/suspension system impact test.



Figure 12.- Forward heat shield damage.

These tests showed that the forward heat shield contacting the parachute could damage some of the suspension lines, but would probably not cause a loss of riser legs.

Forward heat shield/command module impact tests.- Using the suspension line/riser test setup, two additional drop tests with the forward heat shield impacting the spacecraft were performed. In the first test, the forward heat shield impacted the spacecraft upper deck in the minus Y and minus Z bays, causing very light surface damage to the spacecraft, but severe damage to the forward heat shield. In the second test, the forward heat shield impacted the spacecraft near the hatch, breaking the outer hatch window and gouging the ablator. Again, the forward heat shield was severely damaged.

Based on the impact tests and analysis, the worst-case damage which could be expected would occur if the forward heat shield impacted the crew compartment heat shield window. There is a possibility that both the heat shield window and inner window would be broken.

Forward heat shield/parachute canopy test.- A test in which a forward heat shield was dropped onto a parachute was performed to assess the damage which might result to the parachute canopy. To simulate the inflated main parachute, a 95-foot diameter polyethylene balloon was inflated to 0.2-inch of water (the dynamic pressure during steady-state descent) with the parachute placed over the balloon and the suspension lines weighted. By using a guide cable, the forward heat shield was guided to impact the parachute canopy. The impact produced cutting, tearing, and burn-type damage. One parachute radial seam was broken, another was cut, and six sails were damaged. If this type of damage had been experienced in flight, the parachute probably would have remained inflated providing a near-nominal drag effect.

Conclusions from forward heat shield investigations.- The forward heat shield was not the cause of the failure of the main parachute based on two separate sets of data. First, the television tape shows the forward heat shield emerging from the clouds approximately 3 seconds prior to the anomaly. Second, the results of the suspension line and riser impact tests with the forward heat shield show that substantial damage to the room-temperature vulcanizing material on the leading edge of the forward heat shield would have occurred had there been contact. The recovered forward heat shield did not have this type of damage. There was no evidence of heat shield contact with the parachute.

Both the trajectory analysis and the television and observer data show that the forward heat shield did come close to the spacecraft. The analysis predicts that, for future flights, probability-of-contact is less than 1 in 1000. In addition, the tests of the forward heat shield impacting the suspension and riser lines, the spacecraft, and the canopy, indicate that, should contact occur, the resulting damage would not be catastrophic. Therefore, based on the low probability of contact, and the

acceptable damage should the heat shield contact the spacecraft and its parachute system, no corrective action is required.

Riser/Suspension Line Connector Links

One stud in a connector link assembly on the Apollo 15 recovered parachute failed. The failure was caused by stress corrosion cracking, hydrogen embrittlement, or some unknown mechanism. Stress corrosion is a possible cause because the high-strength steel (4130) used in the links is susceptible at high stress levels to cracking in salt water. Hydrogen embrittlement is a possibility because of the susceptibility of the high-strength steel to cracking from dissolved hydrogen. Earlier in the Apollo program, studs which were not properly processed after plating failed because of hydrogen embrittlement.

Link testing.- Several tests were performed on the connector links. The results are discussed in the following paragraphs:

Sustained-load test: Two link assemblies were sustain loaded in tension, axially along the studs, to a stress of 132 000 psi at the minor diameter of the stud threads. The test was to reveal the presence of hydrogen embrittled material; however, the tested links had been exposed to salt water, and therefore, this test was not sufficient to distinguish between delayed failure from salt-water immersion or hydrogen.

The first specimen failed 7.6 hours after load application. The fracture surface had approximately two-thirds of the cross sectional area at the stud shoulder exposed to a corrosive environment (probably sea water) prior to the start of the test.

The second link specimen failed 48.9 hours after load application. This specimen did not have the large pre-corroded area observed on the first specimen; however, approximately 10 percent of the cross-section had corrosion present. The sustained-load induced-fracture area was ductile on both specimens.

Stress corrosion tests: Four studs from the recovered parachute links (lot U) were loaded to a stress of 132 000 psi in tension at the minimum section of the studs. Three of these studs were notched, and the fourth specimen was tested in the original configuration. All four specimens survived 200 hours of sustained load in air. After 200 hours, sea water was placed in contact with the notched area of two of the studs and the load was maintained for an additional 48 hours. The third notched specimen remained in sustained load as a control specimen. Although the sides of the notches exposed to salt water were highly corroded, no failure occurred. The unnotched specimen was removed after 200 hours of sustained load in air and inspected under 25-power magnification for cracks

and none were observed. This unnotched stud was then remounted in a link assembly, torqued to 120 in-lb, which is twice specification level, and placed in sea water for 24 hours. The links and studs were then air dried, disassembled, and examined for cracks. No cracks were found.

Eight additional studs were torqued to 200 in-lb in order to simulate the effect of tolerance buildup of stresses at specification torque levels. Two studs failed during exposure to sea water, thus confirming the possibility of generating salt-water-induced stress corrosion cracking if the parts are within drawing limits.

Tensile tests: Two lot T studs, which had not been exposed to salt water, were placed under load as studs to a stress level of 132 000 psi, as computed for the minor diameter of the stud threads. This stress was maintained for 200 hours in an air environment. The stress was maintained while sea water was placed in contact with the stressed threads. After 48 hours, the sea water was allowed to dry and the specimen was maintained under load for an additional 24 hours. No cracks were found when the specimen was examined under 25-power magnification. Both specimens were then pulled to failure in tension, after exhibiting yielding, at 254 000 psi (normal notch strengthening for this material). No evidence of pre-existing flaws or corrosion was found on the fracture surface.

A total of ten studs (two each from: a pack life parachute, lot U that had not been flown, and recovered parachutes used on Apollo 10, 12, and 13) were loaded in tension to 132 000 psi as calculated for the minor diameter of the threads. No failures occurred in the accumulated 150 hours of air exposure test time on each specimen.

Two other tests were performed to provide base-line data on stud failures. An Apollo 10 stud was purposely charged with hydrogen and placed under a net section stress load of 132 000 psi. The stud failed in 30 minutes and thus validated the hydrogen embrittlement screening test. The second test used lot R links that had originally been rejected due to hydrogen embrittlement. These links were tested to 132 000 psi for 200 hours without failure, indicating that the hydrogen embrittlement characteristics had decayed.

The results of metallurgical examinations and these tests support the following conclusions:

1. Physical evidence for hydrogen-induced delayed failures of lot U and lot T studs does not now exist but, due to the long elapsed time since plating, hydrogen-induced failure cannot be ruled out.
2. Sea water does not induce cracks at the times and nominal stress levels expected, although general rusting of exposed steel occurs rapidly. Stress corrosion cracks can be induced by exposure to salt water at stress levels higher than those expected for a nominal 60 in-lb torque.

3. For the failed studs, the flaws probably occurred after the plating operation.

Studs exposed to hypergolic propellants are to be tested in order to determine if propellant exposure could have caused the observed flaws.

Pull tests: A series of connector link pull tests were conducted. An Apollo link which had been preloaded (nuts torqued) for more than 2 years with no salt water contact was pull tested to destruction (12 700 pounds) to provide a strength reference. Two special high-strength studs were fabricated to allow pull testing of the link end plates. However, the high-strength studs failed at a load of 12 850 pounds, and the end plates remained intact, verifying that the Apollo link studs are the weakest structural members.

The recovered Apollo 15 connector link with the separated stud was fitted with a riser and suspension lines and pull tested to evaluate its capability in the three-nut configuration. The link had failed in the stud thread and the stud had a shoulder remaining in the end plate which could carry load. This link was successfully subjected to two complete flight load cycles, then the load was increased to 5000 pounds (which corresponds to canopy ultimate strength) and successfully held for 2 minutes. These tests demonstrated that the stud failure could have occurred prior to parachute deployment. A final test was made with one end plate removed, simulating a tensile failure of one stud at the shoulder, or two sheared studs. This link failed at 1300 pounds, a value below the opening loads but higher than the steady-state loads.

Reliability and quality assurance records review.- A review was made of the manufacturing and inspection history records of the parachute link assembly manufactured by Northrop Ventura. Records were researched at North American Rockwell, Downey, California; Metal Surfaces, Inc., Bell Gardens, California; and Northrop Ventura, Thousand Oaks, California.

The records show that the parts for Apollo 15 (lot Q plates, and lot U studs) and Apollo 16 (lot W plates and studs) were properly processed in accordance with the latest revision of the Northrop plating specification.

One significant item disclosed by the review was that lot R studs which should have been scrapped were accepted and installed in flight parachutes. Lot R studs were flown in one parachute on Apollo 14, and were installed in a parachute to be used for future flight.

Parachute tow tests.- A series of ground tow tests was conducted to evaluate the characteristics of the inflated parachute and riser load response resulting from severing one, two, and three riser legs of a fully inflated main parachute. Inflation was obtained by towing the parachute

into the wind. When the canopy was fully inflated and stable, selected risers were pyrotechnically severed. Individual riser leg loads, total riser load, and photographic documentation were obtained.

When one of the six riser legs was severed, the canopy remained fully inflated and, in approximately 2 seconds, exhibited full riser load. When two adjacent riser legs were severed, the canopy collapsed but did continue to provide a drag force of approximately one-third the fully inflated value. Three risers were severed in the third test; two were adjacent and the third was separated from them by a good riser leg. When the risers were severed, the canopy collapsed, with the portion opposite the severed risers holding air for several seconds. The load histories for each of the three tests are shown in figure 13. The initial load drop for the one-, two-, and three-riser test was 600, 1700, and 2300 lb, respectively.

These tests indicated that the Apollo main parachute will remain fully inflated and provide normal drag with one of its six riser legs severed. When two or more adjacent riser legs are severed, the canopy will collapse, and lose at least two-thirds of its load-carrying capability.

Conclusions from connector link investigations.- The failed link on the recovered parachute implies the possibility of a similar occurrence on the failed parachute. However, the parachute tow tests indicate that a single link failure would not have caused the load change (approximately 1300 pounds) determined from the spacecraft data. Although the link failure is not believed to have caused the parachute anomaly, a complete records review and a materials test program were performed to determine the cause of the flaws. The records show that the Apollo 15 lot links were processed in accordance with all requirements. The link tests showed that the broken link can carry the flight loads (in the case of Apollo 15 type break). The available evidence cannot rule out either hydrogen embrittlement or salt-water-induced stress corrosion at higher-than-expected stress levels as the possible cause of the failure. In fact, the cause of the flaw is not known.

Command Module Reaction Control System

The command module reaction control system was considered as a possible cause of the anomaly for the following reasons:

a. The propellant depletion firing terminated 3.5 seconds before the spacecraft rates gave evidence of a major disturbance. The excess fuel expulsion which followed the depletion firing was still in progress at the time of failure.

b. The damaged parachute held a position generally above the minus Y roll engines while the fuel expulsion was in progress.

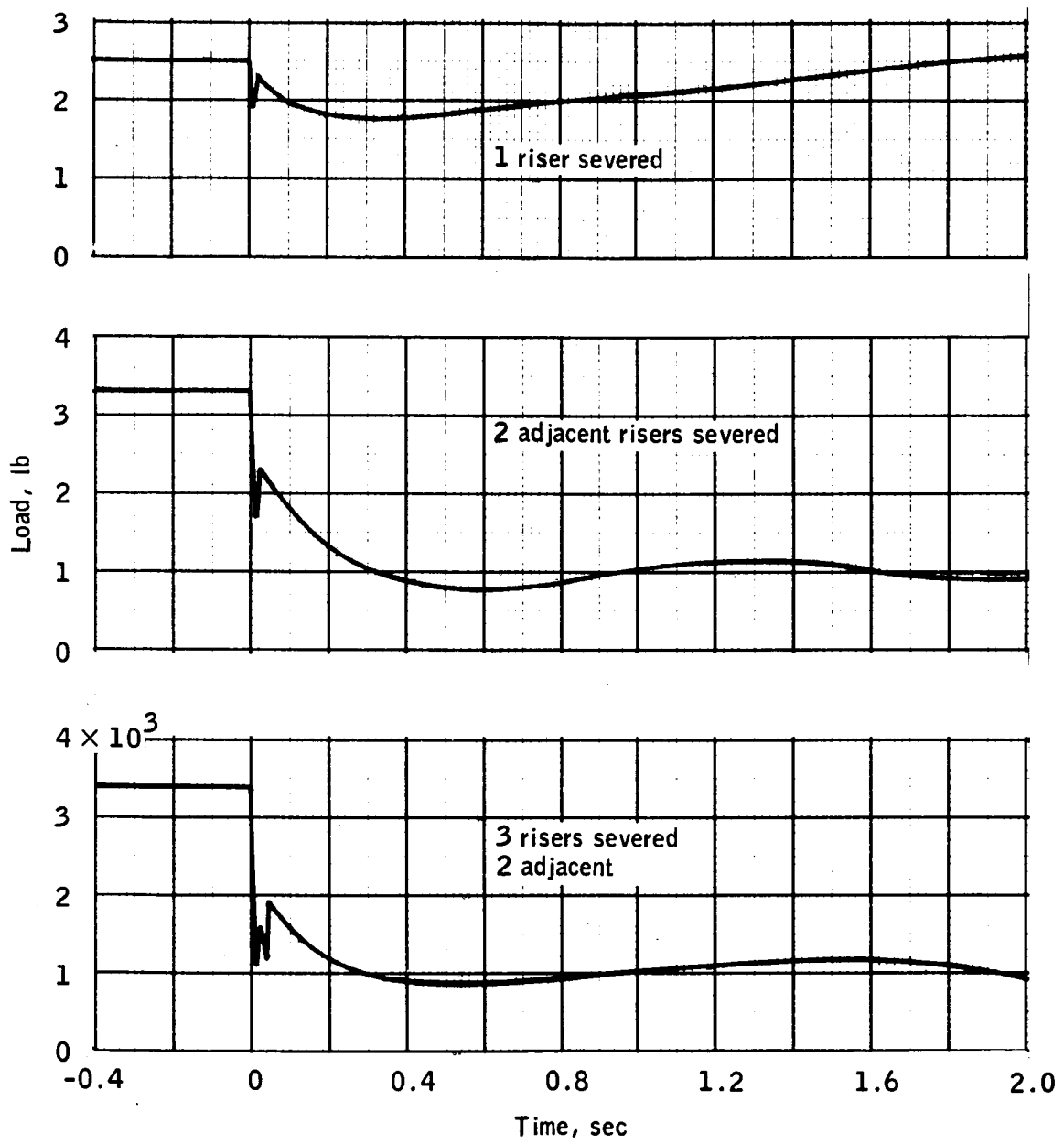


Figure 13.- Parachute tow test loads.

c. Burning fuel can cause damage to the risers, suspension lines, or parachute canopy.

d. Evidence of melting was found on the Dacron protective covering of the fabric riser and the connector links on the recovered parachute assembly.

System Operation.- Both command module reaction control systems were activated normally at 294:07:14. Both systems were used during entry as opposed to previous missions where one system was turned off prior to entry. System performance during the controlled portion of entry was nominal as verified by pressure and temperature data and from spacecraft rates produced by commanded engine firings.

The command module reaction control system control firings were terminated normally at 295:06:44 when the systems were electrically disabled. At this point in the mission, the engines had been fired approximately 680 times and the total firing time was about 160 seconds. The propellant usage had been 20 pounds of fuel and 36 pounds of oxidizer, divided equally between the two systems. Propellant consumption was established by pressure, temperature, and volume calculations and confirmed by the summation of the engine firing times. Usable propellant remaining at 295:06:44, prior to the start of the depletion firing, was 30 pounds of fuel and 53 pounds of oxidizer in each system for a total of 60 pounds of fuel and 106 pounds of oxidizer. Total propellant remaining, including the trapped propellants, was 69 pounds of fuel and 120 pounds of oxidizer.

The command module reaction control system depletion firing was manually initiated at 295:08:22. During this firing, the two systems were interconnected by opening squib valves between the helium manifolds, the fuel manifolds, and the oxidizer manifolds. The engine valves on all but the two plus pitch engines were also opened using the direct coils. System pressures indicated that the depletion firing was normal with oxidizer depletion at 295:09:10. Fuel depletion followed 4.7 seconds later. These times were confirmed by calculations using the propellant remaining prior to the firing, and a mixture ratio and propellant flow rate commensurate with steady-state firing from 10 engines. Between the time of oxidizer depletion and fuel depletion, about 7 pounds of raw fuel were being expelled.

The command module reaction control system line purge operation was manually initiated at 295:09:22. This operation opened four squib valves that enabled the helium gas to bypass the propellant tanks and purge the residual or trapped propellants from the system manifold lines. Regulated helium pressure and helium source pressure data verified a normal purge operation. At 295:09:25 and 295:09:28, colored clouds were seen coming from the spacecraft. This is normal and is caused by the expulsion of unburned oxidizer through the engines by the purge operation. Unburned fuel is also often seen about this time in the form of a white cloud.

Postflight testing of the command module reaction control system showed it to be in normal working order. Testing included leak checks of the propellant tank bladders, engine valve leak tests, engine valve signature traces to verify proper opening characteristics, and electronic tests to verify the electrical wiring and terminal board connections.

Command module reaction control system fuel expulsion tests.- Two tests were performed to investigate the potential effects of a raw fuel expulsion on the parachutes:

The first test was a feasibility demonstration to determine if fuel sprayed on the parachute risers and suspension lines would burn, assuming that there could be an ignition source. A simple nozzle was used to spray raw fuel into a 30 ft/sec air stream and onto a sample of the riser and suspension lines, part of which was surrounded by a Dacron bootie. Hot-wire ignition sources were imbedded in the bootie and riser to simulate an inflight ignition source. These tests demonstrated that, above certain threshold fuel concentration levels, the fuel on the booties would burn in a wick-like manner. This resulted in riser and suspension line failures due to melting of the nylon material.

The second test consisted of firing a command module reaction control system engine followed by fuel cold flow (simulated fuel expulsion). It was performed to investigate the effects of cold flowing raw fuel through a hot engine. For these tests, a reaction control system engine and a minus-pitch nozzle extension were mounted horizontally in an ambient test cell. There was no attempt to simulate the relative air velocity surrounding a descending command module. The test firings consisted of a series of hot firings of 10 to 45 seconds in duration, each followed by a 5-second fuel cold flow (about 0.6 pound of fuel). In every case, the raw fuel expulsion sequence produced burning outside of the engine. Burning fuel vapor, burning fuel droplets, and some unburned fuel were observed during these tests. The flame front existed up to 8 feet from the engine exit plane and unburned fuel was sprayed up to 10 feet from the engine and then ignited by burning droplets.

Conclusions from reaction control system investigations.- As a result of these tests, the hazard of a raw fuel expulsion was demonstrated. In addition, since the failed parachute was positioned over the roll engines for the time period just prior to the anomaly, the effects noted in the second test were, most likely, the cause of the Apollo 15 parachute failure.

CONCLUSIONS

The analysis of the data and results of the special tests lead to the following conclusions:

a. The most probable cause of the anomaly was the burning of raw fuel (monomethyl hydrazine) being expelled during the latter portion of the depletion firing and this resulted in exceeding the parachute-riser and suspension-line temperature limits.

b. The forward heat shield passed extremely close to the command module during the descent phase; however, at the time of the anomaly, the heat shield was 700 feet below the command module.

c. Impact of the forward heat shield on the parachute risers, suspension lines, canopy, or spacecraft will not cause catastrophic damage.

d. The failure of a single connector link will not cause a main parachute to fail.

e. The flaw observed in the recovered parachute connector link probably occurred after the plating operation, and could be due either to salt-water-induced stress corrosion or hydrogen embrittlement.

CORRECTIVE ACTION

Corrective actions for the reaction control system include landing with the propellants onboard for a normal landing and biasing the propellant load to provide a slight excess of oxidizer. Thus, for the low-altitude abort land landing case, burning the propellants while on the parachutes will subject the parachutes to some acceptable oxidizer damage but will eliminate the dangerous burning fuel condition. In addition, the time delay which inhibits the rapid propellant dump is being changed from 42 to 61 seconds. This will provide more assurance that the propellant will not have to be burned through the reaction control system engines in the event of a land landing.

The design of the suspension line connector links has been modified to preclude the development of high stress levels due to torque levels and to reduce the uncertainty of loads due to tolerance buildup. The link material has been changed to Inconel 718 to eliminate the requirement for plating and, therefore, the possibility of hydrogen embrittlement. In addition, the link stud threads are rolled rather than machined to improve metallurgical properties of the material, and the studs are subjected to a proof test designed to screen flaws which could subsequently propagate under salt water exposure.