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APOLLO EXPERIENCE REPORT - COMMAND MODULE UPRIGHTING SYSTEM

by Robert D. White

Manned Spacecraft Center
Houston, Texas 77058

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16. Abstract

A water-landing requirement and two stable flotation attitudes required that a system be developed to ensure that the Apollo command module would always assume an upright flotation attitude. The resolution to the flotation problem and the uprighting concepts, design selection, design changes, development program, qualification, and mission performance are discussed for the uprighting system, which is composed of inflatable bags, compressors, valves, and associated tubing.

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SUMMARY

The recovery of the Apollo command module, like that of the Mercury and Gemini spacecraft, is performed by a water landing of the manned module and subsequent transfer of the crewmen and spacecraft to a recovery ship. As the Apollo command module was developed and manufactured, it was discovered that the command module would float upside down (stable II attitude) as well as upright (stable I attitude). Because all postlanding recovery aids and vehicle hatches would be submerged if the command module should assume the stable II flotation attitude subsequent to water impact, and because the spacecraft could not be designed to be self-righting and yet maintain an acceptable lift-to-drag ratio, a method to return the command module to the stable I flotation attitude was essential. The method selected, termed the "uprighting system," consists of three inflatable bags attached to the command module upper deck, two compressors, valves, and associated tubing. Bag inflation is performed by pumping ambient air into the three bags. Physical and functional descriptions of the uprighting system and the various early concepts considered are presented. The development and verification programs, the problems encountered, and the mission performance are also discussed.

INTRODUCTION

At the inception of the Apollo command module (CM) design, a water landing at earth return was designated as the primary landing mode. This technique was used for both Project Mercury and the Gemini Program. After the water landing, the CM crewmen are transferred to a recovery ship. To guarantee a safe recovery after splashdown, studies were started in 1962 at the NASA Manned Spacecraft Center (MSC) and at the prime contractor facilities to determine the CM flotation characteristics. These two studies involved both small-scale models of the CM and a full-scale boilerplate (BP) test vehicle that approximated the CM configuration.

These early studies of the CM revealed that the basic Apollo shape, with the predicted center-of-gravity (c.g.) location, had two stable flotation attitudes: stable I (vehicle upright) and stable II (vehicle inverted). The stable II attitude was not desirable from the standpoint of crew safety and comfort, crew tasks, postlanding CM ventilation, postlanding location aids operation, and CM sea pickup. Also, the CM could not be configured to be a self-righting vehicle and still maintain an acceptable lift-to-drag ratio (L/D). For these reasons, in April 1964, the Apollo Spacecraft Program Office (ASPO) directed the prime contractor to begin a study to determine ways to prevent the CM from remaining in a stable II attitude.

In this report, the MSC and prime contractor study results of the Apollo flotation attitude problem; the concepts considered to eliminate the problem; and the development, qualification, and performance of the selected concept are discussed.

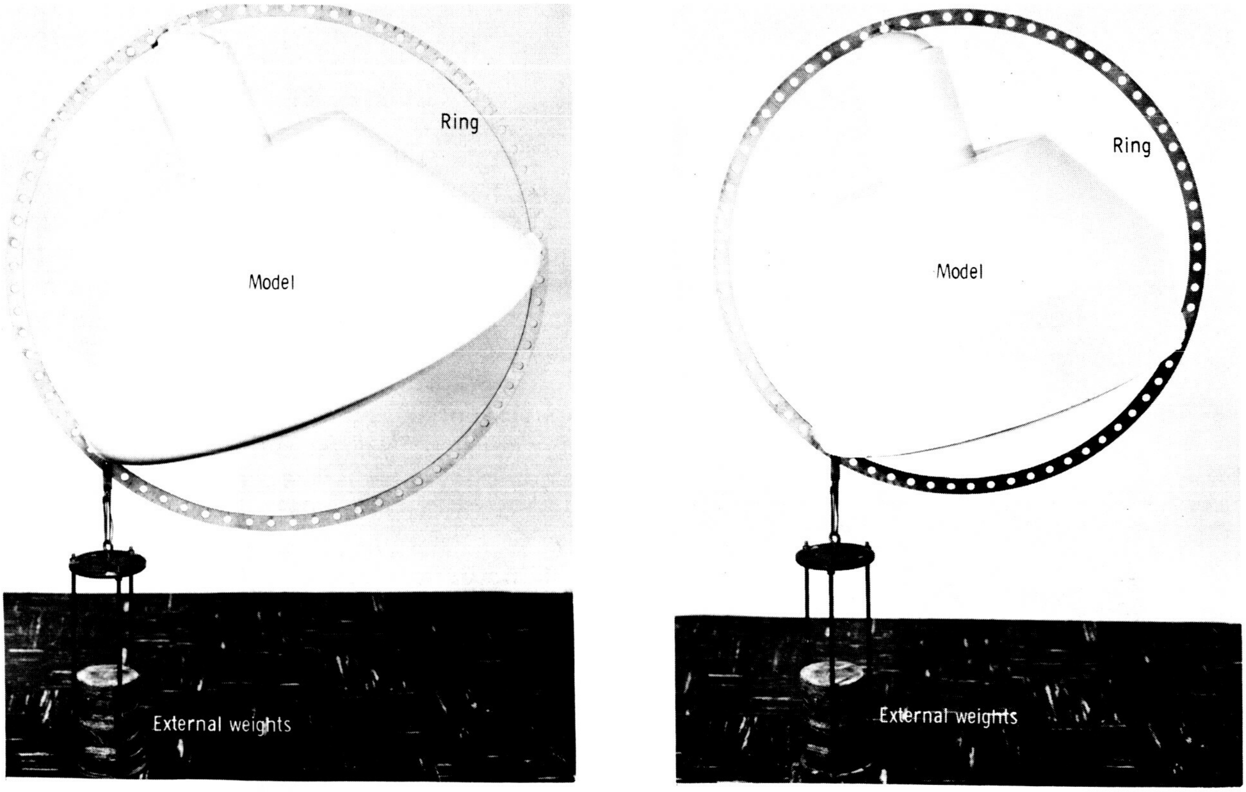
COMMAND MODULE FLOTATION CHARACTERISTICS

To determine the flotation characteristics of the proposed Apollo CM configuration, the MSC and the prime contractor conducted flotation tests in 1962 and 1963. Testing at the MSC was done with 1/5 geometrically scaled models, and the prime contractor used a 1/10-scale model and a full-scale boilerplate. The prime contractor also conducted preliminary investigations using analysis techniques similar to those used by naval architects.

Determination of Flotation Characteristics

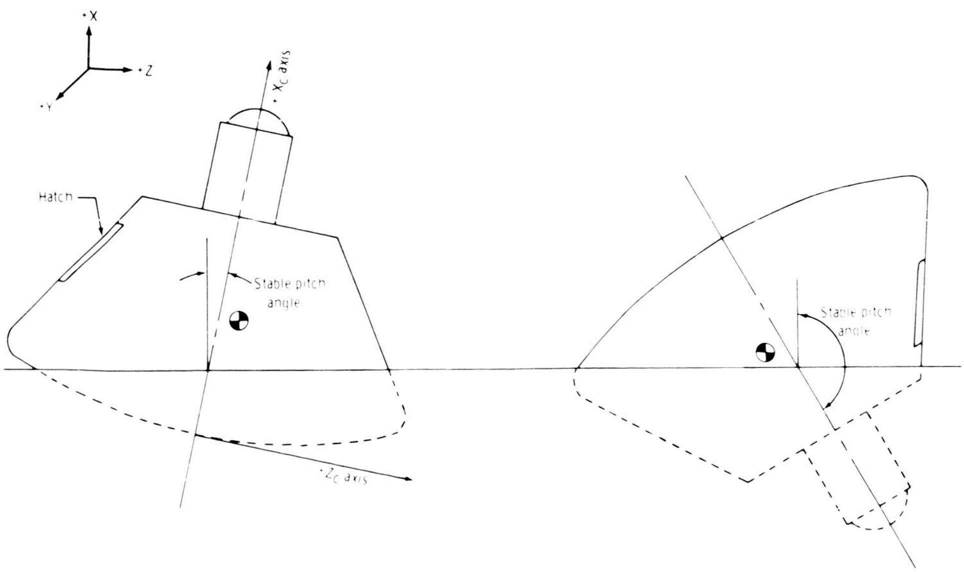
Because the CM heat shield was not watertight, it was known that the total buoyancy effect would be the result of the shape of the CM pressure vessel plus the buoyancy of the submerged outer heat shield structure and all submerged equipment in the aft compartment (between the inner pressure vessel and the heat-shield structure). However, during the early phase of model testing, the amount and location of the hardware in the aft compartment were not finalized. Therefore, for the first phase of testing at the MSC, two models were used: one represented the outer mold line of the CM heat shield and the other represented the pressure-vessel configuration (fig. 1). The actual flotation characteristics were anticipated to fall between the extremes of the outer and inner mold-line test results. Each model was encircled by a steel ring contained in a vertical plane through the axis of symmetry. Each ring had holes at prescribed intervals to allow attachment of an external weight at any desired location. The combined mass of the external weight and the model represented the desired landing weight and c. g. of the CM for testing. By placing the weight and model in water and progressively moving the weight around the ring and reading the flotation angle at each setting, the flotation characteristics could be determined for any c. g. location. A composite of the results for the MSC model tests is shown in figures 2 and 3. Typical stable I and stable II flotation attitudes with respect to the standard CM X and Z axes and the CM side hatch are shown in figure 2. The c. g. zones shown in figure 3 indicate the number of stable attitudes in which the CM can float.

The prime contractor model tests yielded similar information, although the approach was different. The prime contractor built one model with a best-guess simulation of components in the aft compartment. The c. g. of the model was varied by moving internal weights.



(a) External configuration model. (b) Pressure-vessel model.

Figure 1. - Apollo CM model test setup for determining flotation characteristics.



(a) Stable I. (b) Stable II.

Figure 2. - Typical Apollo flotation attitudes and hatch exposure.

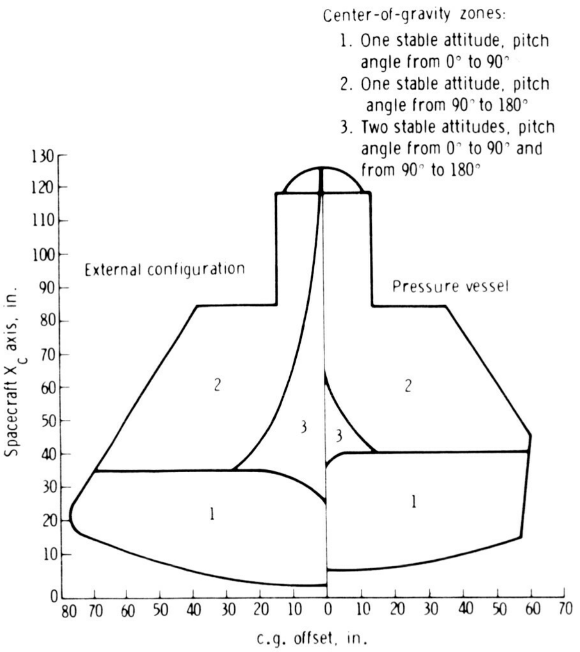


Figure 3. - Zones of significant c. g. locations for CM pressure vessel and CM external configuration at a 9000-pound displacement.

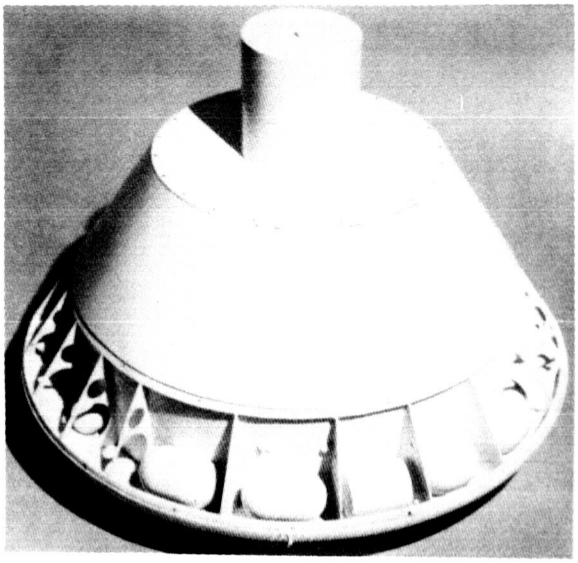


Figure 4. - Apollo CM 1/5-scale flotation model (as seen from +Z axis) with simulated equipment in aft compartment and with cover removed.

Static and Dynamic Flotation Characteristics

During 1964, further refinement to the CM flotation characteristics was made both at the prime contractor facilities and at the MSC with second-generation models. These models represented the CM configuration with the simulated equipment in the aft compartment. The 1/5-scale MSC model is shown in figure 4 without the aft compartment cover. The prime contractor used a refined 1/10-scale model. Static flotation characteristics were defined further with these models.

The prime contractor model was used to study the dynamic response of the spacecraft to sea-wave excitation. A series of tests subjected the model to a "sea" consisting of sinusoidal waves of variable amplitude, length, and frequency. It was discovered that, with certain conditions, the model would flip from one stable position to the other. In early 1965, more quantitative data on the dynamic stability of the CM were obtained in a random-wave facility at the Stevens Institute in New Jersey. These tests confirmed the possibility that the CM would change stable flotation attitudes in rough seas (sea state 4 or greater). Energy spectra of the model response in pitch, heave, acceleration, and so forth in irregular waves were computed from the test data. This information was used to predict CM performance in a sea state 4 for the total 48-hour habitability requirement to which the CM is designed. It was predicted that the CM with the c. g. location determined by flight requirements could overturn as many as four times during the 48-hour period.

Concurrently with the static-flotation and dynamic-wave tests, the prime contractor investigated the dynamics of the CM as it impacted the water. This investigation included both analyses and tests. The drop tests were conducted with the 1/10-scale model and with a full-scale boilerplate.

Analyses of CM performance (when the CM lands on different wave slopes), in addition to the drop-test data, are indicative that the CM could flip over with certain combinations of horizontal velocity and CM roll and pitch orientations at water impact. The CM is most sensitive to overturning when the +Z axis (fig. 2) is in the same direction as the CM horizontal travel. This attitude is defined as 0° roll orientation. Typical conditions for overturning or remaining upright at impact are presented in figure 5.

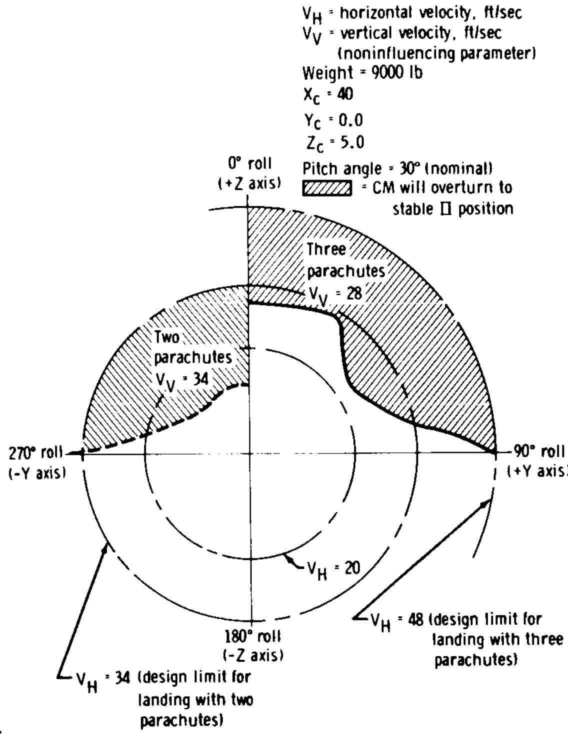


Figure 5. - Typical CM landing dynamics.

COMMAND MODULE UPRIGHTING CONCEPTS

By early 1964, the general technique and necessary hardware for sea recovery of the CM had been established. The approach was to have all recovery aids (radio antennas, sea dye, postflight ventilation, recovery loop, and so forth) located on the upper (parachute) deck of the CM. This requirement meant that the CM must float in stable I to effect a successful recovery. Therefore, on April 13, 1964, the prime contractor was requested by the ASPO to initiate a study to determine techniques for eliminating the stable II attitude; parallel efforts were started at the prime contractor facilities and at the MSC.

Several constraints that had to be considered when evaluating any uprighting concept were identified. One major constraint was that the Apollo Block I CM design had been released, and the primary structures for the first few vehicles had already been built. This constraint meant that whatever uprighting concept was chosen, it would have to be as simple a retrofit to the CM as possible. A second major constraint was the program schedule. The first spacecraft, command and service module (CSM) 009, was scheduled to be delivered to the launch facility at the NASA John F. Kennedy Space Center approximately 16 months after the start of the uprighting concept study effort. The time constraint meant that no extensive development or research programs could be afforded. The concept would have to be chosen, and the hardware would have to be designed, fabricated or procured, test qualified for space flight, and installed and checked out on CM-009 within 16 months. Other constraints included high reliability, small CM weight increase, and severe stowage volume limitations. All stowage areas on the CM were virtually filled with other existing systems such as parachutes, pressure tanks, and wire bundles.

Concept Evaluation

The ASPO-requested study was initiated by investigating two general approaches: a method to prevent stable II from occurring or a method to upright from stable II each time it did occur. Because stable II could be caused by either landing dynamics or postlanding sea dynamics, both possibilities had to be considered when evaluating these techniques.

Prevention of stable II. - The only feasible way to prevent stable II from occurring at impact appeared to be by controlling the roll orientation of the CM before splashdown to approximately 180°, a favorable roll angle for remaining upright at landing (fig. 5). Methods considered were use of roll reaction jets, a torque motor between the parachute suspension line and the CM, and a sea anchor. The first two methods required some type of horizontal-velocity direction sensor. The potential problems of developing a reliable sensor for the Apollo Program were too great, and the weight penalty for a torque motor or jet system was too severe. Thus, the requirements for a sea-anchor orientation scheme were investigated further. The technique developed is presented in figure 6. The major technical problem appeared to be the necessity of keeping a tension load on the anchor cable once it was in the water. Therefore, a takeup reel would be necessary. The tension-load requirement was complicated by ocean currents and winds that were not always in the same direction.

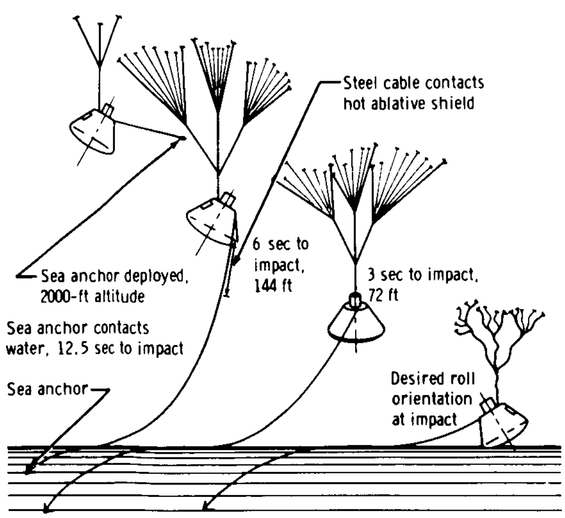


Figure 6. - The CM roll orientation controlled by sea anchor.

The sea anchor would have the promising feature of being an effective arrester against excessive CM pitching in dynamic waves after the CM had landed in stable I, thus contributing to a permanent upright attitude. To reduce further the possibility of stable II, methods of lowering the CM c.g. were investigated. These methods are discussed in a later section.

When the sea-anchor technique of preventing stable II was compared with the concepts of uprighting the vehicle from stable II (presented in the following sections), the system not only was considered too complex but also would have required extensive full-scale development and qualification testing to prove reliable. Hence, the MSC and the prime contractor jointly concluded that it would be best to develop an uprighting system.

Uprighting from stable II. - The investigation of concepts for righting a CM from stable II was divided into two approaches. One approach was to lower the effective c.g. of the vehicle in the -X direction to the extent that the vehicle would be stable only in the upright position (zone 1 of fig. 3). The second approach was to create a moment about the c.g. that would be great enough to upright the CM.

Lowering of the c.g.: To lower the CM c.g. enough to eliminate the stable II attitude would require a significant shift of mass on the vehicle. The first thought was to have the three crewmen on the manned flights move from their couches to the aft bulkhead. However, analysis showed that this technique would lower the c.g. only a fraction of an inch, not enough to right the vehicle. The second approach to this technique was to design the couch strut system to allow manual stroking of the struts to lower the couches the full 16 inches of aft travel. Manual stroking would lower both the crewmen and their couches (a total weight of approximately 1000 pounds). This procedure would lower the c.g. more than an inch and would significantly increase the stability of stable I but would not eliminate stable II. Various problems associated with altering the couch strut design led to the decision not to develop this approach.

Use of external righting moment: Several techniques were considered to retrofit a system to create an external righting moment on the CM. If the CM could be forced from stable II to a position where the tunnel was approximately parallel to the water surface, the CM would then upright itself. The moment required to reach this self-righting position (theoretical stable point) is shown in figure 7. The energy techniques considered to achieve this torque were rockets, sea anchor, water bag, aft compartment flooding, gas bag, and expandable foam bag. The points for the force application of these concepts are shown in figure 8.

Each concept was evaluated by analysis or model testing (or both). The major disadvantages of the rocket concept were the system weight, the potential danger, and the complicated interface required with the CM heat shield. The sea-anchor approach proved unfeasible because it depended entirely on the unpredictable heaving of the sea and the pitch dynamics of the CM.

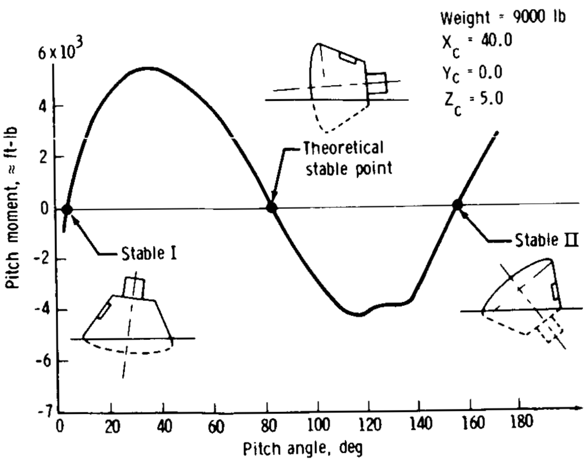


Figure 7. - Typical static stability curve for the CM.

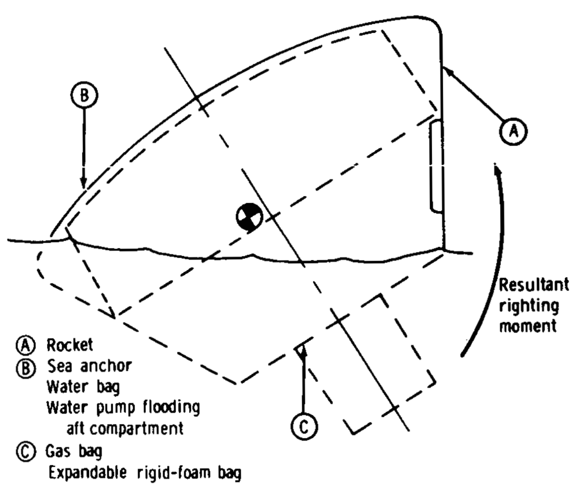


Figure 8. - Typical techniques to produce a righting moment on the CM in stable II with the arrows indicating direction and location of force application.

Both full-scale and 1/5-scale tests were conducted to test the concept of a water bag positioned on the aft heat shield (fig. 8). Sea water was pumped into a bag to produce an overturning force. This concept could be used to upright the CM; however, two practical problems made the concept unattractive. First was the problem of bag deployment from a stowed location. The bag had to be deployed to the desired location on the aft heat shield. Bag deployment would require a complicated design because no penetrations were allowed in the aft heat shield. The second problem was that of constraining the bag in the center of the heat shield while the bag was being filled. Because of sea dynamics and the dome shape of the aft heat shield, the bag would slide over the side unless constrained in three directions.

Another concept evaluated with the 1/5-scale model was that of flooding the aft compartment (between the heat shield and the pressure vessel) with sea water. Although the analysis indicated enough moment could be created to upright the CM by this technique, model tests indicated otherwise. If the concept had been feasible, the requirement to make the aft compartment watertight at landing would have been a significant design problem.

Two uprighting concepts that were very similar in predicted performance were the use of a single bag inflated with gas and the use of a bag filled with an expandable rigid foam. The gas bag could be filled with stored bottle gas or from a compressor pumping air. The inflation rate to the bag could be controlled. In the foam bag, the foam could be produced by a manually initiated chemical reaction actuated after landing. The foam would cool and become rigid in a few seconds. The gas bag appeared much simpler in design and was considered to be a lighter-weight system. However, a filled foam bag had the advantages of being permanent and resistant to abrasion and chaffing. All the model-uprighting tests by the prime contractor and by the MSC with a spherical bag were effective when using the proper bag size. The required bag size was governed by the water-soaked-spacecraft weight and the resulting c.g. location.

Concept Selection

On July 7, 1964, the prime contractor and the MSC held a meeting to review all analyses and test results and to choose a concept for further development and design for the Apollo CM configuration. Most concepts presented had either marginal capability or serious impact on the CM structural design. The only system that was considered within the state of the art was the gas-bag concept. This system appeared to have minimum impact on the weight and design change of the CM. The major disadvantage of the gas-bag concept was the marginal capability of the gas bag to obtain an effective lever arm with the CM at stable II. The ineffective lever arm was caused by the necessary location of the gas bag on the CM upper deck (+Z quadrant) and the relationship to the c.g. line of action in stable II. As can be seen in figure 9, this bag location gives the bag a minimal lever arm to act on. However, as the CM rotates toward stable I, the lever arm increases substantially.

Based on the data and analyses available, the decision was made to start development work on a gas-bag uprighting system. The first trade-off studies evaluated the

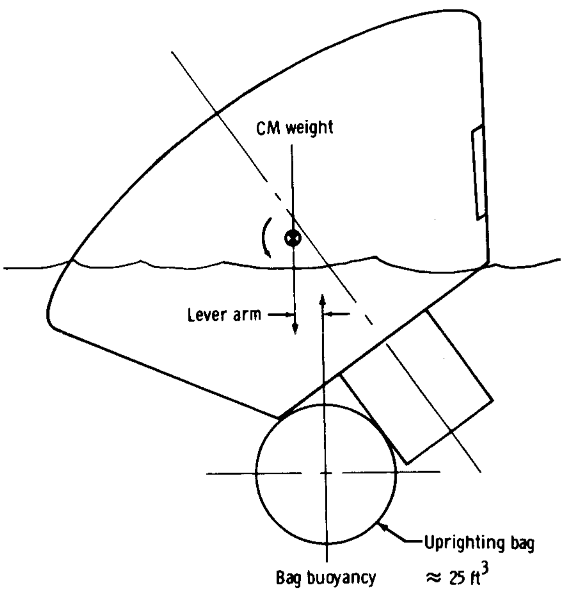


Figure 9. - Uprighting bag of gas or foam.

mode for inflating a bag. Three inflation systems were reviewed: a nitrogen supply in pressure bottles, hydrazine cool-gas generators (being developed for the U.S. Navy), and air compressors. The air-compressor concept was selected primarily for the following reasons.

1. The air compressor was considered an off-the-shelf item.

2. The nitrogen bottles have a limited supply of gas (to provide enough gas for four possible uprightings with bag leakage would incur an excessive weight penalty).

3. The cool-gas generator had better weight and stowage volume characteristics than the other two systems; however, it would have required further development work for application on the Apollo spacecraft.

Also, a study was started to determine the appropriate bag size compatible with the requirements of both uprighting and stowage. However, in August 1964, a program decision was made to lower significantly the entry L/D requirement of the CM to be compatible with a necessary CM weight increase. In effect, the Z axis offset of the CM c.g. was reduced from 6 inches to approximately 5 inches. Unfortunately, because of this reduction in the c.g. offset, there was a resultant decrease in the CM roll stability about the X axis during uprighting. Subsequently, model tests revealed that a single-bag system would not upright the CM but would cause the CM to roll severely until the bag surfaced on the water with the CM at a pitch angle somewhat less than stable II. To overcome the roll problem, a configuration using three smaller bags, giving a pontoon effect, was tried. The design approach of this configuration was that any two of the three bags must be capable of uprighting the CM; that is, any one of the three bags could fail and not jeopardize the system. Model tests proved this approach to be feasible.

UPRIGHTING SYSTEM DESCRIPTION

The Apollo Program had two generations of command modules: the original design was designated "Block I" and the current design was designated "Block II." The Block I CM differed from the Block II CM in that the Block I CM was designed for earth orbit only and was not designed to dock with any other spacecraft. The upper-deck designs of the two were, therefore, different, which necessitated some changes in the design of the uprighting system.

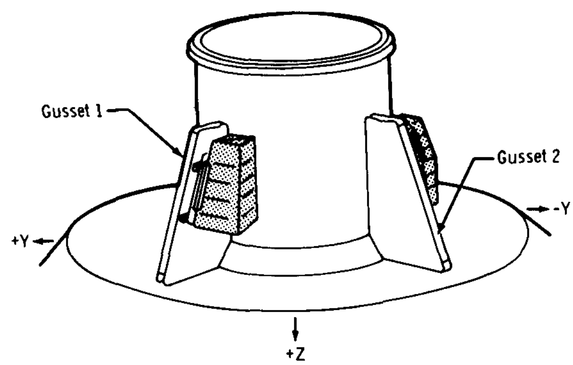
In both Block I and Block II configurations, the system can nominally upright the CM in 5 minutes if both compressors and all three bags are operating. Approximately

12 minutes maximum are required to upright the CM with either a failed compressor or a failed bag. If both a compressor and a bag failed, the system could not upright the CM.

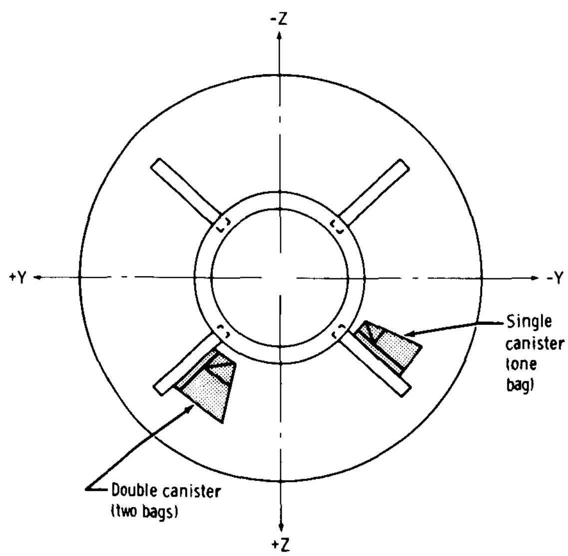
Block I System Configuration and Operation

The Block I uprighting system consisted of three air bags, two air compressors, and the associated plumbing. The following paragraphs describe the major components of the system.

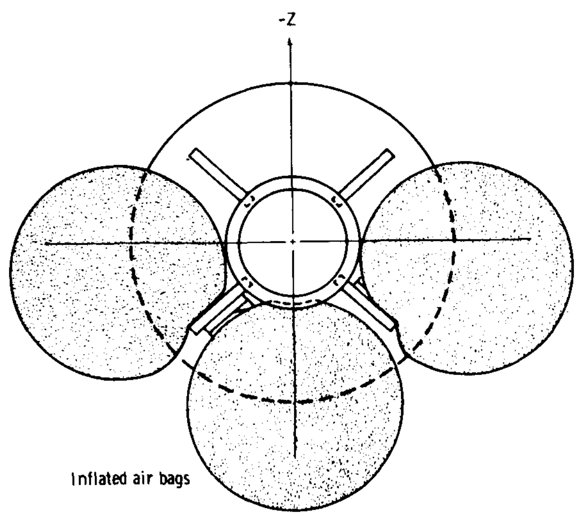
Inflatable bags and canisters. - The Block I uprighting system used three inflatable air bags stowed in two rigid, sheet-metal canisters on the upper deck of the CM (figs. 10 and 11). The bags that deployed into the +Y and +Z bays of the upper deck were stowed in a canister attached to the +Z side of gusset 1. The bag that deployed into the -Y bay was stowed in a canister attached to the -Y side of gusset 2. All three bags were made of Dacron cloth impregnated with polyurethane. Each bag was made from geodesic patches bonded together to form a 43-inch-diameter sphere. The bag operating pressure was 4 psig with a burst pressure greater than 11 psig. The bags were attached to the CM gusset structure by steel cables that attached internally at the "north pole" of the bag and exited near the "south pole" through a sealed grommet. As the bag inflated, the grommet slid down the cable.



(a) Side view, stowed.



(b) Top view, stowed.



(c) Top view, deployed.

Figure 10. - Location of uprighting bags, stowed and deployed, in the Block I configuration.

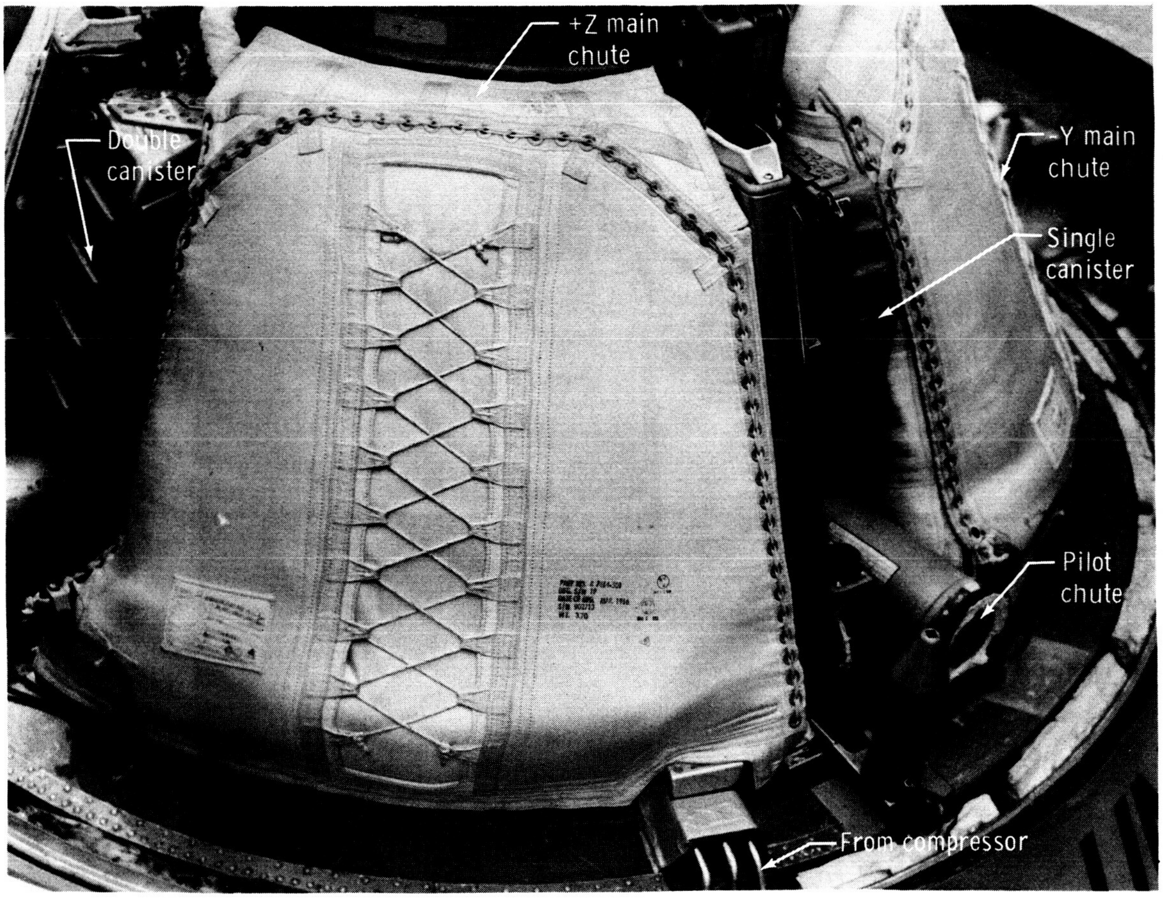


Figure 11. - Block I canister installation.

The bags were packed compactly into canisters by a vacuum-pack process; that is, using ambient pressure to conform the folded bag to the canister mold line by drawing a vacuum on a packing fixture. The canisters were closed by using a special press fixture. This high-density packing was necessary because of the small stowage volume available to the bags on the upper deck. The latching mechanism (fig. 12) on each canister was actuated by the inflation of an air bladder connected to the bag plumbing; therefore, in operation, the canisters released the bags when the air compressors were turned on for bag inflation.

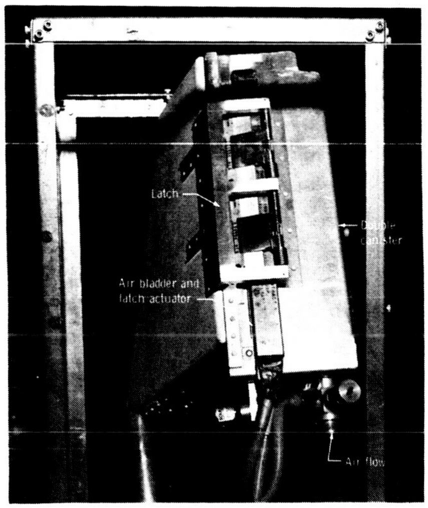


Figure 12. - Bag canister latch mechanism.

Air compressors. - The bags were inflated by electric-motor-driven compressors located between the inner and outer structure of the aft compartment. The first Apollo spacecraft (CSM-009) had only one compressor because of hardware unavailability. The compressor was located near the +Y axis as shown in figure 13. All subsequent spacecraft had a second compressor also located in the aft compartment (near the -Y axis) in mirror image to the +Y compressor. The compressor pump was a positive-displacement type and was mated to the motor to form an integrated assembly. With a nominal 28-V dc power source, the output from each compressor was approximately 5 cfm for an outlet pressure of 10 psig. The compressor was designed to operate for a minimum of 50 hours without maintenance. Also, the compressor was capable of ingesting water through the air inlet for 15 seconds without damage.

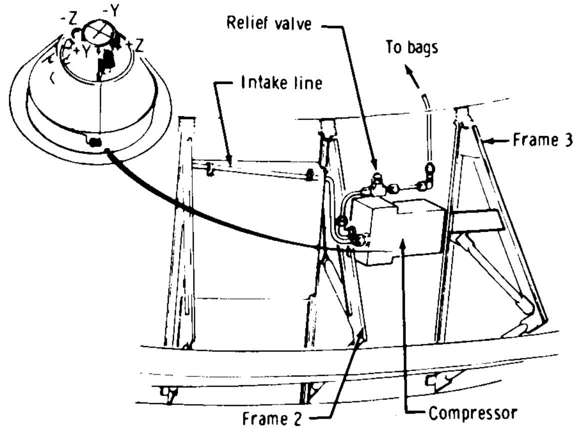


Figure 13. - Uprighting system compressor location (CM-009).

Solenoid valves. - Three solenoid valves (one for each bag) were located on the upper deck gussets (fig. 14). Each valve had three positions (vent, fill, and seal or off) that could be selected manually with control switches in the CM for manned flights or controlled by the logic sequencer for unmanned flights. The vent position was required during launch so that, as the CM gained altitude, the uprighting system plumbing could vent as the outside pressure dropped. This venting prevented any premature actuation of the canister pneumatic latching mechanism and also prevented any pressure buildup in the bags. The fill position was used when bag inflation was desired. The control switches were left in the fill position until the bags were fully inflated and the CM uprighted. The off position was used to seal the bags after inflation.

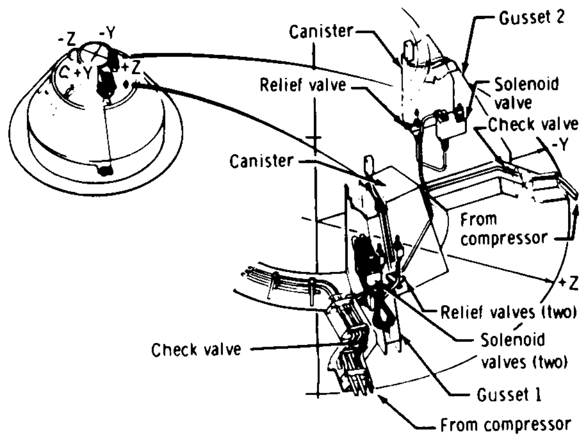


Figure 14. - Uprighting system valve locations.

The compressors were electrically wired to each solenoid valve control switch such that when any switch was placed in the fill position to open the solenoid valve, both compressors would turn on. For the unmanned flights, the control switches were operated by the CM logic sequencer. The inflation command was controlled by an attitude sensing switch that functioned after impact. The attitude switch commanded power to the uprighting system 1 minute after the CM X axis rotated past 70° in the +Z direction or 55° in the -Z direction from the vertical direction.

Plumbing and wiring. - The plumbing for the uprighting system was routed from the compressors to the upper deck between the inner and outer structure. To prevent overinflation, a relief valve was located near each compressor and near the hose connection of each bag (figs. 13 and 14). Also, in the event of a leak, each compressor was isolated from the other by two check valves, one downstream from each compressor, as shown in figure 14. The plumbing schematic diagram is shown in figure 15. The total uprighting system schematic diagram is shown in figure 16.

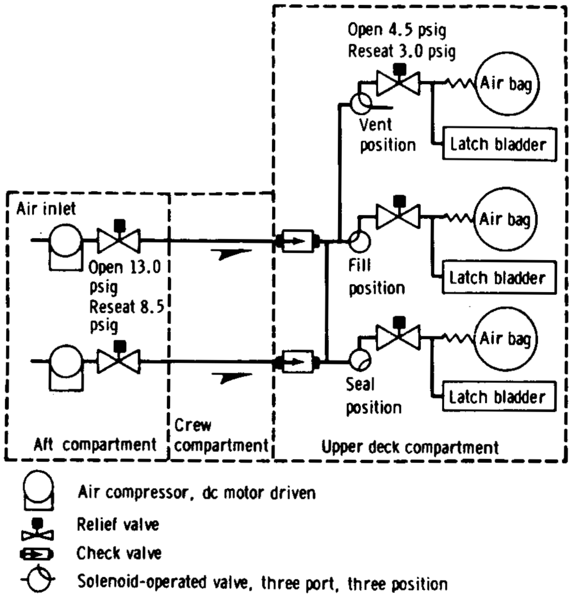


Figure 15. - Uprighting system plumbing schematic diagram.

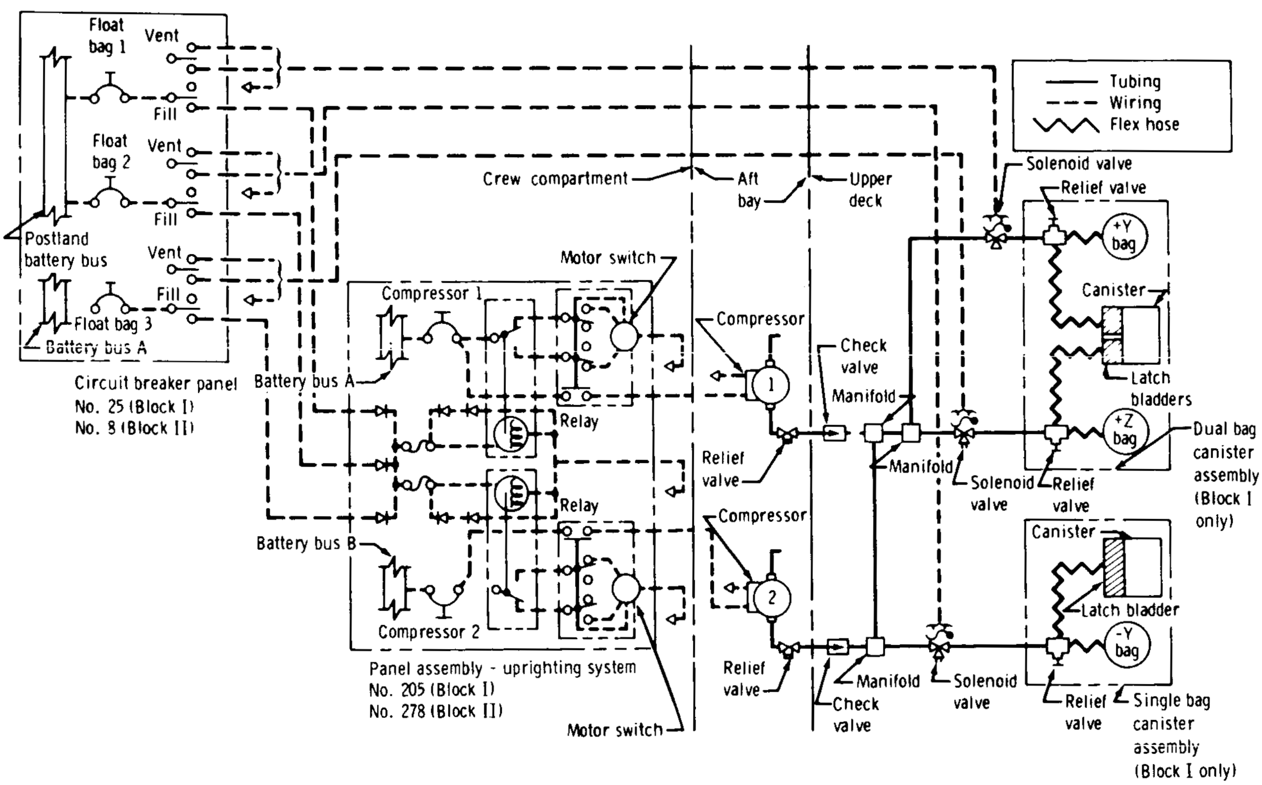


Figure 16. - Uprighting system schematic diagram.

Block II System Configuration

The uprighting system hardware components being used on the present Block II CM are primarily the same as those used for Block I. Specifically, the check valves, relief valves, solenoid valves, and compressors are the same. However, the compressors are located in slightly different positions because of space availability. The diagrams in figures 15 and 16 are the same for Block II except the canisters and latch bladders (discussed in the following section) no longer exist. The only significant design change between the Block I and Block II uprighting system configurations is in the inflatable bags and containers.

Unlike the Block I bag stowage problem of retrofitting into available space, the Block II bag stowage was allocated during Block II upper-deck design. This space allocation allowed a more reasonable stowage location for each bag with respect to tiedown points and ease of inflation. One bag is stowed beneath each of the main parachute packs on the CM upper deck in the particular bay where the bag inflates. In figure 17, a stowed bag is shown before the parachute is installed. The system configuration on

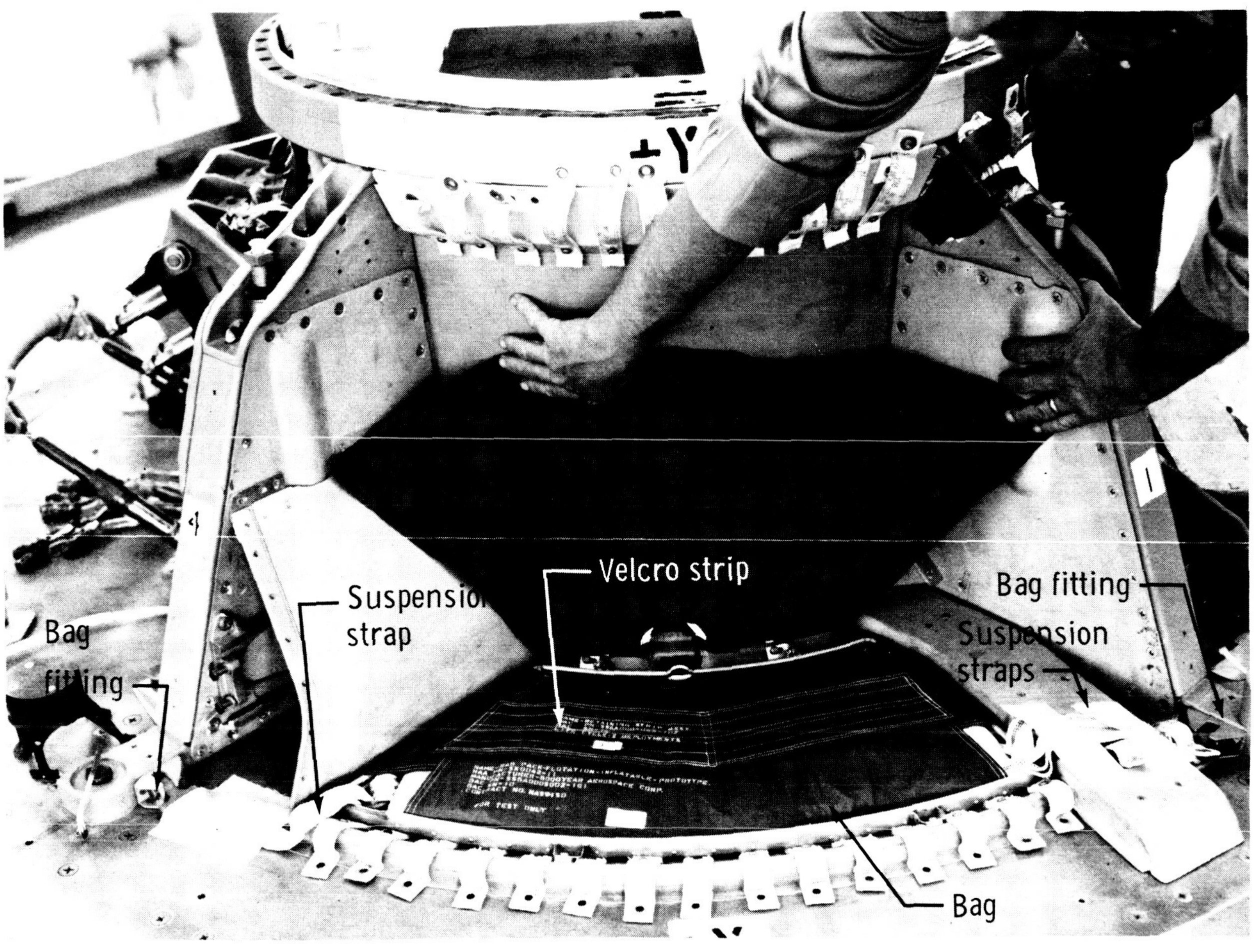


Figure 17. - Stowed +Y bag of Block II uprighting system.

the CM upper deck is shown in figure 18. The parachute pack protects each bag and prevents it from unfolding during preflight and flight operations. Consequently, Block I type protective stowage canisters are no longer needed. Each bag is packed in an irregular shaped "piepan" type metal container having two fabric flaps held closed by a Velcro strip (fig. 17). The Velcro pulls apart when the bag begins to inflate. The skirt being held up in figure 17 is a cover that protects the Velcro strip during parachute deployment.

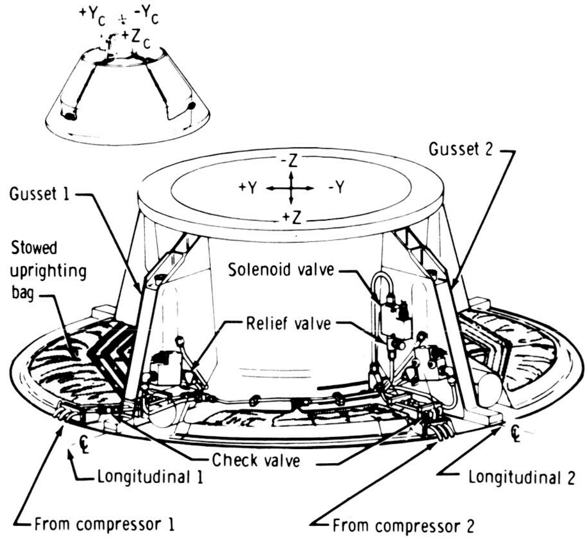


Figure 18. - Block II upper-deck configuration of uprighting system.

As in the Block I uprighting system, the Block II bags are made of Dacron cloth impregnated with polyurethane. Also, the +Y and -Y bags have the same geodesic patch construction to form 43-inch-diameter bags. However, the +Z bag is made with "banana peel" construction to form a 34-inch-diameter bag (fig. 19). The reason for the smaller diameter bag is discussed in a later section. Because of the advantageous stowage locations of the Block II bags, the undesirable feature of the Block I suspension system (that is, the steel cable and the sliding bag grommet) could be eliminated. The Block II bags use a simple suspension system made of Dacron straps attached externally to the bag by a series of fan patches. The straps transmit the bag buoyancy force to structural fittings on the upper deck gussets. Each bag has two fittings. Figure 20 is an underwater photograph showing a typical suspension system under load. Typical locations of the two bag fittings are shown in figure 17.

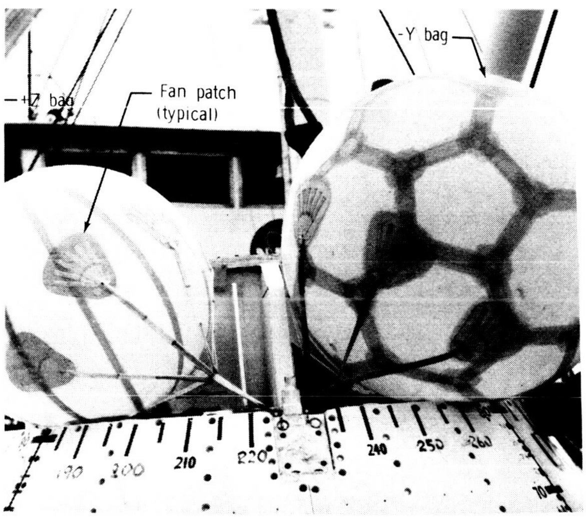


Figure 19. - Block II uprighting bags.

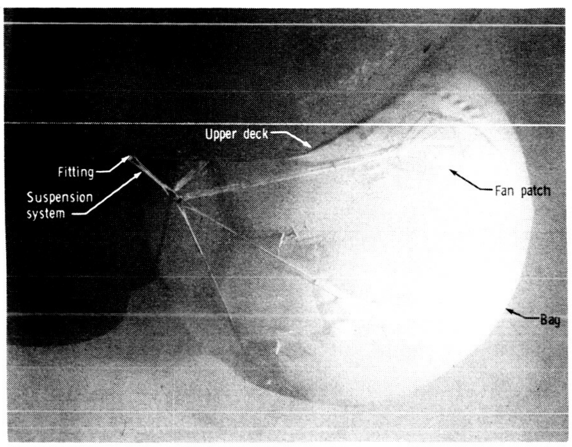


Figure 20. - Typical Block II bag inflated under water at stable II.

DELVELOPMENT TEST PROGRAMS

The performance characteristics of the uprighting systems considered were found to be extremely difficult to predict analytically. For this reason, the investigation of the uprighting system relied primarily on development tests. Tests were performed by the MSC, the prime contractor, and the component vendors. The development test program logic is given in figure 21. The major phases of the programs are discussed in the following sections.

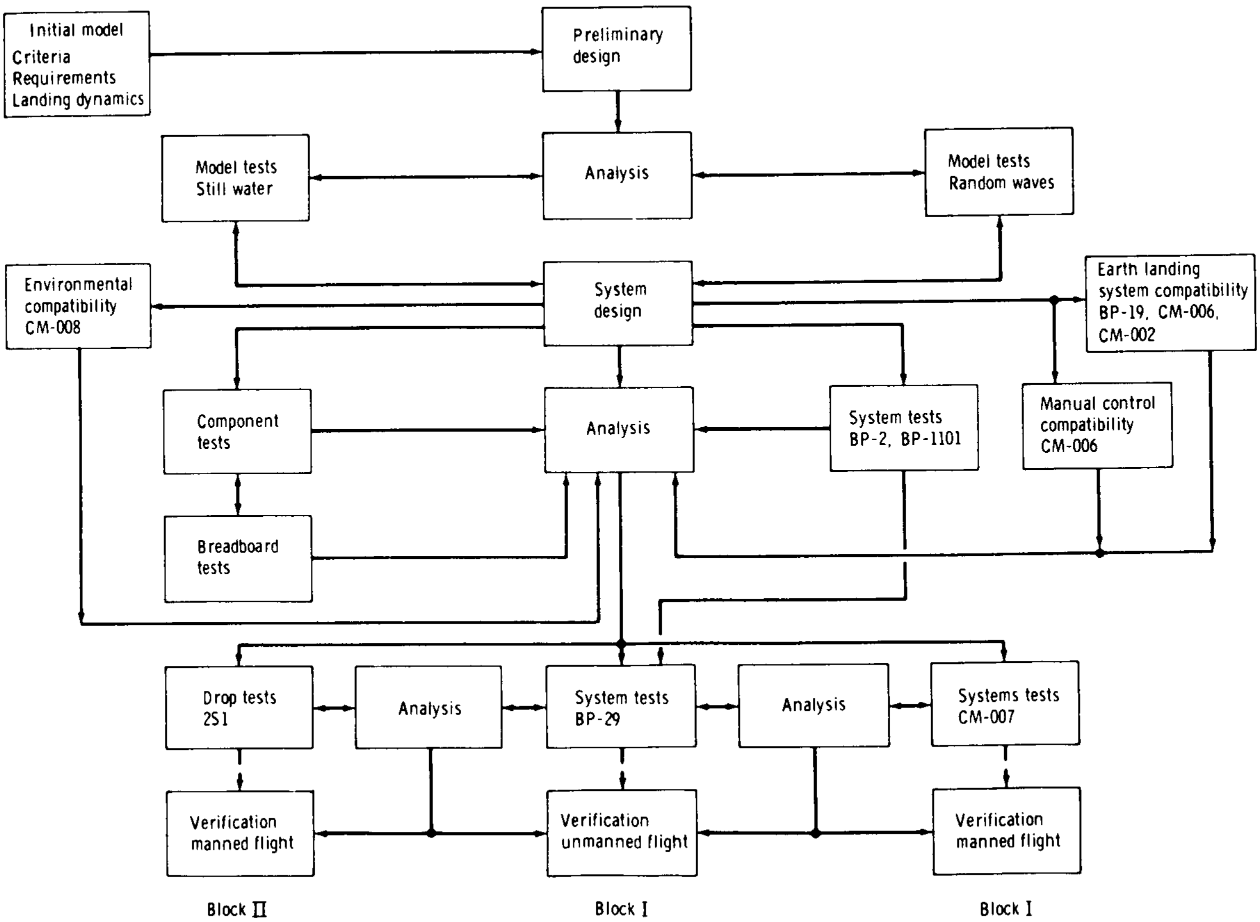
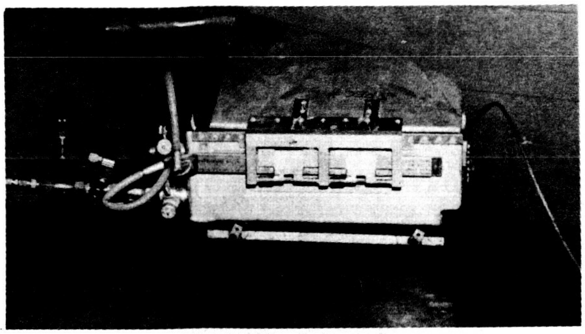


Figure 21. - Command module uprighting system development logic diagram.

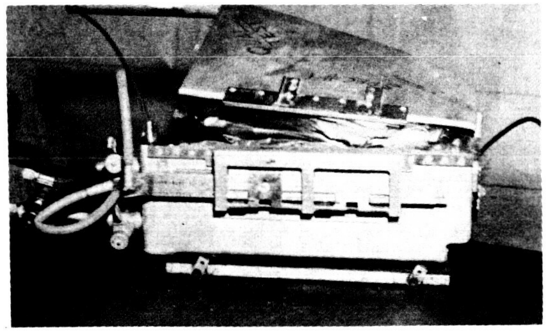
Component Development Tests

Vendor testing was performed on the compressors to establish the water-restrictor valve design and to determine the compressor water-ingestion capability. Several valve configurations were tried until a suitable design was established.

Because of the high packing density required for both the Block I and the Block II stowed bags, extensive tests were conducted to determine an acceptable procedure for packing. Also, tests were conducted to determine the ability of the bags to deploy at initiation of inflation. The tests conducted to determine the sensitivity of the pneumatic unlatching mechanism of the Block I canisters are depicted in figure 22. The Block II bag fan-patch configuration was tested by the vendor for structural capabilities at different pull angles, as shown in figure 23.



(a) Cover engaged.



(b) Cover disengaged.

Figure 22. - Block I canister unlatching test.

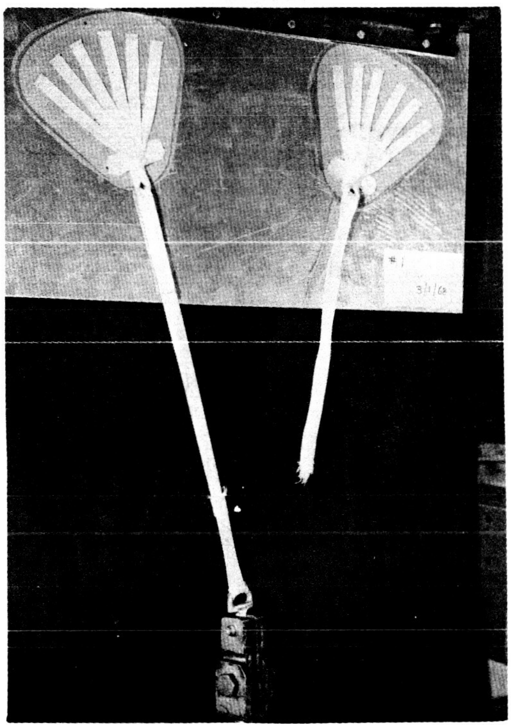


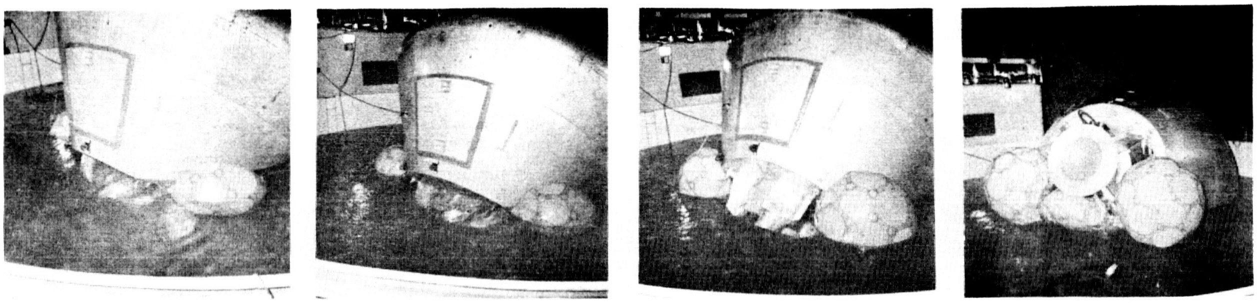
Figure 23. - Fan-patch/suspension-straps test at ultimate loads.

Small-Scale Model Tests

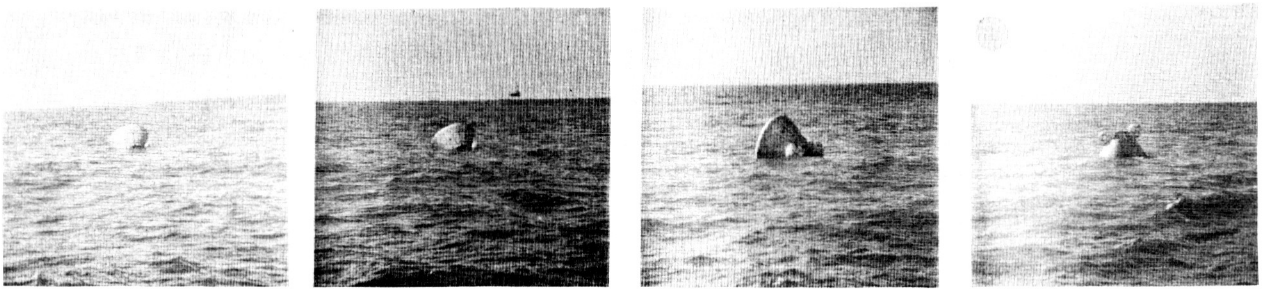
As discussed earlier, scaled models of the CM were used extensively by the prime contractor and the MSC. The models were used initially to define the CM flotation characteristics and later to evaluate the different proposed uprighting concepts. After a concept had been chosen, the prime contractor used its model to determine the best locations for the bag tiedown fittings.

Full-Scale Tests

Full-scale boilerplate tests were used to investigate all facets of the uprighting system. Essentially all the full-scale testing was conducted at the MSC. However, a boilerplate CM (BP-2) was used at the prime contractor test site to investigate the capabilities of the preliminary design. The principal boilerplates used at the MSC to investigate the three-bag uprighting system were BP-1101 and BP-29. These boilerplates were used for tests conducted both in a water tank and at sea (fig. 24). These tests identified most of the design problems with all the different components integrated into a complete system. Most of the changes resulting from these problems are discussed in a later section. Also, the sea tests defined what could be expected of the uprighting system when it was operating in a dynamic environment of wind and waves. The tank tests defined the effect on uprighting as the CM thermal insulation absorbs water. A spacecraft (CM-007) was used in ground testing to qualify all the postflight equipment used in recovery operations; the testing included the uprighting system.



(a) Nominal uprighting (three-bag) in the tank.



(b) A +Z bag failure uprighting at sea.

Figure 24. - Typical uprighting tests with BP-1101.

After all the Block I uprighting tests were completed, the boilerplate vehicles were modified to simulate the Block II design, and most of the uprighting tests were repeated. The modification of each was primarily in the upper deck and tunnel area.

Other test vehicles were used to evaluate the uprighting system. With these vehicles, the uprighting system was subjected to thermal-vacuum tests, water-impact tests, drop tests to verify the stowage compatibility of the uprighting system with the parachute system, and crewmember repositioning tests to determine the feasibility of two crewmen moving from the couches to the aft bulkhead to lower the CM c.g. This crew-movement procedure was found feasible and is used to complement the design changes discussed in a later section.

As a result of the full-scale tests, comprehensive curves have been generated to show the CM uprighting capabilities for any CM landing c.g. location. A plot showing both a three- and a two-bag configuration capability, as a function of the CM landing c.g. location on three axes X_c, Y_c, and Z_c, is depicted in figure 25. Generally, for a typical spacecraft, it is assumed conservatively that Y_c will be -0.5 inch, and the worst-case curve shown in figure 25 is used. A standard curve (fig. 26) is used to ballast any CM, if required, to allow uprighting with two bags after two crewmen have moved to the aft bulkhead. To date, no Apollo spacecraft has had to be ballasted because of uprighting limitations.

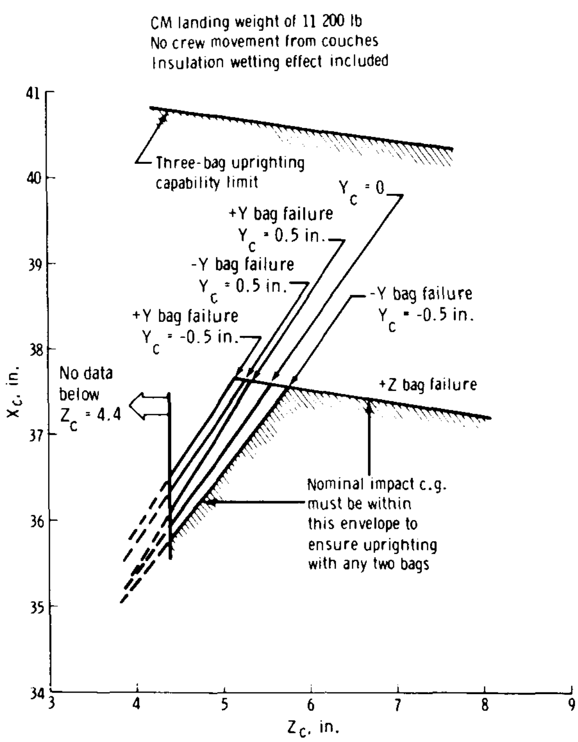


Figure 25. - Apollo Block II CM c.g. limitations of uprighting system.

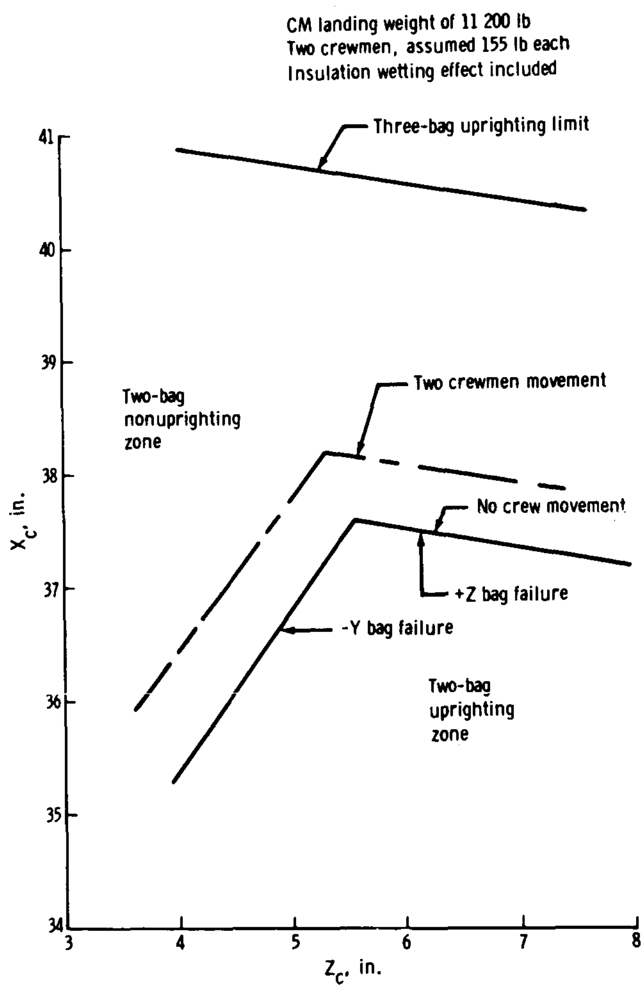


Figure 26. - Standard Apollo Block II uprighting curve.

HARDWARE QUALIFICATION

The uprighting system was qualified for flight by component- and system-level testing of two or more flightlike units at mission environments. Also, each system is required to pass end-item acceptance and checkout tests conducted on the assembled spacecraft.

Except for the bags, all components of the uprighting system were qualified simultaneously for Block I and Block II. Each uprighting system component was qualified by its vendor, and the total system was qualified by full-scale vehicle tests. The major environments in which the components were qualified are presented in table I. The hardware qualification schedule is shown in table II.

TABLE I. - QUALIFICATION OF UPRIGHTING COMPONENTS

Component	Tests conducted												
	Design proof tests											Off-limit tests	
	Acceptance functional	High temperature	Low temperature	Vacuum	Vibration	Shock	Salt	Acceleration	Life	Immersion	Burst	Structural	Water ingestion
Compressor	X	X	X	X	X	X	X	X	(a)	X			X
Relief valve	X	X	X	X	X	X	X	X	(a)				
Check valve	X	X	X	X	X	X	X	X	X	X			
Solenoid valve	X	X	X	X	X	X	X	X	X	X			
Canister	X	X	X	X	X	X	X	X	X	X		X	
Bladder	X	X	X	X	X	X		X	X	X	X		
Uprighting bags	X	X	X·	X					X	X	X		

[a]No separate life test-operational cycling is accumulative during performance of environmental tests.

TABLE II. - SCHEDULE FOR QUALIFICATION OF UPRIGHTING COMPONENTS AND SYSTEMS

Test	1965												1966											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Components																								
Compressor															X	X	X	X						
Relief valve (high and low pressure)													X	X	X									
Check valve												X	X	X	X									
Solenoid selector valve							X	X																
Canister															X	X	X							
Bladder canister										X	X	X	X											
Uprighting bags[a]						X	X	X	X	X	X	X	X											
Systems																								
BP-29 qualification test of CM-009 system											X													
BP-29 qualification test of CM-011 test																		X						
CM-007 Block I qualification test (manned vehicle system)																						X		

[a]Block I configuration; Block II bags were qualified by July 1968.

MISSION PERFORMANCE

The Apollo spacecraft uprighting system has been flown on 13 missions (table III): four on Block I spacecraft and nine on Block II spacecraft. On five of these missions, the uprighting system was required to upright the CM from the stable II position.

Block I Performance

At landing, all of the Block I command modules purposely had relatively low c.g., and the probability of the vehicle coming to rest in stable II was small. The Block I mission performance of the uprighting system substantiates this c.g. position because the system was required to operate only once (CM-020) during the Block I program (as shown in table III). Also, because CM-020 had a low c.g., the vehicle was uprighted by wave dynamics and very little air in the bags. The CM uprighted approximately 58 seconds after the compressors turned on. The bags partially became inflated (fig. 27) because, as programed, the compressors were turned off again at uprighting by an attitude switch in the CM logic sequencer.

TABLE III. - MISSION PERFORMANCE OF THE UPRIGHTING SYSTEM

Mission		CM number	Landing attitude	
			Stable I	Stable II
Block I	AS-201	009	X	
	AS-202	011	X	
	Apollo 4	017	X	
	Apollo 6	020		X
Block II	Apollo 7	101		X
	Apollo 8	103		X
	Apollo 9	104	X	
	Apollo 10	106	X	
	Apollo 11	107		X
	Apollo 12	108		X
	Apollo 13	109	X[a]	
	Apollo 14	110	X	
	Apollo 15	112	X	

[a]Bags were inflated by crew choice.

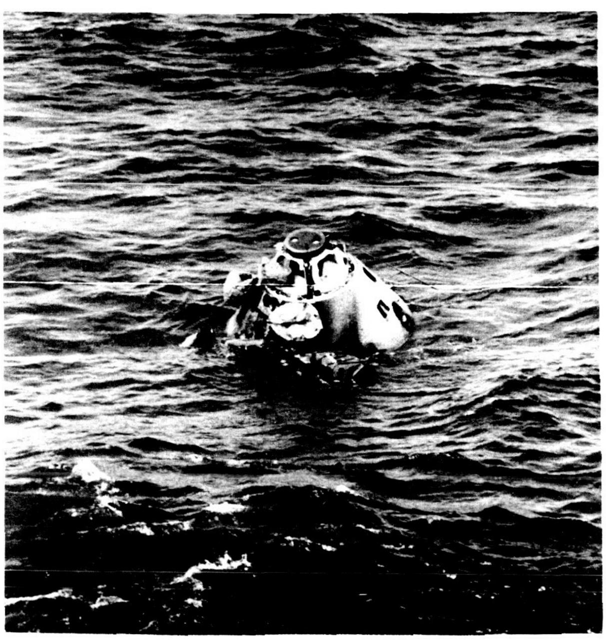


Figure 27. - Apollo 6 spacecraft (CM-020) after uprighting.

Block II Performance

The Block II spacecraft were much less stable during water landing than the Block I spacecraft, as can be seen in table III. This lack of stability is attributed to the higher c. g. locations at landing for Block II spacecraft. All the Block II CM landing centers of gravity and attitudes are plotted on the uprighting capability curve shown in figure 28; also shown for reference is the c. g. of CM-020 (Block I).

All four of the Block II spacecraft that went to stable II were uprighted by three bags in approximately 5 minutes (nominal), and no problems with the system were encountered. A photograph of the Apollo 11 spacecraft just after uprighting is shown in figure 29.

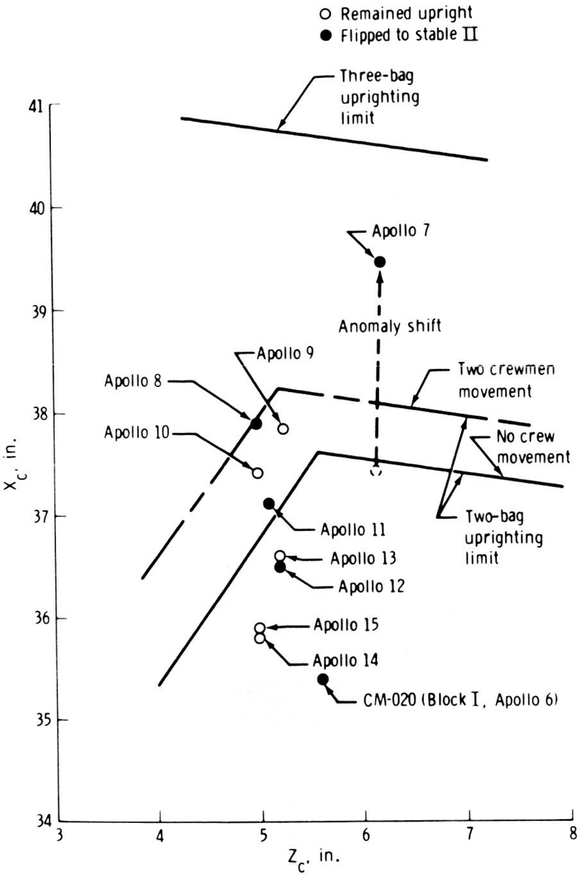


Figure 28. - History of Apollo CM landing c.g. locations and landing attitudes.

Figure 29. - Apollo 11 spacecraft after uprighting.

One anomaly associated with the Apollo 7 CM would have prevented an uprighting if one of the three bags had failed. While the vehicle was in the stable II, water seeped through a faulty hatch valve, and the tunnel was flooded with approximately 400 pounds of water. As can be seen in figure 28, this flooded tunnel adversely affected the CM c.g.; however, because all three bags inflated, the vehicle uprighted. The hatch-valve design was changed for all subsequent spacecraft.

SIGNIFICANT DESIGN CHANGES

Several significant design changes have been made in the uprighting system since its inception. These changes were caused either by vehicle weight and c.g. changes or by weaknesses identified by development testing.

Block I Design Changes

All the Block I uprighting system design changes resulted from failures that occurred during hardware test programs, which were discussed previously. Most of the problems were identified after production of the hardware had started, and in some cases, after the hardware had been used in flight. The required changes resulted in the uprighting systems used on the first two command modules not being of the same configuration as used for subsequent vehicles. The following is a brief listing of the significant changes.

1. The bag fill hose was reinforced to prevent kinking during bag deployment.

2. The bag fittings on the gussets were changed from aluminum to stainless steel to prevent recurrence of breakage.

3. The bag cables were changed to larger diameter cables to be compatible with the measured loads, and each cable end fitting was made a universal swivel.

4. The Y bags were changed from a two-cable and two-grommet configuration to a single cable and single grommet design to allow easier movement of the grommet down the cable.

5. One of the two +Z bag cable fittings was moved to the top of the gusset (off the upper deck, as in fig. 30) to force the bag into a better position after inflation.

6. The +Z bag cables were shortened and were restrained in place during the first part of inflation by using tape bonded to the CM tunnel (fig. 30) to ensure that the bag stayed in the upper deck area at the start of inflation.

7. The bag metal grommets were strengthened to prevent bending under the load and subsequently causing bag failure.

8. The +Y bag (stowed in the +Z bay) was attached to a loaded spring (fig. 31) to ensure bag deployment into the +Y bay at the time of canister opening. Previously, the +Y bag would sometimes stay in the +Z bay and foul the +Z bag.

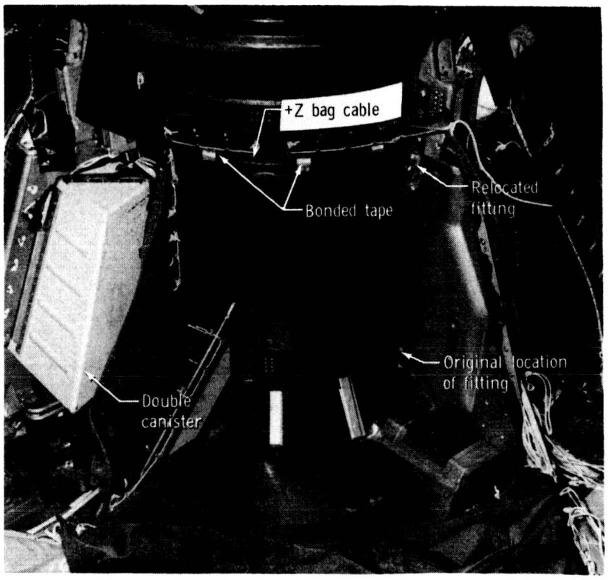


Figure 30. - Block I +Z bag restraint system.

9. The compressor intakes were relocated to prevent excessive water ingestion if a Y bag failed.

10. The bag stowage canisters were reinforced to accept loads that could be induced by wraparound of a parachute riser during parachute deployment.

11. For unmanned flights, the control sequencer was changed from sequential bag inflation (timer allowed 5 minutes per bag) to simultaneous inflation (total inflation time, 15 minutes). This change was required to prevent excessive wave dynamic loads on the first sequenced bag cables. With simultaneous inflation, the bags shared the load.

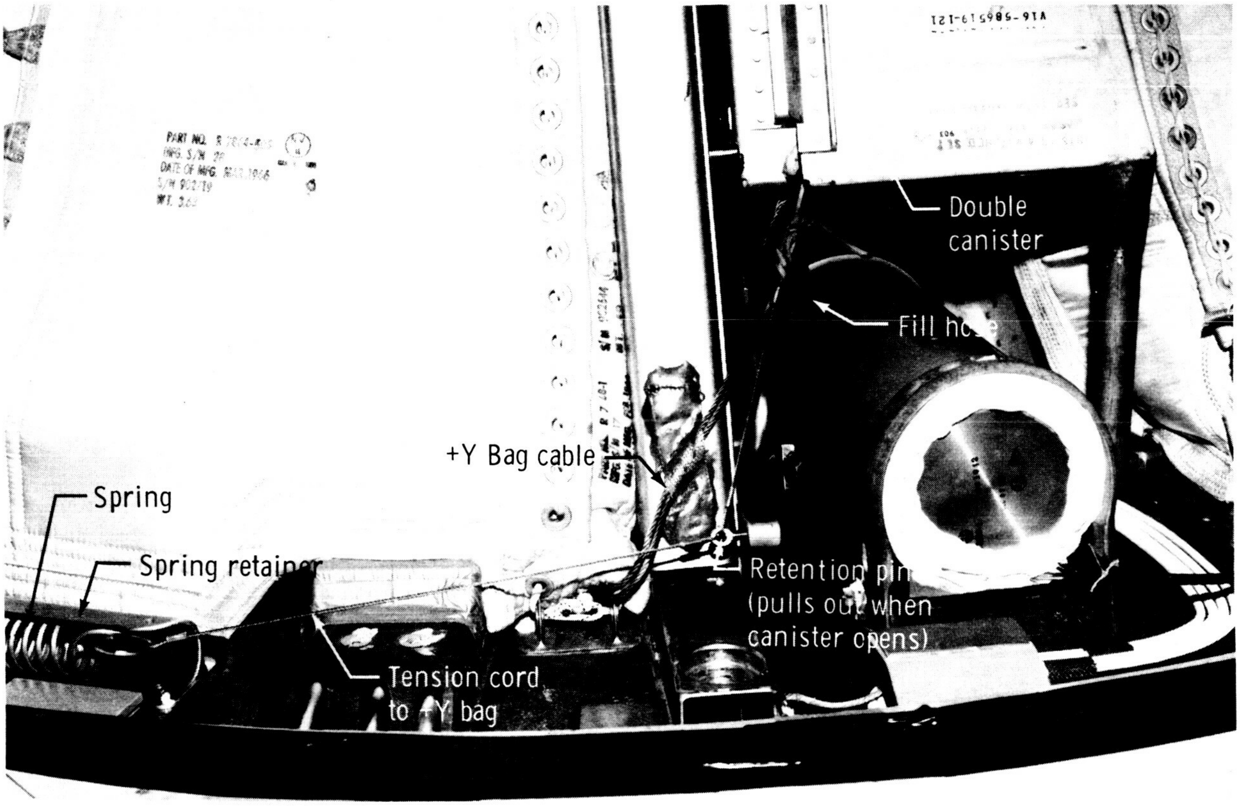


Figure 31. - Block I +Y bag repositioning spring.

12. The required change in the control sequencers was discovered too late to be implemented on CM-011 without severe schedule impact. Therefore, a restrictor orifice was placed downstream from each compressor (on CM-011 only) to prevent full inflation of each bag at 5 minutes by causing the relief valve to crack. The soft bag could act as a shock attenuator in sea dynamics. Different size orifices were checked on CM-011 until the predetermined pressure at 5 minutes was obtained in a test bag. However, this orifice configuration would not allow for a compressor or bag failure and still ensure an uprighting. The CM did not go to stable II, and the upright system was not used in this Block I mission.

Block II Design and Procedure Changes

As discussed in an earlier section, the Block II uprighting system is a simpler configuration than the Block I system because the Block II system was included in the upper deck design rather than being retrofitted. Only one significant design change has been made in the Block II uprighting system. As a result of the Apollo CM postfire-redesign effort, the CM weight increased significantly. This redesign created a critical situation with respect to increased lift-off weight and parachute-hang weight. To alleviate the situation, the program office decided to remove approximately 500 pounds of ballast from the CM. However, an overall weight increase and a c.g. shift resulted from the redesign. The weight increase and c.g. shift caused the CM to be incapable of uprighting from stable II if one bag failed. No such problem occurred if all three bags inflated. The net changes in weight and c.g. location corresponded to a reduction of the nominal entry L/D from 0.32 to 0.28.

In full-scale performance definition tests at the MSC, the uprighting capability of the CM was determined to be marginal with two Y bags inflated; if the bags had been held tighter in their respective bays, uprighting would have occurred. However, a Y/Z bag combination resulted in a roll of the CM about its X axis to a new stable position where uprighting did not occur.

Development tests were conducted at the MSC to investigate different suspension systems for the bags and to investigate smaller sized +Z bags (30- and 34-inch diameter) to reduce the roll problem but yet provide enough buoyancy to cause uprighting. Also, tests were performed to determine the feasibility of two crewmen moving from the couches to the aft deck to lower the c.g. As a result of these tests, the uprighting system was redesigned to provide uprighting capability with any two bags and with two crewmen moving aft.

The bag design changes are listed as follows.

1. All bags had the fan patches relocated and the corresponding suspension straps shortened to cause the inflated bags to be held tighter in the bays (fig. 32). The shorter straps necessitated an improvement in the bag packing procedure so that the straps could reach the CM fittings during bag installation on the upper deck.

2. The suspension strap material was changed from nylon to Dacron to reduce the stretch of the straps under dynamic loading.

3. The +Z bag was reduced in size from 43 to 34 inches in diameter to achieve less roll of the CM while inflating only one Y bag and the +Z bag.

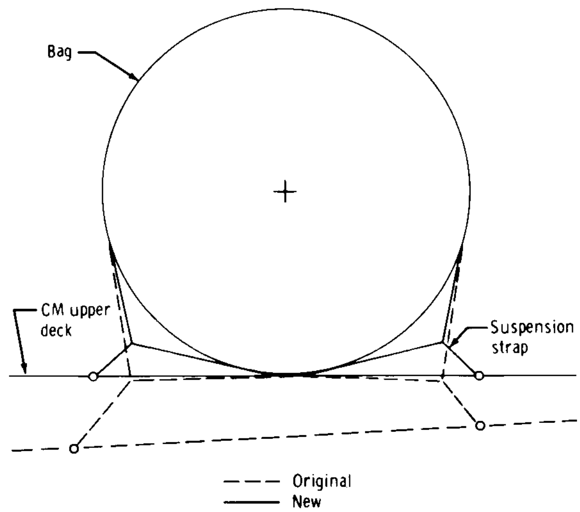
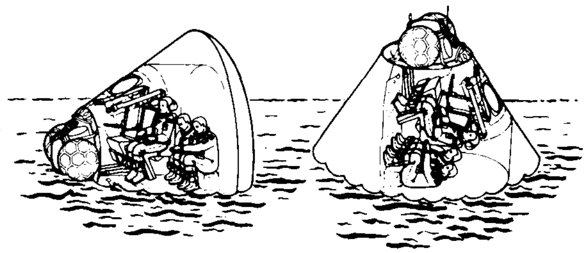
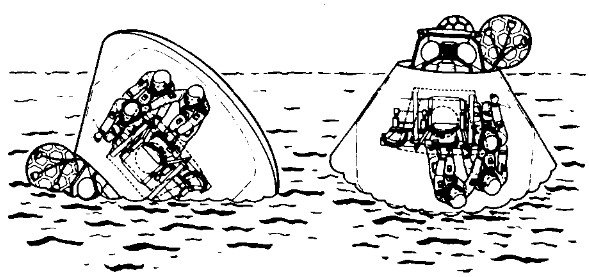


Figure 32. - Typical Block II suspension configuration change.

These changes, coupled with the crew-movement technique, met the new L/D requirements and allowed the uprighting system to fulfill its design requirements. The crew-movement technique and its effects are shown in figures 33 and 34.



(a) For a failed Z bag.



(b) For a failed Y bag.

Figure 33. - Crew relocation from couches to aft bulkhead to aid in failed bag uprighting.

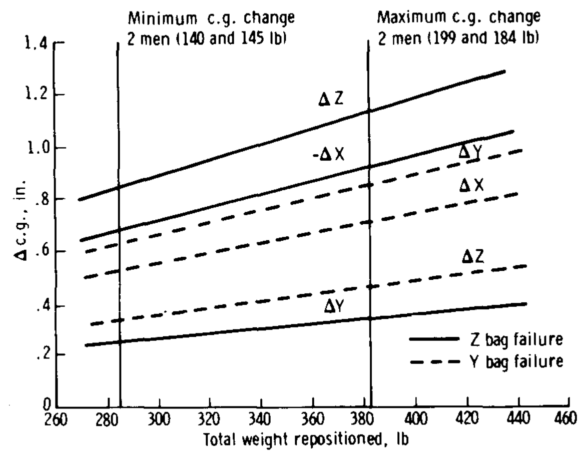


Figure 34. - The effective change in the CM c.g. when two crewmen move from couches to aft bulkhead to aid uprighting after a bag failure.

CONCLUDING REMARKS AND RECOMMENDATIONS

During the Apollo command module Block I development and testing of the uprighting system, the problems encountered caused concern about system reliability. The concern was not unwarranted because the severe constraints and schedule placed on the system design caused many compromises that adversely affected the performance capability of the system. However, the Block I uprighting system was eventually qualified for manned flights. The Block II uprighting system did not have as many design problems, and therefore, confidence in the system increased after the first two Apollo manned flights uprighted perfectly.

Although the Apollo command module has a satisfactory uprighting system, the system could have been optimized had it been developed together with the basic command module structural design. If water landing is a landing mode for future spacecraft, difficulties can be precluded in the selection, design, and testing of an uprighting or flotation system by use of the following recommendations.

1. Investigate and understand the vehicle flotation characteristics and limitations as early in the design phase of the vehicle as practical.

2. In the system design, anticipate significant changes in the vehicle mass properties, particularly in the center-of-gravity location and weight, as the program advances.

3. Integrate the system with the initial design of the spacecraft rather than retrofitting into the design.

4. Design all test vehicles or boilerplates to represent the flotation characteristics of the spacecraft accurately to avoid contradictory data, and design for easy manipulation of the simulated weight and center of gravity during tests.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, October 16, 1972
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