NASA TECHNICAL NOTE

NASA TN D-7780

NASA TN D-7780

APOLLO EXPERIENCE REPORT - SPACECRAFT STRUCTURE SUBSYSTEM

by P. D. Smith

Lyndon B. Johnson Space Center
Houston, Texas 77058

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TND-7780		

4. Title and Subtitle

APOLLO EXPERIENCE REPORT
SPACECRAFT STRUCTURE SUBSYSTEM

5. Report Date

OCTOBER 1974

6. Performing Organization Code

7. Author(s)

P. D. Smith, JSC

8. Performing Organization Report No.

JSC S-400

10. Work Unit No.

914-50-31-00-72

9. Performing Organization Name and Address

Lyndon B. Johnson Space Center
Houston, Texas 77058

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Note

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

The JSC Director waived the use of the International System of Units (SI) for this Technical Note, because, in his judgment, the use of SI Units would impair the usefulness of the report or result in excessive cost.

16. Abstract

The flightworthiness of the Apollo spacecraft structure was verified primarily through a rigorous, vehicle level, ground test program and flight tests. The failures and anomalies encountered during this testing were the major factors considered in determining necessary modifications to the basic design of the spacecraft structure. In this report, these failures, their causes, and their resolutions are discussed. A description of the spacecraft structure and discussions of the ground and flight test programs are presented.

17. Key Words (Suggested by Author(s))

- Apollo Spacecraft
- Structural Design
- Structural Failure
- Structural Engineering
- Ground Tests
- Flight Tests

18. Distribution Statement

STAR Subject category: 31.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None	60	$3.75

APOLLO EXPERIENCE REPORT EDITORIAL COMMITTEE

CONTENTS

Section	Page
SUMMARY	1
INTRODUCTION	1
DEVELOPMENT OF STRUCTURE	3
STRUCTURAL DESCRIPTION	4
Block I	4
Block II	10
TEST DESCRIPTION	14
Block I	14
Block II	23
SIGNIFICANT PROBLEM AREAS	25
Block I Ground Test Anomalies	25
Block II Ground Test Anomalies	29
Flight Anomalies	32
CONCLUDING REMARKS	34
REFERENCES	35
APPENDIX A — DEVELOPMENT TESTS SUMMARY	36
APPENDIX B — COMPONENT TESTS SUMMARY	43
APPENDIX C — COMPLETE MODULE TESTS SUMMARY (BLOCK I)	47
APPENDIX D — DYNAMIC TESTS SUMMARY	49
APPENDIX E — STATIC STRUCTURAL TESTS SUMMARY (BLOCK II)	51

TABLES

Table		Page
I	APOLLO CM DESIGN CHANGES FOR WATER IMPACT	17
II	APOLLO BOILERPLATE FLIGHT HISTORY	18
III	BOILERPLATE CONFIGURATIONS	19
IV	SPACECRAFT 011 AND 012 CONFIGURATION DIFFERENCES	22

FIGURES

Figure		Page
1	Block I spacecraft configuration	2
2	The LES assembly	4
3	The LES structure	4
4	The LET structure and insulation	5
5	Block I CM boost protective cover	5
6	Block I CM heat shield	6
7	Block I CM inner structure	6
8	Block I CM inner shell	6
9	Block I service module	8
10	Block I SM general arrangement	8
11	The CM/SM interface	9
12	Spacecraft/lunar module adapter	9
13	Adapter panel separation lines	10
14	Structural stiffener	10
15	Block II integrated stations and axes	11
16	Block II boost protective cover	11

Figure		Page

17 Block II CM heat shield 12

18 Block II CM inner structure 12

19 Block II service module 13

20 Block II SM general configuration 13

21 Honeycomb splice joint 33

APOLLO EXPERIENCE REPORT

SPACECRAFT STRUCTURE SUBSYSTEM

By P. D. Smith
Lyndon B. Johnson Space Center

SUMMARY

In July 1961, NASA distributed to potential contractors the original Apollo spacecraft development statement of work containing the basic ground rules for design of the Apollo spacecraft. A contractor was selected to design, develop, and fabricate the launch escape system, command module, service module, and spacecraft/lunar module adapter. Structural development progressed from the basic ground rules outlined in the statement of work through development testing to obtain design information, through component tests, and then into static and dynamic tests of full-size modules and combined modules. Concurrently with the ground testing, boilerplate vehicles were manufactured and flown to obtain data during abort and normal boost flights. These data were then used in the design and testing of spacecraft modules.

This report discusses the structural evaluation from the awarding of the contract through ground and flight tests to the time of the first lunar landing mission in July 1969. The spacecraft modules are described, and ground and flight tests having structural significance are discussed as well as anomalies occurring during the ground and flight tests.

The conclusions reached in this report are that rigorous test programs are needed to uncover any weakness in structural design or manufacturing defects; that care should be exercised in the design and inspection of honeycomb sandwich construction; and that extreme care should be taken to assure that correct boundary conditions are imposed on the component during testing.

INTRODUCTION

The Apollo spacecraft structure has five modules: the command module (CM), the service module (SM), the lunar module (LM), the spacecraft/lunar module adapter (SLA), and the launch escape tower (LET). The structure of the LM is discussed in a separate report, but the structural systems of the other modules are discussed in this report.

The Apollo structural subsystem consists of the primary structural framework, the structural shell, mounts for tanks and engine, and a support structure for equipment and electrical and plumbing lines. The CM boost protective cover (BPC) and the CM/SM fairing are also part of the structural subsystem.

The Apollo structure evolved in two phases referred to as Block I and Block II. When the spacecraft design began, the concept of a lunar orbit rendezvous (LOR) mission had not been approved; therefore, the CM was not designed to dock with another vehicle. The first phase of the vehicle design (denoted Block I) was well underway when it was decided to proceed with an LOR mission. The most practical approach was to continue the Block I design effort and test program and to provide docking hardware and other changes to the spacecraft later. The vehicle configuration that included the docking hardware was designated Block II. The Apollo Block I spacecraft configuration is shown in figure 1.

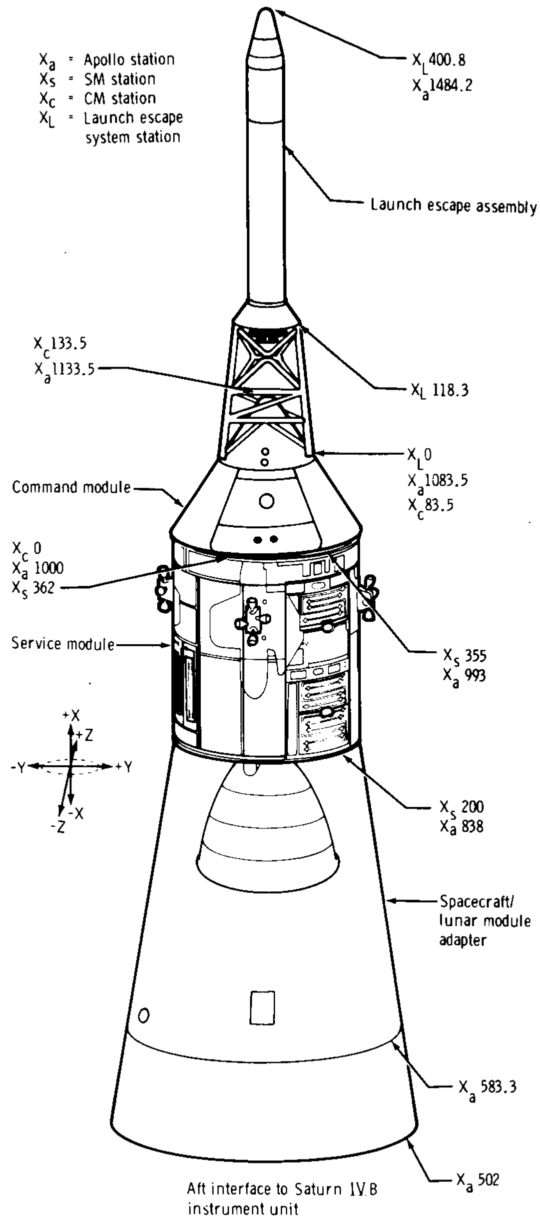


Figure 1. - Block I spacecraft configuration.

The development plan for the structural subsystem specified that the structural elements would be designed based on the maximum flight load conditions and on the worst-case environmental conditions expected during the mission. These loads and environmental conditions were changed continually as they were defined more accurately. Development tests were conducted on the elements and subassemblies of the spacecraft to verify the basic techniques used for analysis, design, and manufacturing. Wherever possible, well-known and reliable design techniques, types of structures, and structural materials were used to avoid extensive development. The Apollo Program was the first spacecraft program in which extensive use was made of large, bonded, honeycomb sandwich panels as a primary load-carrying structure.

The flightworthiness of the Apollo spacecraft structure was verified primarily through a rigorous, vehicle level, ground test program. This ground testing was supplemented by flight tests and a formal loads and stress analysis. The problems involved in developing and verifying the structural subsystem and the manner in which these problems were resolved are discussed. Because verification of the structural design was accomplished mainly by ground testing, the failures and anomalies encountered during this testing were the primary factors considered in determining the modifications to the basic structural design. These anomalies and their resolutions are discussed and a detailed description of the spacecraft structure is contained in this report. The ground and flight tests are also described.

DEVELOPMENT OF STRUCTURE

The Apollo statement of work (SOW) contained the ground rules for design of the structure, described the basic functions of the spacecraft (SC), and specified that the structural subsystem would be designed to protect the crewman and the equipment from meteoroids, radiation, and thermal extremes. In addition to normal flight loadings, the structure would be designed to withstand (1) tumbling of the escape vehicle at maximum dynamic pressure during launch, (2) an entry acceleration of 20g measured along the axis of symmetry, and (3) aerodynamic noise emanating from the launch escape system (LES) during both the launch and escape modes.

The development plan contained the following milestones: basic concept design, determination of external and internal loads, analysis of the structure for these internal loads, development of materials and processes, development testing, verification testing and analysis in lieu of testing, major ground tests, and flight tests. Development of the baseline structural configuration of the spacecraft began with established mission requirements, progressed into functional requirements, and then evolved into a design concept. Trade-off studies were conducted to establish the proper design approach. Changes to the basic configuration resulted from design improvements and from deficiencies discovered during analysis of ground and flight test data. Additional requirements for modifications were determined during manufacturing, installation, design reviews, and stacking (joining of modules) of the flight article.

The Block I spacecraft was certified partly by a formal loads and stress analysis. Beginning in 1967, a complete, formal structural analysis for Block II was prepared using SC-103 as a baseline vehicle (ref. 1). Data on the most recent external and internal loads, on vibration and thermal environments, and on the latest design weights and trajectories were used. Changes to the flight characteristics and the weight of the launch vehicle, as well as data obtained from instrumented spacecraft flight vehicles, were incorporated into the analysis of the Block II design. In addition to baseline analysis, loads for each subsequent mission were compared to baseline loads, and any new structural modifications were analyzed.

The testing of the Apollo structure was planned so as to ensure against uncertainties in design and fabrication. Development tests were conducted to obtain basic design information before assembly testing. Components were then tested to verify the design concept. Complete modules were tested to verify design strength and to establish the confidence needed to proceed with flight tests. The plan used in the testing of major modules was to test all critical loading conditions where practical. When loads were multidirectional, a sufficient number of selected conditions to verify the structural strength were tested. When both thermal and mechanical stresses were present, heat was applied or mechanical loads were increased, where practical, to account for thermal effects. This ground test program identified areas that needed to be modified and provided confidence that the structure could withstand the design environment.

STRUCTURAL DESCRIPTION

Block I

This section describes the structural subsystems as designed originally. Modifications to this original design are discussed in chronological order.

Launch escape system. - The LES is designed to propel the CM away from the remainder of the spacecraft and booster during an abort from the launch pad through the early portion of the second-stage boost when the LES is jettisoned. The LES configuration is illustrated in figures 2 and 3. The LES includes the nose cone, canard assembly, pitch control, launch escape and tower jettison motors, structural skirt, tower structure, tower/CM separation assembly, BPC, and forward heat shield separation and retention assembly. However, only the tower, structural skirt, and BPC are considered part of the structural subsystem.

The LET assembly is a truss made of welded titanium tubing with fittings at the ends for attachment to the structural skirt and CM (fig. 4). The tower is insulated to protect it from aerodynamic heating and impingement from the launch escape motor plume.

The structural skirt is a truncated cone that distributes the loads among the four tower attach points to the launch escape motor. The forward ring of the skirt mates with a flange on the aft end of the motor (fig. 3). The skirt assembly is made of titanium and is protected from aerodynamic heating and impingement from the launch escape motor plume by an ablative coating.

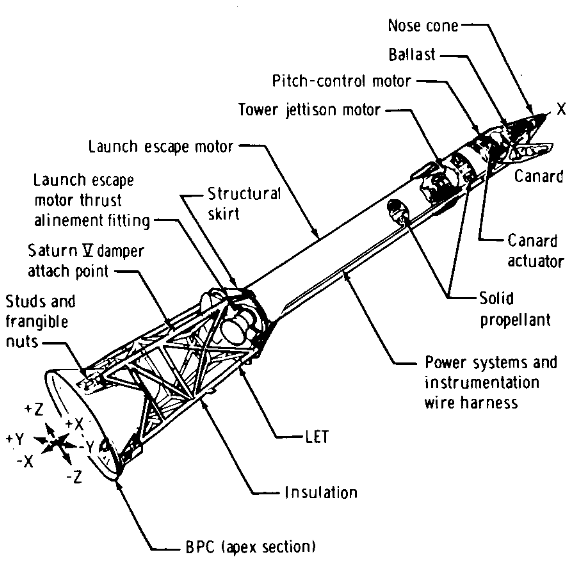


Figure 2. - The LES assembly.

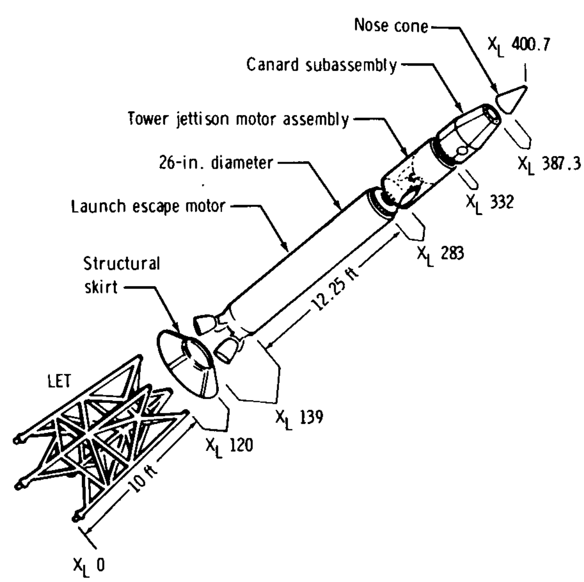
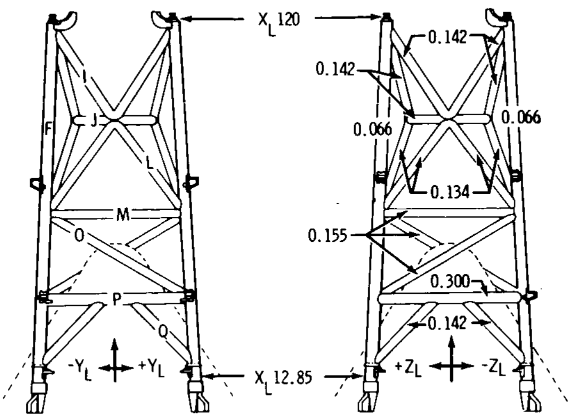


Figure 3. - The LES structure.



Tube J: 2.5-in. outside diameter, 0.15-in. wall
Tubes I, L, M, O, Q: 2.5-in. outside diameter, 0.05-in. wall
Tubes F, P: 3.5-in. outside diameter, 0.125-in. wall

Dimensions denote ablative material thicknesses in inches

Figure 4. - The LET structure and insulation.

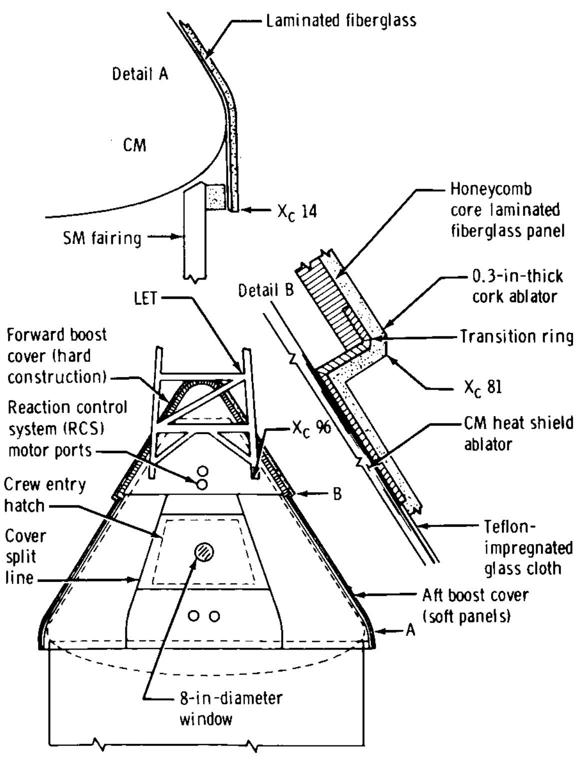


Figure 5. - Block I CM boost protective cover.

The BPC protects the CM from damage caused by aerodynamic heating during the boost phase or by launch escape motor plume heating in the event of an abort. It is attached to the LES tower and is jettisoned with the LES. The BPC (fig. 5) consists of the following three basic assemblies.

1. The forward cover is a conical-shaped hard cover that extends from station X_c 81 forward to the apex of the spacecraft. It is connected to the LET at station X_c 96. The hard cover is made of 0.69-inch-thick fiberglass honeycomb sandwich material and has a coating of cork bonded to the outer surface.

2. The flexible aft cover is designed so that it drapes over the CM heat shield. It extends from station X_c 81 to station X_c 14 and is made of three layers of material: an inner layer of glass fabric impregnated on the inner surface with Teflon, a center layer of 0.0095-inch-thick Nomex fabric, and an outer layer of 0.3-inch-thick cork.

3. The hatch panel covers the CM hatch and is made of fiberglass honeycomb sandwich material with a layer of Armalon bonded to the inside surface. A window permits crew visibility from inside the CM.

Command module heat shield. - The CM heat shield encloses the inner structure and consists of the forward, crew compartment, and aft sections (fig. 6). The heat shield is constructed of ablative material bonded to brazed PH 14-8 steel honeycomb panels. The forward section is conical, extends from station X_c 81 to station X_c 133, and houses the Earth-recovery system and two reaction control system (RCS) pitch engines. It is jettisoned before landing to permit deployment of the parachutes. The crew compartment continues the conical shape and extends from station X_c 81 to station X_c 23. The crew compartment heat shield is attached to the inner structure

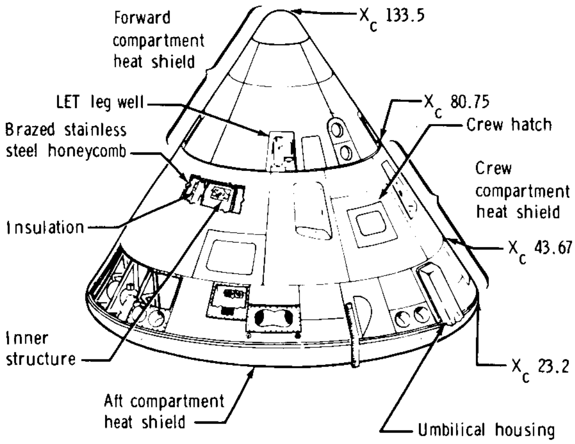


Figure 6. - Block I CM heat shield.

by longitudinally oriented stringers and frames and by one circumferential frame. The frames are located between stations X_c 23 and X_c 43, and the stringers are located between stations X_c 43 and X_c 81. Slotted holes in the frames and stringers permit radial movement caused by thermal effects. The aft heat shield is a shallow, spherically contoured assembly that encloses the large end of the CM and is attached to the aft bulkhead of the inner structure with 59 bolts. These bolts are installed in oversize holes to permit the heat shield to move relative to the inner structure.

Command module inner structure. - The CM inner structure is a pressure vessel that houses the crew, the equipment required for crew comfort and safety, and the equipment required to control and monitor the spacecraft systems. Figures 7 and 8 show the CM inner structure. The structure provides a load path from the LES/CM interface (fig. 1) to the CM/SM interface. The CM has an internal volume of approximately 365 cubic feet. The inner structure is enclosed by the CM heat shield for thermal protection and is subdivided into the forward apex, forward sidewall, aft sidewall, and aft bulkhead sections.

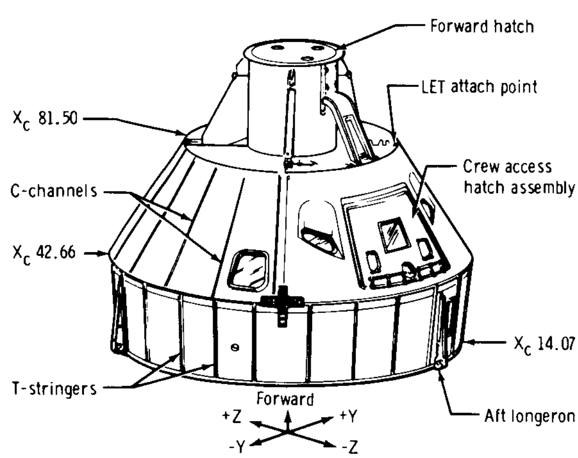


Figure 7. - Block I CM inner structure.

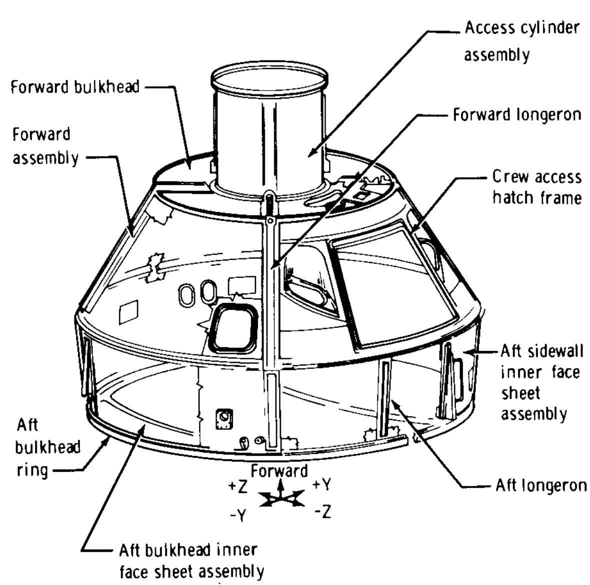


Figure 8. - Block I CM inner shell.

Forward apex: The forward apex structure consists of the access cylinder assembly and a flat forward bulkhead, both made of aluminum honeycomb. The volume between the inner mold line of the forward heat shield and the outer mold line of the apex structure houses the Earth-landing system and its associated interfaces, the forward heat shield ejection system, the pitch engines of the CM RCS, and part of the postlanding uprighting system.

The forward bulkhead contains four support longerons, which attach to the LET feet by explosive bolts. The longerons are continuous across the bulkhead and down the forward sidewall to the ring at station X_c 42. The two longerons on the plus-Z side of the bulkhead have integrally machined lugs that extend into the crew compartment and mate with the struts of the crew couch foot attenuator. The two longerons on the minus-Z side of the bulkhead have bolt-on fittings that partially support the fixture for the main display panel. All four longerons have integrally machined flanges that attach to the four apex gussets.

Forward sidewall: The forward sidewall (forward half of the crew compartment) is a truncated cone with the base at station X_c 42.7 and the top intersecting the forward bulkhead. The structure is made of aluminum honeycomb and contains the sidewall portion of the longerons as integral members. Two additional longerons are bonded to the inner mold line 23 inches on either side of the minus-Z axis and extend from station X_c 81.5 to station X_c 42.7. Both longerons have integrally machined lugs that extend into the crew compartment and mate with the crew couch head attenuator struts.

The crew compartment sidewall has six major penetrations: a crew hatch, two rendezvous windows, two side windows, and a guidance and navigation frame. Each penetration has a machined frame welded to the inner skin and bonded to the honeycomb core and outer face sheet.

Aft sidewall: The aft sidewall is an inverted truncated cone with the base at station X_c 42.7 and the top intersecting the aft bulkhead at station X_c 14.07. The volume between the inner mold line of the crew compartment and aft heat shield and the outer mold line of the aft sidewall contains the engines and tanks of the RCS system, part of the environmental control system (ECS), the waste water tank, four crushable ribs, part of the CM postlanding uprighting system, part of the CM/SM umbilical, and equipment that can withstand being exposed to the environment of space. The aft sidewall is a honeycomb sandwich shell with nine integral longerons. Six of these longerons are coincident with the radial beams of the SM and serve as part of the CM/SM load interface. Two of the remaining three longerons are continuations of the main forward longerons. The third supports a strut from the crew couch.

The aft sidewall contains 23 T-stringers bonded to the outside face sheet to interface with the crew compartment heat shield frames. The primary shear and torsion load path from the crew compartment heat shield to the inner structure is through fiberglass angles bolted to the aft sidewall at about station X_c 41.7. The aft sidewall contains a continuous machined ring that is welded to both the inner skins of the sidewall and aft bulkhead and the integral longerons. The honeycomb cores and outer face sheets of the aft shell are bonded to this ring. Two fittings are bolted to this ring and to two aft longerons and interface with the Z-Z attenuator struts of the couch.

Aft bulkhead: The aft bulkhead is a shallow, honeycomb dome with the concave side upward. It is attached to the aft sidewall at the ring at station X_c 14. This bulkhead forms the lower end of the crew compartment and supports the aft ring in a radial direction.

Service module. - The SM contains the spacecraft primary propulsion system, RCS, fuel cells and associated equipment for providing electrical power, and radiators for environmental control and electrical power subsystems cooling. A fairing encloses the space between the SM and CM and houses the structural connection between the two modules.

The SM structure is shown in figures 9 and 10. The SM outer structure is a cylindrical section of 1-inch-thick bonded aluminum honeycomb sandwich. The upper end of the SM is enclosed by a 1-inch-thick aluminum honeycomb bulkhead, and the aft end is enclosed by a 3-inch-thick aluminum honeycomb bulkhead. A heat shield attached to the aft side of the aft bulkhead protects the bulkhead structure and service propulsion system (SPS) tanks and plumbing from heat caused by the SPS engine being fired. The interior is subdivided by six one-piece radial beams. The upper ends of these beams are made in the form of triangular trusses with circular pads to support the CM. Three tension ties structurally join the CM to the SM; explosive devices sever these ties to separate the CM from the SM. One of these tension ties is shown in figure 11.

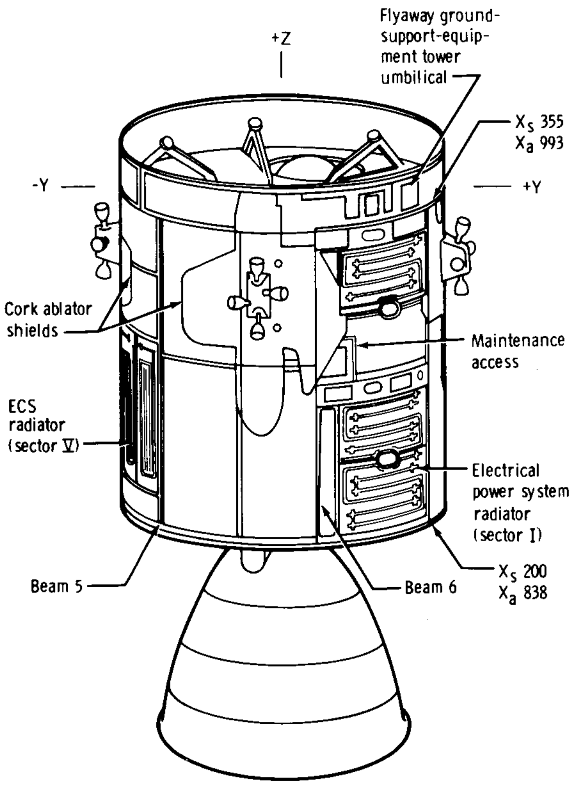


Figure 9. - Block I service module.

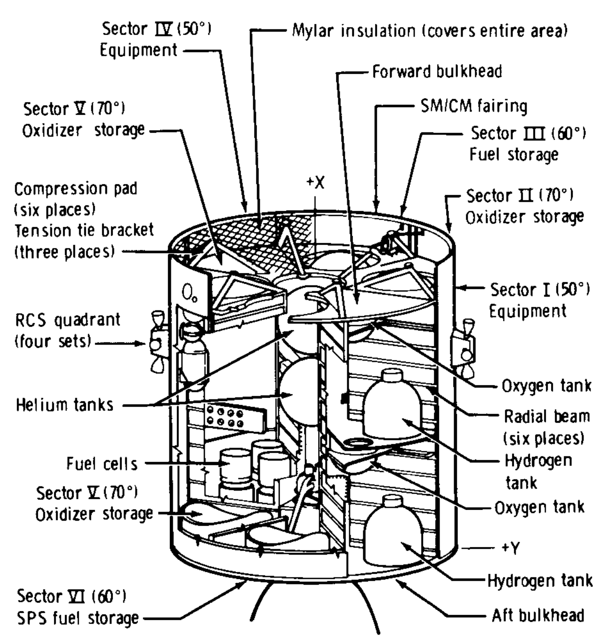


Figure 10. - Block I SM general arrangement.

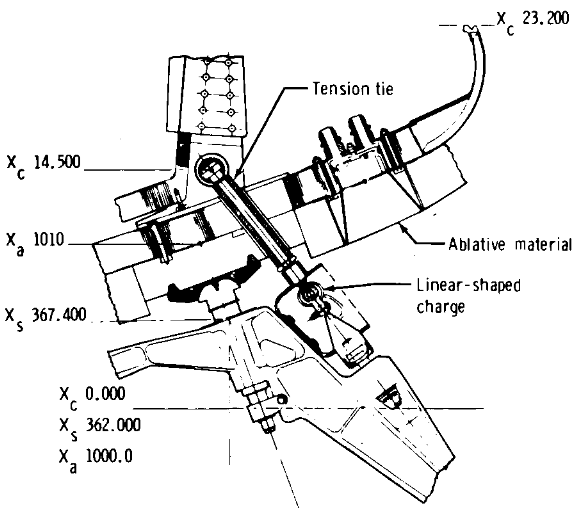


Figure 11.- The CM/SM interface.

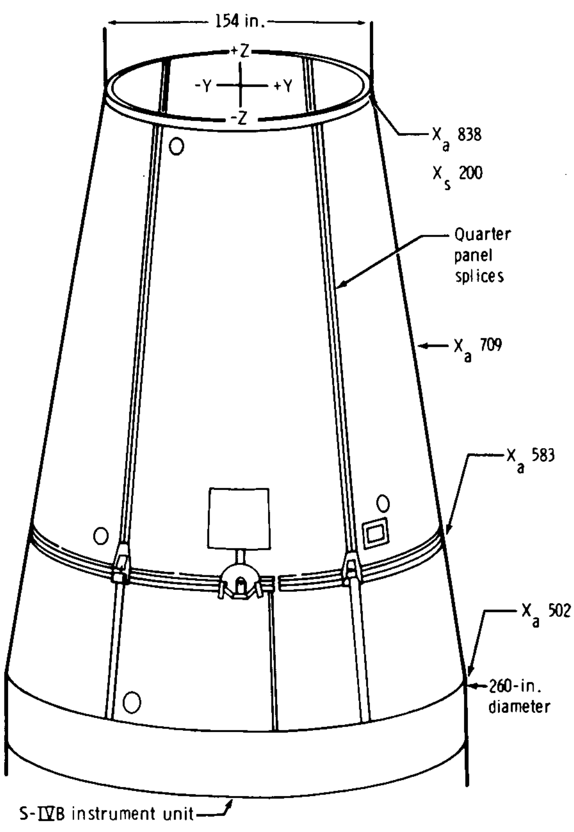


Figure 12. - Spacecraft/lunar module adapter.

The center tunnel formed by the radial beams houses the SPS engine and two helium pressurization tanks. The SPS propellant tanks are located in four of the six bays and are supported on the aft bulkhead. The four RCS engine quadrants are mounted to the SM external shell, and the associated tanks are attached to the interior of the shell on hinged doors.

Spacecraft/lunar module adapter. - The SLA is the load-carrying structure between the SM and the instrument unit (IU) of the launch vehicle. It protects the LM during the boost phase of flight and supports the LM on four ball joints located at station X_a 585. Figure 12 shows the dimensions of the SLA.

The conical shell is divided into two sections: the upper section from the SM interface to the LM attachment plane and the lower section from the LM attachment plane to the IU interface. The upper and lower sections of the shell consist of four quarter panels spliced together with longitudinal plates. The panels are 1.7-inch-thick aluminum honeycomb sandwich. The frames are bonded into the panels and are spliced at the quarter-panel joints with mechanical fasteners. The lower section has chemically milled areas of varying thicknesses in both face sheets to distribute the concentrated loads from the LM into the shell. Both the upper and lower sections have reinforced access holes that are covered by doors during flight.

Pyrotechnic devices separate the SLA from the SM and simultaneously cut the SLA forward section longitudinally at its four splice joints and circumferentially at the LM attachment plane. The four panels then deploy approximately 40° to expose the LM for docking or to permit the SPS to propel the command and service module (CSM) from the SLA and booster if an abort is required after jettisoning of the LET. The pyrotechnic separation lines are shown in figure 13.

Apollo flight vehicles SC-009, SC-011, and SC-101 did not include an LM but used a stiffening member in the SLA in place of the LM. This stiffener, shown in figure 14, weighed approximately 70 pounds and provided the stiffness necessary to stabilize the SLA shell structurally.

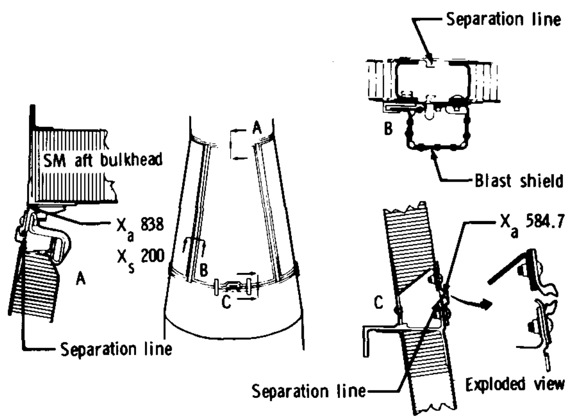


Figure 13. - Adapter panel separation lines.

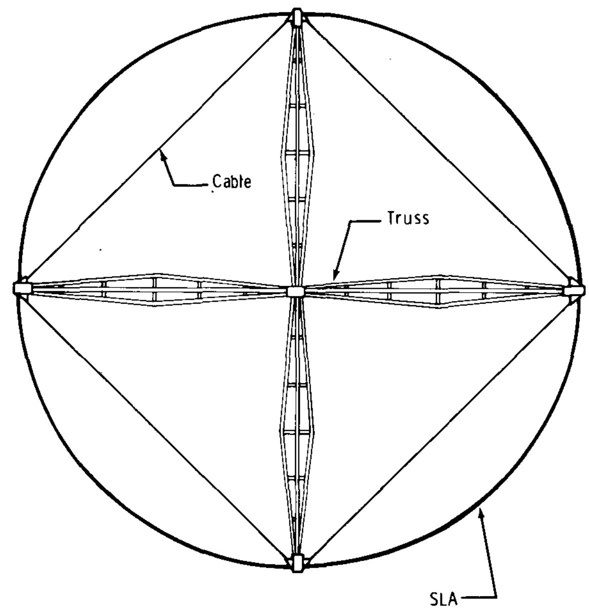


Figure 14. - Structural stiffener.

Block II

More than a year before the first Block I spacecraft was flown, the Block II spacecraft design was begun. The structural experience gained from the boilerplate flights and from the Block I structural ground test program was combined with the new requirements for a vehicle that could dock with an LM and perform a lunar mission. A sketch showing the Block II spacecraft general arrangement with station numbers is shown in figure 15.

Structural changes from Block I to Block II were numerous; the major changes are described in the following sections. Some of the vehicle descriptions are taken from reference 1.

Launch escape system. - Modifications were made to conform the BPC to the modified CM shape caused by relocation, deletion, and changes to such parts as umbilicals, antennas, RCS engines, and ablator thicknesses. Figure 16 shows the Block II BPC.

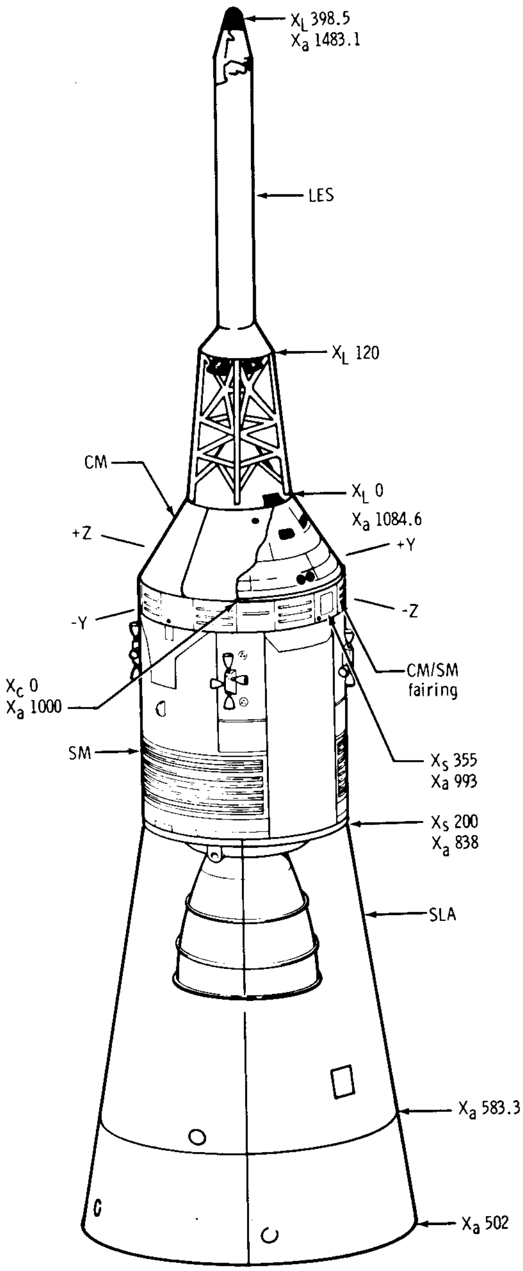


Figure 15. - Block II integrated stations and axes.

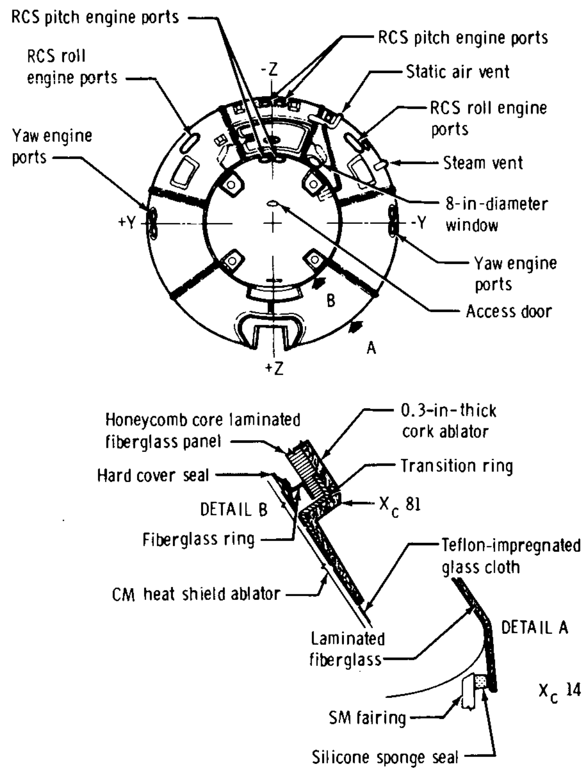


Figure 16. - Block II boost protective cover.

Command module. - The Block II heat shield configuration is shown in figure 17. The forward portion was modified to a truncated cone. The stainless steel honeycomb substructure was modified to essentially the same substructure as that flown on SC-017 and SC-020. Figure 18 shows the inner structure of the Block II CM. Changes made in the tunnel area to provide docking capability included adding a docking ring and latches and a thermal isolation ring. The CM/SM umbilical was relocated to the plus-Z axis, and the parachute attachment

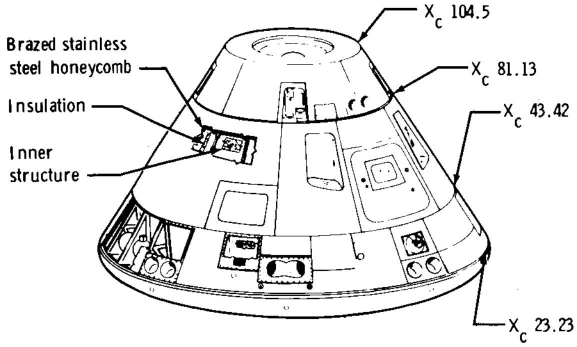


Figure 17. - Block II CM heat shield.

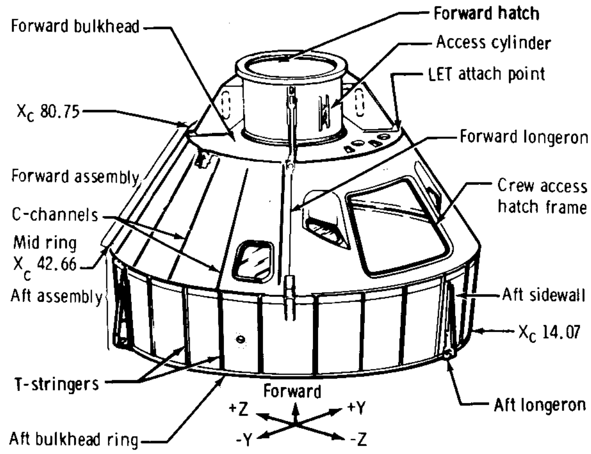


Figure 18. - Block II CM inner structure.

was modified to a single attachment fitting for the two drogue and three main parachutes. All storage bays were modified because of repackaged and redesigned CM equipment. The three CM/SM tension ties were strengthened.

All Block II command modules used the unified side hatch. After the SC-012 fire, the CM two-hatch system was redesigned to provide a single, integrated, outward-opening hatch. This redesigned hatch was made with an aluminum slab inner structure and an ablative material heat shield outer structure; fiberglass honeycomb insulation was sandwiched between the two structures. On SC-106 and subsequent vehicles, the hatch was modified by machining the slab to 0.1-inch thickness in many small areas to reduce weight.

Service module. - The Block II SM is illustrated in figures 19 and 20. The required factor of safety for the structure aft of the forward bulkhead was reduced from 1.5 to 1.4 because total weight increases to the CM and LM would have caused an increase in weight of the SM and SLA structure if the factor of safety had remained at 1.5. The booster was designed primarily with a factor of safety of 1.4; therefore, the decision was made to design the SM and SLA with a 1.4 factor of safety. The required structural factor of safety forward of the SM forward bulkhead was kept at 1.5 to make the CM, LES, and CM/SM interface stronger than the remainder of the spacecraft and booster. The structure between the SM forward bulkhead and the CM provides the base for a CM abort and was not designed to be the "weak link" in the structure used during aborts. The forward bulkhead was modified to permit equipment to be mounted on it. The longer Block I SPS tanks had been installed through holes in the forward bulkhead; the shorter Block II tanks were supported by three struts attached to the forward dome.

Equipment previously located in bay I was relocated to reserve bay I for experiment equipment. The three fuel cells were relocated to the forward end of bay IV, and the two oxidizer tanks for the fuel cells were located on a common shelf in bay IV. Electronic equipment previously in bay I was relocated to the forward bulkhead.

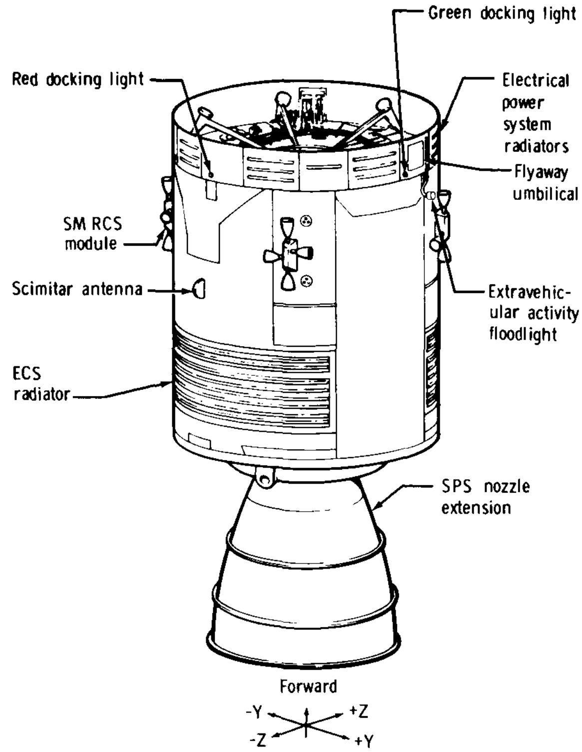


Figure 19. - Block II service module.

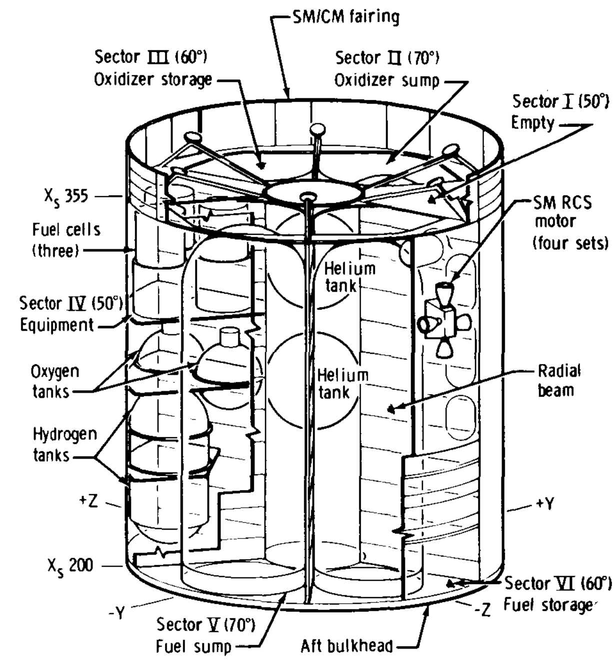


Figure 20. - Block II SM general configuration.

The thicknesses of the radial beam webs were changed from 0.018 ± 0.005 inch to 0.015 ± 0.003 inch. The electrical power system (EPS) radiators were relocated to the CSM fairing.

The outer shell panels that enclosed bays II and III and bays V and VI (SPS tank bays) were changed to two 130° panels. This permitted the ECS radiators to be continuous across the 130° panel, and the radiator tubes were oriented horizontally instead of vertically as in the Block I design. The outer skin material of the shell panel was changed from 7178-T6 to 2024-T81 aluminum to provide greater strength at elevated temperatures. The thicknesses of the panel face sheets also were changed. Additional RCS propellant tanks were added, which required lengthening the RCS doors to approximately 96 inches.

The SM also was modified to relocate the CSM umbilical to the plus-Z quadrant. Six sway braces also were installed (two each on beams 2, 4, and 6) to reduce axial-torsional coupling at the CM/SM interface.

Spacecraft/lunar module adapter. - Only minor modifications were made to the original SLA design. Before the LM was flown on the late Block I flights (SC-017 and SC-020), 10 new access ports were added to the vehicle structure for servicing the LM on the pad; 4 access ports were deleted; and the personnel access door on the plus-Z axis was enlarged to accommodate LM equipment while on the pad.

The LM design weight increased from 26 500 pounds at the time of the original SLA design to 29 500 pounds and then later to 32 000 pounds. The loads imposed by the 29 500-pound LM required some design changes to the LM attachment ring at station X_a 585; however, because the decision had been made to reduce the design factor of safety of the SLA from 1.5 to 1.4, the effect of the LM weight change from 29 500 pounds to 32 000 pounds was minimized.

The SLA panels originally were designed to deploy to $40^\circ \pm 5^\circ$. To provide additional clearance for extracting the LM, this angle was changed to $45^\circ \pm 5^\circ$. In the spring of 1968, the panels were designed to be jettisoned, and this design was first flown on the Apollo 9 mission. At the same time, a spring system also was designed to eject the LM.

TEST DESCRIPTION

Block I

Static tests. - The development test program was started in the latter part of 1962 and continued through 1965. The majority of the development tests were tests in which new methods of construction, joints, and material properties were verified before proceeding to assembly tests, full-scale module testing, and stacked configuration tests. Appendix A lists the Apollo Test Requirements (ATR) number and briefly describes the purpose of each development test.

Component-level development testing was conducted to evaluate and verify specific areas of the modules for specific environments before full-scale module testing began. A summary of these tests is presented in appendix B.

Module-level tests. - Tests of CM or CSM complete assemblies were conducted to demonstrate that the structure would meet the design requirements under critical load and environmental conditions. During the tests of the command and service modules in the stacked configuration, a stub tower was used to introduce loads into the upper end of the CM, and a short cylindrical section was used to simulate the adapter at the aft end of the SM. The stack was tested to Saturn V maximum $q\alpha$, lift-off, and first-stage end-boost conditions. The load was applied in the direction to produce the analytically determined critical loading on the structure. The various module-level tests are identified in appendix C together with the ATR number and test objectives.

Dynamic tests. - Dynamic testing was conducted at the development, component, full-size module, and stacked module levels. Appendix D briefly decribes the objectives of the tests and lists the ATR numbers. Two series of dynamic tests were conducted at the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)); one used a boilerplate vehicle (BP-9), and another used a production SM and a boilerplate CM (BP-27).

In mid-1963, two vibration test programs were conducted by MSC on the BP-9, SM, insert, and adapter assembly at Ellington Air Force Base, Houston, Texas. These tests were designed to determine the dynamic characteristics of the BP-9 structure. The results of the first test program indicated a possible structural deficiency; as a result, modifications were made to several ring frames and longerons. The second test program was conducted to determine dynamic characteristics of the modified structure. These tests provided data that were later correlated with instrumentation data produced during the flight of the boilerplate structure.

The dynamic testing of a boilerplate CM and a production Block I SM structure was conducted on BP-27 at MSC in January and February 1965. Although designated as a boilerplate, the SM was actually a production model with mass simulated and dummy equipment installed to provide correct dynamic response. The CM was a true boilerplate. This series of tests was designed to determine the overall lateral modes of the stacked command and service modules in the free-free configuration and to obtain the shell modes of the SM.

After these tests, BP-27 was shipped to the NASA George C. Marshall Space Flight Center (MSFC) to be mated with other spacecraft and booster modules for dynamic testing. The test configuration consisted of an LET, a launch escape motor, the BP-27 CSM, SLA-1, a cruciform flight stiffener in lieu of an LM, an IU, and a Saturn IVB (S-IVB). Data from the tests revealed significant oscillating torsional movement of the CM with respect to the SM. Investigation revealed that the single sway brace designed to provide torsional restraint at the CM/SM interface was not tight. The sway brace had an oversize hole in one end to permit easy installation of the brace, and the testing had further elongated the hole. A new sway brace was installed with a tight-fitting bolt that reduced the torsional motion but did not eliminate it. The sway braces on all subsequent spacecraft were drilled on assembly and installed with tight-fitting bolts. Additional torsional restraint was recommended in September 1965. Because insufficient evidence was available to prove that a change was mandatory, no modification was made. Later MSFC Saturn V dynamic test data and MSC analysis showed that one sway brace was insufficient. Five braces were installed on Block I SC-017 and SC-020, and six were installed on all Block II spacecraft. The five-brace configuration was installed on the MSFC test vehicle and demonstrated successfully.

Acoustic environment tests of the SC-007 Block I command and service modules were conducted in 1965.

Landing impact tests. - The landing impact test program on Block I vehicles was designed to test the integrity of the spacecraft structure only and did not include testing of the internal attenuation struts of the crew couches.

The Apollo spacecraft was originally designed to land on land; however, in the spring of 1964, the primary landing mode was changed to a water landing. This change was made primarily because water landing sites are more numerous throughout the world and because energy-absorbing systems for land landings are more complicated than those required for water landings. The increased weight of the vehicle increased the rate of descent to the point where it was doubtful the structure could withstand a land landing.

The Block I landing impact test program consisted of numerous impacts of boilerplate test vehicles on both land and water. These drop tests began in 1962 and used BP-1 and BP-2 as test articles. These boilerplate vehicles were not structurally similar to the spacecraft but could be classified as rigid-body vehicles. The drop tests had the following objectives.

1. To evaluate crew shock attenuation system at land impact

2. To evaluate vertical and transverse acceleration loads at land impact

3. To determine and evaluate the stability and dynamics of the vehicle

4. To evaluate g-forces on the primary structure and simulated crew couch

5. To confirm preliminary criteria and determine if any new conditions existed

The first test article to approach any similarity to the flight vehicle was BP-28, which was built to test the aft heat shield, aft bulkhead, and plus-Z toroidal area. Because the manufacturing tooling was in use for flight hardware, the construction of BP-28 differed somewhat from the flight hardware. For example, the aft heat shield was made from aluminum honeycomb instead of steel honeycomb and therefore required a different total thickness and different face sheet thickness to obtain the same cross-sectional moment of inertia as the production heat shields. On the first BP-28 drop, the aft heat shield crushed on impact and pierced the aft bulkhead of the inner structure. This failure is discussed later in this report. After the BP-28 failure, the aft heat shield was redesigned by making the face sheets thicker and using denser honeycomb core in the impact area of the heat shield.

At this time, consideration was given to cutting one of the two legs of the main parachute harness to increase the hang angle from the nominal of 27.5° to approximately 35°, thus decreasing the impact pressures on the aft heat shield. The heat shield was designed with thicker face sheets and a denser core extending into the plus-Z/minus-Y quadrant as opposed to a design symmetrical about the Z-Z axis.

The plus-Z quadrant of the forward bulkhead and tunnel was also found to be understrength for pressures caused by water impact angles above 27.5°. The tunnels on SC-009 and SC-011 were filled with foam. The forward bulkhead and tunnel areas were modified on SC-017 and subsequent vehicles. These changes are shown in table I. The modifications consisted of replacing the honeycomb core in the plus-Z quadrant with densified core, using thicker face sheets and doublers on the tunnel, and adding densified core to some areas of the tunnel.

Block I impact testing was concluded with seven BP-28 water drops, two CM-007 water drops, and one BP-12A water drop to verify the sides and forward bulkhead area and the redesigned heat shield.

TABLE I. - APOLLO CM DESIGN CHANGES FOR WATER IMPACT

Component	SC-002 and SC-009	SC-011	SC-017, SC-020, and Block II
Aft heat shield face sheets	Bonded doublers Stepped 0.042, 0.022, and 0.012 in. Dual hang-angle capability	Chemically milled Stepped 0.050, 0.030, and 0.020 in. Dual hang-angle capability	Chemically milled Stepped 0.050, 0.030, and 0.020 in. Single hang-angle capability
Honeycomb core	No change	Densified core at impact area	Densified core at impact area
Inner aft sidewall face sheets	No change	Doubler 0.020-in. aluminum; 180° segment (outer only)	0.032-in. aluminum was 0.016-in. aluminum; 180° segment (outer only)
Forward bulkhead core	No change	No change	Densified plus-Z quadrant
Docking tunnel face sheets	No change	No change	0.025 in. was 0.016 and 0.010 in. (outer) plus- and minus-Y quadrant 0.050 in. was 0.016 and 0.010 in. (outer) plus-Z quadrant Doubler 0.016 in. (inner) plus- and minus-Y quadrant Doubler 0.040 in. (inner) plus-Z quadrant
Core			Densified core plus-Z quadrant, plus- and minus-Y quadrant

Flight tests. - The Block I flight development program was separated into boilerplate and spacecraft flights. Pad abort tests (using only the LES motor for propulsion) and higher altitude abort tests (using Little Joe II rocket boosters) were conducted at the White Sands Test Facility (WSTF) on several boilerplate vehicles and one production spacecraft. Flights from the NASA John F. Kennedy Space Center (KSC) used both boilerplate and spacecraft vehicles and were launched on Saturn I, Saturn I-B, and Saturn V boosters. The boilerplate flight history is documented in table II.

Boilerplate: The boilerplate vehicles used for flight were structurally similar. The command modules were made of 0.19-inch welded aluminum plate with internal longerons that distributed the loads from the LET and provided connecting points for six SM longerons. The command modules were covered with cork for protection from heating before the use of the BPC on BP-23. All service modules, adapters, and inserts used for the Saturn flights were constructed with six longerons, 0.16-inch aluminum shells, internal frames, and stringers. The service modules were approximately 152 inches long; the adapters and inserts for the Saturn flights were 92 inches and 52 inches, respectively, with 154-inch diameters. The launch escape towers were very similar to production models. Table III lists each flight boilerplate and the modules used to make up each configuration.

Spacecraft: The flight test program for the Block I spacecraft was planned to certify the spacecraft structural design and LES for later manned flights. In the flight test program, emphasis was placed on man rating Apollo hardware in space and providing sufficient levels of flight test verification and proficiency in flight operation to ensure mission success.

TABLE II. - APOLLO BOILERPLATE FLIGHT HISTORY

Mission	Boilerplate	Purpose	Launch date	Launch site	Report number
PA-1	BP-6	To demonstrate that the Apollo spacecraft could abort from the launch pad and to recover the spacecraft crew	Nov. 7, 1963	White Sands Missile Range, N. Mex.	TM X-5321
A-001	BP-12	To determine aerodynamic and operational characteristics of the launch escape vehicle (LEV) during an abort at a transonic velocity and high dynamic pressure To confirm capability of LES to propel CM away from Little Joe II launch vehicle	May 13, 1964	White Sands Missile Range, N. Mex.	MSC-R-A-64-1
AS-101	BP-13	To demonstrate the compatibility of the spacecraft with the launch vehicle in launch and exit trajectory and environment for Apollo Earth-orbital flights To demonstrate the primary mode of the LET jettison using the LET jettison motor	May 28, 1964	John F. Kennedy Space Center, Fla.	MSC-R-A-64-2
AS-102	BP-15	Same as for AS-101 except that alternate mode of tower jettison was demonstrated using pitch-control and launch-escape motors	Sept. 18, 1964	John F. Kennedy Space Center, Fla.	MSC-R-A-64-3
A-002	BP-23	To demonstrate satisfactory LEV performance using canards and the BPC To verify the abort capability in the maximum dynamic pressure region with conditions approximating the Saturn emergency detection subsystem limits	Dec. 8, 1964	White Sands Missile Range, N. Mex.	MSC-R-A-65-1
A-003	BP-22	To demonstrate satisfactory LEV performance at an altitude approximating the upper limit for the canards (Test conditions were not achieved because of a failure of the Little Joe II launch vehicle; however, the LEV performed satisfactorily under the actual abort conditions.)	May 19, 1965	White Sands Missile Range, N. Mex.	MSC-A-R-65-2
PA-2	BP-23A	To demonstrate the ability of the LES using canards and the BPC to abort from the launch pad and to recover the spacecraft crew	June 29, 1965	White Sands Missile Range, N. Mex.	MSC-A-R-65-3

TABLE III. - BOILERPLATE CONFIGURATIONS

Boilerplate	Configuration
BP-6	LES, CM, and pad abort adapter (truss)
BP-12	LES, CM, SM, and 10-in. extension to mate with Little Joe II
BP-13	LES, CM, SM, insert, and adapter
BP-15	Same as BP-13
BP-23	Same as BP-12
BP-22	Same as BP-12
BP-23A	Same as BP-6

Mission A-004; SC-002: The first spacecraft flight was that of SC-002 in January 1966. The primary structural objective of this flight was to demonstrate the integrity of the LES structure for an abort in the power-on tumbling boundary region. This vehicle consisted of an LES (including BPC), CM, SM, and an aluminum ring that mated the SM to the Little Joe II booster. The structure was basically a production model. The heat shield for the CM had cork for an ablative material, and the substructure had bonded doublers as described in table I. The CM was modified because, in May 1965, an analysis revealed that 18 of the 24 frames in the CM aft compartment were understrength. Further analysis determined that SC-002 would be satisfactory if one of its aft frames (number 9) was modified and a precompressed gasket was installed between the aft and crew compartment heat shields. This gasket was also included on all heat shields having spacecraft-type ablative material. The gasket provided a vertical load path from the aft heat shield to the crew compartment heat shield for some of the loads that would otherwise have been transferred through the aft frames. The SM had no operating systems. Four steel plates, weighing 2000 pounds each, were installed for ballast on the aft bulkhead of the SM in sectors II, III, V, and VI. One RCS engine was production type with mass-simulated tanks; the other three engines and tanks were simulated.

Before the SC-002 flight, several structural changes had been required. The dynamic tests conducted on BP-27 at MSFC had revealed the need for a tight-fitting sway brace at the CSM interface, and the dynamic testing on SC-007 SM had shown several areas of concern, one of which was the integrity of the SM radial beams. To further test the beams, 14 channels of flight instrumentation on SC-002 were reallocated to continuously record strains of the webs of radial beams 2, 4, and 5. The purpose of the 14 strain measurements was to obtain data on the dynamic response of the radial beam webs to the acoustic environment during flight so that a comparison of these fluctuating stresses could be made with stresses obtained during the simulated ground acoustic test of SC-007. This comparison would ascertain whether the radial beam webs were prone to fatigue failure. Adhesive-backed damping tape was installed on one side of the web on radial beam 2 to assess the effectiveness of that tape in reducing the dynamic response of the webs.

The flight plan for SC-002 was to launch on the two-stage Little Joe II booster; initiate an abort maneuver at approximately 60 000 feet; orient the launch escape vehicle (LEV) to the proper CM base-down attitude with the canard system; jettison the tower; and proceed to impact with the normal parachute Earth-landing mode.

The SC-002 was launched at WSTF on January 20, 1966, at 8:17 a.m. m.s.t., and the CM landed 410.0 seconds later. Significant excerpts from the postflight report state:

"Analysis of the flight data indicates that spacecraft 002 performed with no structural problems throughout the flight. Interface loads calculated for the maximum load flight conditions throughout the flight show that the limit load capability of the structure was not exceeded. ... The measured differential pressure (on the CM) was lower than the planned pressure (11.1 pounds per square inch differential (psid)) because: (a) the plume impingement pressures were about 80 percent of those predicted for a nominal mission, and (b) the internal pressure in the aft compartment was higher than planned by approximately 1.5 PSI .... Based upon tracking and onboard films, in addition to the pressure data, the boost protective cover performed as planned .... Examination of all spacecraft strain, pressure, and acceleration data indicated that the spacecraft performed adequately in the launch environment .... Service module outer shell and interior vibration data show levels much lower than those obtained in acoustic tests simulating the flight environment. One exception to this is the vibration level of the inner flange of radial beam 5 which was approximately the same as that obtained in the acoustic tests, although the spectral distribution was different. This high level indicates a much greater transmissibility from the outer shell to the radial beam inner flange than was obtained in the acoustic tests. At present this phenomenon is not understood." (Subsequent examinations suggest that the radial beam inner cap braces failed due to expansion of the SM during transonic flight. The braces were modified for SC-011 and subsequent vehicles.) "Command module vibration data show levels lower than those obtained in acoustic tests. The majority of data throughout the flight was close to the noise of the instrumentation systems."

Mission Apollo-Saturn 201 (AS-201); SC-009: After the successful flight of SC-002, the flight test program proceeded to SC-009, already on the launch pad at KSC. On mission AS-201, SC-009 was launched on a Saturn I-B launch vehicle. Lift-off occurred from KSC on February 26, 1966, at 11:12 a.m. e.s.t., and the CM impacted in the South Atlantic Ocean near Ascension Island approximately 37 minutes later.

The structural test objectives were to demonstrate the structural integrity and compatibility of the launch vehicle and spacecraft, to confirm loads, and to verify operation of the CM heat shield for entry from low Earth orbit. A complete description of the mission is given in reference 2. Spacecraft 009 was structurally similar to SC-002 but included for first flight both the SLA and flight stiffener.

Analysis of the flight data showed that the vehicle loads were less than expected and that all loads were well within the capability of the spacecraft. Data from the spacecraft vibration instruments indicated relatively low levels except on the SLA panels, which exceeded the expected levels. Based on these data, the environmental vibration criteria for the SLA panels were updated.

Mission AS-202; SC-011: Spacecraft 011 was launched by a Saturn I-B booster on August 25, 1966 (ref. 3). The structural objectives were essentially the same as for SC-009. Spacecraft 011 was approximately 11 000 pounds heavier than SC-009 primarily because of additional SPS propellant. The SLA had a television camera mounted inside to view the four SLA panels as they deployed. The structural configuration was essentially the same as that of SC-009 except for the following differences.

1. The LES tower leg fitting was changed from a casting to a die forging.

2. The CM aft sidewall outer skin thickness was changed from 0.016 to 0.036 inch.

3. A doubler was added under the parachute retention bracket.

4. The aft heat shield of SC-011 had integral variations in the skin gage where SC-009 had bonded doublers. The shear-compression pads were strengthened on the SC-011 heat shield.

5. The spherical washers used to determine the amount of preload in the tension tie linkage were replaced on SC-011 with strain-gaged bolts to provide better accuracy. The structural capability was the same as that of SC-009.

6. The SC-011 SLA hinge backup structure was strengthened.

The structural flight test objectives were satisfactorily accomplished. However, during the CSM/SLA and S-IVB separation, the SPS plume impinged on two of the opened SLA panels, breaking the retention system on these two panels. Failure of the retention system was assumed because two of the panels moved out of the camera field of view. A proximity SPS firing of this type normally would not occur except during an SPS abort; therefore, this failure of the panel retention system was considered acceptable. Flight data indicated that all loads were low during the mission.

Spacecraft 012: Many structural modifications were made to SC-012. A matrix of configuration differences between SC-011 and SC-012, together with the reason for each, is given in table IV.

All applicable ground testing had been completed satisfactorily and SC-012 was considered structurally acceptable for manned flight when the disastrous CM fire occurred on the launch pad at KSC in January 1967.

Apollo 4 mission; SC-017: Spacecraft 017 was the first spacecraft to be launched on a Saturn V booster. The primary structural objective of the unmanned SC-017 was the demonstration of structural and thermal integrity and compatibility of the launch vehicle and spacecraft. The structural configuration was essentially the same as that of previous spacecraft except that four sway braces had been added at the CM/SM

TABLE IV. - SPACECRAFT 011 AND 012 CONFIGURATION DIFFERENCES

Item	SC-011	SC-012	Reason
CM heat shield honeycomb material	Precipitation hardened (PH) 15-7	PH 14-8	PH 14-8 has less notch sensitivity and more uniform heat treatment characteristics.
CM aft frames and fittings	Normal frame	Strengthened frame	To obtain a factor of safety of 1.5 for the frames and fittings.
CM roll engine panel assembly material	PH 17-4 corrosion-resistant steel	6Al-4V titanium	To reduce weight and facilitate manufacturing.
CM inner structure outer skin over most of plus-Z half of aft sidewall	Basic 0.016-in. skin with a 0.020-in. doubler	Basic 0.032-in. skin	Basic 0.032-in. skin is a more efficient structure.
CM inner structure secondary equipment support	Face-sheet-to-core bond allowable, 650 psi	Face-sheet-to-core bond allowable, 400 psi	To increase design confidence of equipment support.
CM forward tunnel	Normal tunnel filled with foam for additional support	Tunnel skins and honeycomb core strengthened	To make SC-012 structurally capable for the latest water landing loads. Schedule problems on SC-011 did not allow the strengthening.
Pilot parachute mortar canister fitting to CM forward bulkhead joint	Bonded	Bolted	To obtain a factor of safety of 1.5.
CM forward bulkhead joint to forward sidewall	Skin joint	Strengthened skin joint by using a doubler and cherry rivets	Change was made because of low production quality verification (PQV) results.
Flotation bag attach points and cables	Normal attach points and cables	Strengthened attach points and cables	To obtain a factor of safety of 1.5.
Pad at the CSM station 1010 interface	Pad adjusted by varying the shim thickness	New design of pad for adjustment	The ablator mold line for SC-012 and subsequent vehicles was not known. The pad allowed adjustment to varying CM ablator thicknesses.
SM RCS tank bracket material	Aluminum	Fiberglass	New thermal requirement to prevent the fuel in the tanks from freezing.
SLA longitudinal debris catcher material	Fiberglass	Aluminum	Fiberglass catcher failed the qualification tests.

interface. Interference from equipment prevented the installation of a sixth sway brace as in the Block II design configuration. Another mission structural objective was to confirm launch loads and dynamic characteristics. Details of the flight are presented in reference 4. The mission was completed as planned, and the primary structural objective was accomplished satisfactorily.

Apollo 5 mission: The Apollo 5 flight was designed to check out the LM. Because this flight was primarily concerned with the LM, it is mentioned only for continuity.

Apollo 6 mission; SC-020: The flight of SC-020 was the last unmanned mission and the last mission of the Block I flight test program. The structural performance of SC-017 (Apollo 4) had been satisfactory, and no problems were expected on SC-020.

Both missions had secondary objectives of demonstrating CSM/SLA/LTA[1]/Saturn V structural compatibility and determining spacecraft loads in a Saturn V launch environment. The structural instrumentation was essentially the same as that on SC-017.

The structural configuration of SC-020 was essentially the same as that of SC-017 except for incorporation of the new unified CM hatch and a modification to two SPS tank skirts. Based on results of the SM static test that showed the tank skirts in bays II and VI to be understrength, a modification to these two skirts was made on the pad at KSC in March 1968.

During the first boost stage of the mission, portions of an SLA panel failed and separated from the spacecraft. The SLA continued to sustain the flight loads, however, and the mission was accomplished successfully. Details of the flight are presented in reference 5 and in the section entitled "Flight Anomalies."

Block II

Static tests. - Although considerable static testing had been accomplished to verify the Block I design, the structural modifications, increased weight, and center-of-gravity changes of the Block II design required an extensive ground test program. However, most of the development test work accomplished for Block I spacecraft was applicable to Block II spacecraft, so the Block II test program consisted mainly of component testing and full-scale module testing. Appendix E contains a list of the structural tests in the Block II program and gives the title, ATR number, and objective of each test.

Dynamic tests. - The Block II structural dynamic tests were conducted on SC-105 at MSC (ref. 6). Both vibration and acoustic tests were conducted during February and March 1968. This program had two primary objectives: (1) the demonstration of the structural integrity of Block II CSM wiring, plumbing, bracketry, and installed subsystems when subjected to the dynamic loads resulting from spacecraft exposure to the aerodynamic noise environment of atmospheric flights, and (2) the demonstration of the structural integrity of the Block II CSM when subjected to the low-frequency vibratory motions produced during atmospheric flight.

The only structural anomaly that occurred during the dynamic testing was a bent SPS tank support strut. The strut is attached to the top of the SPS fuel storage tank. Investigation of installation procedures determined that this failure was caused by improper installation. The installation procedures were modified to prevent such damage from reoccurring.

Water landing impact tests. - Part of the Block II water drop test program was conducted at the contractor plant and part at MSC. The portion of the test program conducted by the contractor established that the Block II CM could land on water safely at its specification weight. The MSC test program was conducted because changes to the

---

[1] Lunar module test article.

CM equipment and the resulting increased weight required a redefinition of the compatibility of the structure at these new conditions. The contractor test program consisted of two drops, designated impact tests 103 and 104, and used CM 2S-1 (also designated CM-99). The 2S-1 configuration was a production-type CM except that it had (1) cork in place of the heat shield ablator, (2) a Block I type aft heat shield, (3) an SC-002 inner crew hatch, (4) simulated uprighting bags and container assembly, and (5) a simulated astrosextant ablator panel. The tests were conducted with three instrumented anthropomorphic dummies in the crew couches.

Impact test 103 was conducted on November 11, 1966. The measured vertical velocity was approximately 31 ft/sec and the horizontal velocity was approximately 47 ft/sec. The primary test objective was to verify the structural integrity of the crew compartment heat shield, forward sidewall, forward bulkhead, tunnel, and ablative hatch with respect to water leakage. Structural damage that occurred included buckling of the crew hatch inner skin, numerous cracks and tears in the fiberglass panels and fairings in the plus-Z quadrant on the forward bulkhead, and a skin puncture in the forward bulkhead probably caused as a result of the fairing failure. A small quantity of water leaked into the spacecraft, possibly through the pressure relief valve.

Impact test 104 was conducted on December 16, 1966. This drop had a measured vertical velocity of approximately 34 ft/sec and a horizontal velocity of approximately 39 ft/sec. The primary test objective was to verify the structural integrity of the aft heat shield, the aft bulkhead, the aft inner sidewall, and the secondary structure. The configuration was similar to that used in impact test 103 except that a Block II symmetrical core aft heat shield was used. The drop test was successful.

The water impact test program was conducted at MSC during the summer of 1968 and used BP-28A and CM-099 as test articles. A total of nine water impact tests was conducted. Of these, eight drops were conducted with vertical velocity only. The ninth was dropped with both horizontal and vertical velocities. Drop conditions and weight were selected to represent the latest CM rate of descent and impact angle. During the fourth and fifth drop tests, the face sheets of the aft heat shield wrinkled outside the bolt circle, the corrugated torus section buckled near the interface between the aft heat shield and sidewall, and cork used to simulate the ablator separated from the outer skin near where the torus buckled.

During the ninth drop, the core located in the minus-Z side of the minus-Y axis of the aft heat shield sheared. A buckle also occurred along a joint at the quarter panel splice in the minus-Z/plus-Y quadrant of the aft heat shield. The aft bulkhead buckled and the face sheet separated from the core; however, there was no evidence of core shear. The CM remained watertight in all three (fourth, fifth, and ninth) drops. These tests verified the structural capability of the CM for the latest weights and impact velocities.

Flight tests. - The Block II spacecraft structure had been adequately qualified by Block I ground and flight testing and Block II ground testing and was therefore considered operational. The flights of Block II spacecraft had no structural objectives, and the spacecraft carried only minimum structural instrumentation. Structural descriptions of the flight vehicles and discussions of structural performance during all Block II flights are presented in the mission postflight reports.

SIGNIFICANT PROBLEM AREAS

Most problems encountered during the development and verification of the Apollo structural subsystem were discovered in the ground test program when the structure failed to meet specified criteria when exposed to environments and loads. Each failure was carefully analyzed, and the specific test criteria were reassessed. In some cases, this reassessment revealed that the test conditions were too severe and should be made more realistic. In other cases, structural inadequacies that required design modifications were identified. Some modifications required retesting; others were certified by analysis.

Significant problems encountered in the ground and flight test programs and the resolutions of these problems are discussed in this section.

Block I Ground Test Anomalies

Command module static tests (ATR 111014). - Several tests were conducted to demonstrate that the support structure of the CM Earth-landing system was adequate. One of these tests, conducted on CM-006, was planned to demonstrate the strength of the pilot parachute mortar and the hardware that attached it to the upper bulkhead. The mortar fittings were attached to the upper bulkhead by bonding the fittings to the outside face sheet of the aluminum honeycomb. When the static load was applied, the bond between the mortar fitting and the bulkhead failed in tension at 63 percent of limit load. Inserts were bonded into the aluminum honeycomb, and mechanical fasteners were used to attach the mortar to the inserts. This modification was incorporated on SC-004, tested successfully to 150 percent of limit load, and then installed on all Block I spacecraft.

Command module static structural-thermal test (ATR 251003). - One objective of this test was to evaluate under simulated entry conditions the structural-thermal characteristics, such as deflections, stresses, gaps, misalinements, and temperatures of the heat shield components. The test was conducted on CM-004A. The CM had been designed with a tight-fitting joint between the crew compartment heat shield and the aft heat shield so that, during atmospheric entry, the hot boundary-layer gases would not enter the cavity between the inner structure and the heat shield. However, during the test, deflection data indicated there was a separation between the aft heat shield and the crew compartment heat shield. A silicone rubber seal was placed at the interface between the two heat shields to prevent hot gases from entering the cavity. This seal was compressed by tightening the bolts that attached the aft heat shield to the inner structure. No additional testing was conducted for this condition, and the addition of the seal was certified by analysis.

Water impact test (ATR 101001). - The Block I landing impact test program was planned to demonstrate the structural integrity of the CM for landing both in water or on land. The first water drop test with a test article representative of the spacecraft used BP-28. This test article was designed to be used for many drops and was constructed so that damaged sections could be replaced with minimal difficulty. Because the manufacturing tooling was in use for flight hardware, BP-28 was constructed differently than flight hardware. For example, the aft heat shield was made from aluminum honeycomb instead of steel honeycomb and therefore required a different total sandwich thickness and different face sheet thickness to obtain the same cross-sectional moment of inertia as the production heat shields.

On October 30, 1964, BP-28 was dropped into water at impact velocities of 34.2 ft/sec vertical and 44.5 ft/sec horizontal, which represented the most severe three-parachute landing condition. The aft heat shield crushed on impact and pierced the aft bulkhead of the inner structure. The test article sank within 2 minutes. Although BP-28 was not a production configuration, it was sufficiently similar to show that a redesign was necessary. Aft heat shield pressure impact data (from one-fourth-scale and full-scale water drop tests) were used to redesign the aft heat shield. The aft heat shield was strengthened on SC-011, SC-017, and SC-020 by using denser honeycomb core in the plus-Z quadrant and chemically milled face sheets varying in thickness from 0.050 to 0.012 inch. Spacecraft 009 was strengthened by bonding doublers onto the heat shield. The BP-28 drop tests and one BP-12A drop test were conducted to verify the integrity of the structural modification made to SC-009. Five additional BP-28 drop tests and two CM-007 drop tests were conducted to verify the structural integrity of the modifications to SC-011, SC-017, and SC-020.

Combined module static test (ATR 131003). - A series of tests was conducted on a stacked CSM (SC-004) to evaluate the integrity of the CSM interface structure for critical maximum $q\alpha$ and first-stage, end-boost loading, to evaluate the integrity of the CM structure in the tension-tie area for critical tension loading at lift-off, and to verify analytical loads and stress analyses. The configuration consisted of a portion of the LET, a CM, an SM, and a short cylindrical section for a base. The SPS tanks were not production models; they were aluminum cylinders with aluminum skirts and were fitted with a thick circular plate inside the cylinder for attachment of the loading fixture. Production tanks were made of titanium and had aluminum skirts. The skirts of the aluminum and titanium tanks were not similar.

During the end of the first-stage-boost test condition, noises were heard emanating from the spacecraft at 140 percent of limit load. Strain and deflection measurements were recorded, and the test was terminated. Inspection revealed extensive damage to the SM aft bulkhead. The bulkhead honeycomb core had crushed adjacent to the outer shell in sectors II, III, and V (fig. 10). Face-sheet-to-core delamination also had occurred adjacent to the outer shell in sectors II and V and in sector II along radial beam 1 on the aft side of the bulkhead. Bond separation had occurred between the bulkhead forward face sheet and a ring in sector II adjacent to radial beam 2 as well as in sectors II and VI adjacent to radial beam 6. Bond separation also had occurred between the bulkhead core and radial beam 1. Two possible solutions to this problem were to strengthen the bulkhead on the test article and all flight vehicles and retest to the design requirement of 150 percent of limit load or to accept the demonstrated capability of 140 percent of limit load. The latter solution was chosen because it was the least costly and did not require a retest. The Block II SM was being designed with a factor of safety of 1.4 for the portion aft of the upper bulkhead. Therefore, the acceptance of a factor of safety of 1.4 was considered logical. No further testing of the first-stage end-boost condition was conducted at that time.

After the tests were completed on the stacked CSM-004 (for first-stage end-boost condition), it was discovered that, although the SM aft bulkhead had been loaded corresponding to the correct total propellant load, bays II and V had been underloaded because of an incorrect simulation of the propellant loading on individual tanks. Although the Block I SPS oxidizer tanks are of equal size, they are filled for flight by filling the sump tank in sector II first and then allowing oxidizer to overflow into the storage tank in sector V. This results in more oxidizer being stored in the sump tank than in the storage tank. Fuel tanks are filled in the same way. Test loads were calculated by dividing the total oxidizer and the total fuel loads equally between the sump and storage tanks. This error caused areas of the aft bulkhead to be loaded to only 122 percent of their end-boost-limit load condition. An additional test was conducted to properly verify the integrity of the aft bulkhead. The SM static test article used in the original tests (SC-004) was no longer available, so the SC-008 SM was used.

Service module static test (ATR 321082). - The test configuration consisted of SM-008 with tanks in bays II and VI. These tanks were modified to include an approximately 3-foot-long section of production-type lower tank and skirt. The other two tanks in bays III and V were the aluminum cylinders used in the SC-004 test. Because one fuel tank and one oxidizer tank had production-type lower sections and skirts, simulated tanks could be used in the other two bays. The CM was represented by a beam arrangement (called a spider), and a cylindrical base section was used.

The test was conducted in February 1968. At 90 percent of limit load, the test was interrupted because of high strain readings in the sector II (oxidizer sump) tank skirt. Inspection revealed no abnormalities, so the test was continued. At 97 percent of limit load, the tank skirt in sector II buckled. The tank skirt failure was located aft of the skirt-to-tank attachment rivet line; it ran from approximately 9 inches to the left of the sector II center line to approximately 27 inches to the right of the center line, when looking inboard. A test of the material properties of the failed structure showed tensile values above specification requirements. The aft bulkhead of the SM distributes the tank skirt loads into the outer shell of the SM and through radial beams adjacent to the tanks. The distribution of stresses on the tank skirt is a function of the stiffness of the tank skirt, the aft bulkhead, and the attachment of the bulkhead to the radial beams and outer shell. The analytically determined stiffnesses used to design these components were in error; this error resulted in the tank skirt being underdesigned. Static load tests previously had been conducted successfully on the SPS tanks and tank skirts by the manufacturer. However, these tests were conducted with the tank skirt mounted to a rigid base, thus producing incorrect boundary conditions on the skirt and resulting in improper testing of the skirt. The tank skirt was modified by adding riveted doublers and was retested successfully to 140 percent of limit load.

These test failures emphasized the need for the test article to be as structurally similar to the flight article as practical because tests of individual components might not provide the proper boundary conditions. The testing of the SC-004 SM using aluminum cylinders to represent the tanks not only produced the incorrect loading into the tank skirts but also produced the wrong load distribution into the aft bulkhead and radial beams of the SM.

Service module dynamic test (ATR 121006). - Three separate dynamic tests involving the Block I SM were conducted. The first test, conducted in June 1965, subjected

SM-007 to the acoustic environment of the launch and boost phases. This test resulted in 31 separate anomalies or failures, such as cracks in radial beam webs, cracked brackets, sheared rivets, broken radial-beam cap-strip tension angles, and a broken radial-beam horizontal rib. The angles that connected the radial-beam stiffeners were replaced with round tubular struts that connected the radial-beam edge members. The cracked brackets were also strengthened. Results of the SM-007 acoustic test indicated that the dynamic response of the vehicle structure was significantly higher than the analytically predicted response, and essentially all equipment and components in the SM had to be requalified to the higher measured vibration levels.

As a result of the SM-007 test, the components were requalified and the primary structure modifications were verified through an acoustic test of a 180° sector of the SM. The 180° sector was built to provide versatility for testing components; that is, shelves could be fitted with equipment while other components were being tested.

Dynamic response data from the SC-002 flight in January 1966 were much lower than similar data from either the SM-007 or the 180° sector test. Those data revealed that the SM-007 and the 180° sector were overtested. Both the SM-007 test and the 180° sector tests were conducted in a horizontal-flow reverberant test chamber, with a volume that was approximately 4 times that of the SM. The overtest was attributed to inadequate calibration and control of the acoustic test facility. Those inadequacies caused the measured vibration response data to be too high, particularly at frequencies less than 150 hertz.

In 1965, a dynamic test of the Block I orbital insertion configuration (LES, CSM, SLA, IU, and S-IVB booster stage) was conducted at MSFC. During the test, torsional oscillating movement of the CM was observed at the CM/SM interface. This anomaly was discussed in the description of the Block I dynamic tests.

Spacecraft/lunar module adapter (ATR 321033). - Static load testing of the adapter subjected the structure to the critical Saturn V ultimate maximum $q\alpha$ loads. The purposes of the tests were to prove the structural integrity of SLA-2 and LTA-10 for the Saturn V flight configuration, to demonstrate the structural compatibility of SLA-2 and LTA-10, and to determine the interaction loads between SLA-2 and LTA-10 during the midboost flight phase. When the applied test load had reached 108 percent of limit load, a loud rumbling noise was heard. The test loads were immediately reduced to zero. Two strain gages showed high residual strains. Investigation in the area of these gages revealed that (1) the inner face sheet of the SLA aft quarter panel had buckled directly aft of the station X_a 583 frame between the minus-Z and minus-Y axes; (2) the web of the aft section ring at station X_a 583 was bent locally; (3) the inner face sheet of the aft quarter panel had buckled locally; and (4) a void was created under the buckled inner face sheet. This void was approximately 3 inches wide by 72 inches long on each side of the 315° splice (45° between the minus-Z and plus-Y axes).

An investigation of the failure revealed that fittings used to mount the pyrotechnic panel thrusters had been omitted from the test article. On flight articles, the fittings are located just aft of the X_a 583 ring at four locations, 45° with respect to the lateral axes. Stress analysis had not shown that these thrusters were necessary to sustain the test loads; therefore, the thrusters were omitted from the test article. Another possible reason for this failure was slippage of the splice plate that joins the upper and lower portions of the SLA at station X_a 583. Test data revealed that, at about 20 percent of the limit load, the stress distribution between the inner and outer face sheets above the X_a 583 ring had changed. This change was attributed to slippage of the bolts in the splice plate. When the load in the splice plate exceeded the amount of load carried by friction between the bolthead and splice plate, the bolts slipped until the shank of the bolt contacted the splice plate. The holes in the splice plate are drilled larger than the bolts to allow clearance for mating of the two sections either with the SLA empty or with the LM installed. In addition to repair of the damaged areas, the following modifications were made to the SLA test article.

1. The thruster fittings were installed.

2. A strap doubler was added to the inner flange of the lower ring at station X_a 583 to prevent the ring from buckling.

3. Panel splices were added beneath the four thruster fittings to help distribute the load from the thrusters into the panels.

4. Additional 0.25-inch bolts were added to the splice plate at station X_a 583, 45°, 135°, 225°, and 315°, to provide additional load-carrying ability across the splice.

5. The torque of all the bolts in the X_a 583 splice plate was increased from 80 ± 10 in-lb to 110 ± 10 in-lb to prevent the splice plate from slipping at low loads.

Before the thruster fittings were installed but after the structure was repaired, a load test was conducted to determine the effect of the repairs on the distribution of stress from the forward SLA section to the aft section. Then, the thruster fittings were installed, and the test was repeated. The second test showed that the stress levels in the area of the thrusters had been reduced by approximately 45 percent.

After the test article was modified, the SLA static test was conducted successfully to 150 percent of limit load. Again, this test demonstrated that the test article configuration should be as structurally similar to the flight configuration as practical.

Block II Ground Test Anomalies

Although considerable static testing had been done to verify the Block I design, an extensive ground test program was required for the Block II spacecraft because of structural redesign, increased weight, changed weight distribution, and updated loads.

During the Block II static test program, several structural failures occurred; some of these led to modifications and retesting. In some cases, a reassessment of the loads and environment revealed that the test conditions were too severe and should be modified based on the latest environment; in these cases, no structural modification or retesting was required. In other cases, structural inadequacies were identified that required design modification and retesting. Only those test failures that required modification or retesting are discussed in this section.

Command module static tests (ATR 222003). - The CM static tests were conducted in three parts, as discussed in the following paragraphs.

Abort load test: The CM test article 2S-2 was subjected to external pressure distribution and internal component body loads simulating the critical flight abort loads. At approximately 148 percent of limit load, cracks occurred in both the inner and outer face sheets near longeron 1 between the plus-Y and plus-Z axes. The upper end of the cracks was on the forward bulkhead at plus-Z, approximately 2 inches outboard of the tunnel wall. The crack followed a circular weld path to longeron 1 where it turned 90° and extended radially outboard along the longeron to the sidewall and down the sidewall adjacent to the longeron. Investigation revealed an excessively thick bond line between the cabin wall outer face sheets and the longeron that allowed movement between the longeron and face sheets. Excessively thick bond lines were also found on all command modules. A strap doubler extending on either side of the longeron was added to all flight command modules to provide increased strength in the failed area. Test article 2S-2 was also modified with the strap doubler and satisfactorily retested to ultimate load. It was known that bond lines made unintentionally thick resulted in reduced properties of the bonded joint. Because most of the command modules had been completed through the bonding stage of manufacturing, only the outside doubler was added to the vehicles.

Main parachute load test: While the CM 2S-2 test article was being subjected to loads representing three-parachute maximum deployment loads at the critical riser pull angle (tangential direction), a structural failure occurred at approximately 128 percent of limit load. The horizontal beam broke loose from gussets 3 and 4, the vertical beams broke loose from the forward bulkhead, and the outer face sheet between gussets 3 and 4 tore loose from the thermal isolation ring and core. Because a flight schedule impact would have resulted if the static test program had been delayed until repairs were made to the 2S-2 CM, CM-102 was diverted to the static test program.

Because of the parachute load test failure, doublers were added to the inside and outside of the tunnel of CM-102 near the parachute riser attach point. After this change, the spacecraft was successfully tested. Because CM-101 was further along in manufacturing, a somewhat different modification was used for that vehicle than for subsequent command modules. Both modifications were verified by static tests. The cause of this anomaly was a design deficiency that resulted from the inability to predict load paths and load distribution accurately. After the main parachute tangential load test, a main parachute vertical load test was conducted. This vertical load test was terminated at approximately 135 percent of limit load when loud noises from within the spacecraft indicated structural failure had occurred. Investigation revealed that three tee brackets connecting the main display console to the forward bulkhead had become unbonded from the lower surface of the forward bulkhead. Inspection of the area beneath the brackets revealed voids between the face sheet and core. Analysis showed the failure was caused by strain incompatibility between the display console and upper bulkhead. The analysis also indicated that the tie between the console and the bulkhead was unnecessary. The voids were repaired, the tees were left detached from the test article, and the test was completed satisfactorily. The display panel connections to the brackets were removed from subsequent spacecraft.

Forward heat shield mortar reaction load test: While testing simulated loads imposed by firing the pilot parachute mortar, the upper support bracket failed at 58 percent of limit load. The bracket was made from fiberglass to provide thermal isolation of the mortar from the heat shield. The bracket was underdesigned because of the inability to predict accurately the material properties in curved laminated fiberglass components. A titanium bracket was found to be thermally acceptable and was designed and tested successfully to 150 percent of limit load.

Combined CM/SM static test (ATR 222002). - Static structural tests were conducted on the mated CM and SM to ultimate load conditions of critical boost phases during the Saturn V launch. The major objective of these tests was to verify the integrity of the primary structure; a secondary objective was to determine the load and stress distribution throughout the CSM. The test article configuration consisted of a short section of the LET used as a fixture to apply loads to the CM, a structurally representative CSM, and a short cylindrical section attached to the aft end of the SM as a base support.

Maximum $q\alpha$ load condition: The applied loads were oriented to produce a maximum compression stress in the outer cap of SM radial beam 2. At 120 percent of limit load, the test was terminated when a strain gage on radial beam 2 failed to stabilize after loading was stopped. Inspection of the test article revealed that the single sway brace had buckled. The sway brace was connected between the apex of radial beam 6 and the SM upper bulkhead. This brace, together with the torsional capability of the radial beams, was designed to provide the torsional load path between the command and service modules. The following three possible causes of the sway brace test load being larger than expected were identified.

1. Misalinement of the test fixture used to apply axial load introduced additional torsion into the sway brace.

2. The radial beam trusses at the upper end of the radial beams were all misalined so that a corkscrew effect occurred when an axial load was applied to the CM. The misalinement exceeded the worst possible tolerance condition.

3. The secondary effects of body loads were not known and therefore were not accounted for in the design of the sway brace. Analytical predictions of this additional torsional load were not possible and the additional load had to be determined by test.

The test fixture was realined, the sway brace was redesigned to a larger and stronger tube, and the test was successfully conducted to ultimate load. Five sway braces were added later when the torsional loads at the interface were determined to be greater than previously predicted.

At 140 percent of limit load during the retesting of the maximum $q\alpha$ load condition, strain gages located on the SM aft bulkhead between the SPS tank and outer shell changed nonlinearly and registered residual strain after the test load was removed. Inspection revealed a face-sheet-to-core delamination on the aft bulkhead. The core beneath the void area was filled with bonding material on the test article and on subsequent spacecraft. No retesting for the maximum $q\alpha$ condition was required because the more critical end-boost condition test would be used for the bulkhead certification.

First-stage end-boost load condition: The first-stage end-boost load condition test was terminated at 120 percent of limit load after a loud noise emanated from the test article. Strain gage readings had been recorded at 120 percent of limit load just before the noise and were recorded again before removing the load. The second reading showed a sharp increase in strain in sector III of the SM aft bulkhead. The increase in strain was attributed to a load redistribution; however, because considerable time would have been required to remove loading fixtures and SM panels to perform a detailed inspection, the test was continued and achieved 140 percent of limit load without any additional problems. Inspection revealed that extensive debonding of the face sheet to core and exterior angle to face sheet had occurred on the SM aft bulkhead. Because of the history of structural failure in the Block I SM aft bulkhead and the difficulty in predicting the failing load of honeycomb structure, modification was judged necessary. The bulkhead was modified in the failed areas on the test article and on subsequent flight service modules by filling the core in bays II and V with bonding material and by installing doublers in each bay designed to prevent separation of the angle from the face sheet. The SM with the modification was successfully retested.

The bulkhead failure was primarily due to an inaccurate prediction of load distribution from the tank skirts into the flat bulkhead and then into the adjacent radial beams and shell. The load path between the tank skirt and shell was considerably stiffer than predicted and thus received more of the tank load than predicted when the bulkhead was designed.

Flight Anomalies

The only significant structural anomaly encountered in the flight test program occurred during the first-stage boost phase of the Apollo 6 mission — the second Saturn V flight and the last Block I mission. Approximately 2 minutes 13 seconds after lift-off, abrupt changes of strain, vibration, and acceleration were indicated by onboard instruments in the S-IVB, IU, SLA, LM, and CSM. Airborne photography showed objects falling from the area of the SLA (SLA-9); however, the spacecraft continued to sustain the required loads, and the mission was not impaired.

A failure investigation was begun immediately; however, because the SLA is not recovered after a mission, the investigation was limited to analysis of flight data, airborne photography, manufacturing history (inspection records and material review items), ground test data, and review of design and stress analysis data.

The findings of the various reviews and studies were that no basic weakness existed in the SLA design and that the SLA loads at the time of the anomaly were less than those demonstrated in the ground test program. When the anomaly occurred, two independent pressure transducers registered pressure drops indicating a hole or holes had opened in the spacecraft. The suspected holes, the shift in instrument readings, and the photographs of objects falling from the SLA led investigators to the conclusion that portions of the SLA honeycomb panels had failed and had fallen from the spacecraft. It was also concluded that because the designed structural capability of the SLA was more than adequate for the flight loads experienced, the failure occurred because of an undetected manufacturing defect. One possible cause of the failure was separation of face sheets from the honeycomb core because entrapped moisture in the honeycomb cells became heated during boost, thereby increasing the pressure inside the cells until the face sheets were blown off.

To eliminate the problems associated with entrapped moisture on each subsequent SLA, small holes were drilled in the inner face sheets of the panels to permit venting during ascent. Cork insulation was applied over the entire external surface, whereas only the lower portion of the SLA had been insulated with cork on previous flight tests. The reduced SLA skin temperatures afforded by the increased insulation would lower thermal stresses, reduce pressure inside the honeycomb cells, and prevent reduction in material properties caused by higher temperatures.

After the manufacture and inspection of SLA-9 but before the SLA-9 flight, radiographic inspection of splices was begun to supplement the ultrasonic inspection. This improved the inspection of splice joints and resulted in the detection of a slipped blind splice plate at station X_a 709 on a later SLA. A postflight review of the SLA-9 C-scan records (from ultrasonic inspection) indicated that the blind splice plate at station X_a 709 also could have been mislocated or slipped, thereby weakening a joint. To eliminate the possibility of a defective splice joint at station X_a 709, this joint was redesigned to enable more accurate inspection. As shown in figure 21, the honeycomb panel splice joint at station X_a 709 on SLA-9 consisted of an inside (blind) and an outside splice plate on the outer face sheet, two core splices, and a splice plate on the inner face sheet arranged such that the splice plate edges and the core splices were at approximately the same stations. The inspection procedure used on SLA-9 and each previous SLA included ultrasonic inspection of all honeycomb panels with C-scan printouts of the ultrasonic inspection being made and retained for permanent record. The alinement of splice plate edges and core splices, which used a foam core filling material, made the interpretation of the ultrasonic inspection data extremely difficult. To remedy this situation, the splice joint at station X_a 709 was redesigned by removing the blind inside splice plate from the outer face sheet, enlarging the outside splice plate on the outer face sheet, and relocating the core splices so that the plate edges and splices were not alined. This provided a clear area for ultrasonic and radiographic inspection and made interpretation of these inspections much easier and more accurate. This redesign was implemented on SLA-22 and each subsequent SLA; all other SLA panels had been manufactured at that time. The redesign was considered a product improvement and not a mandatory design change.

Although the cause of the Apollo 6 structural anomaly could not be determined conclusively, the most likely causes have been eliminated. The inspection records of each SLA after SLA-9 have been thoroughly reanalyzed, and the aforementioned modifications have been implemented to provide confidence in the flightworthiness of each SLA. No SLA structural anomalies have occurred since the Apollo 6 flight.

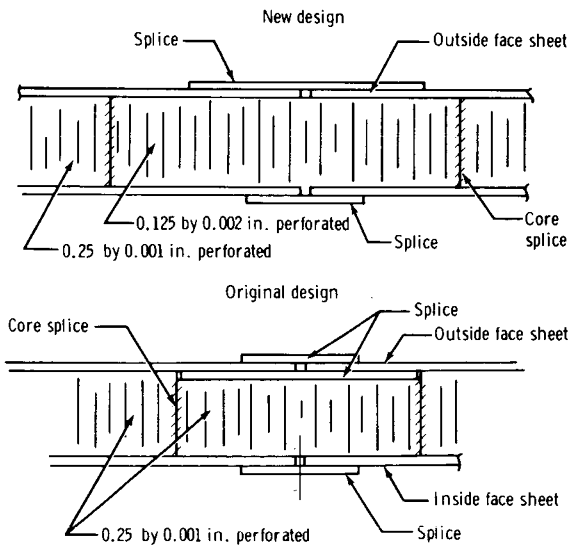


Figure 21. - Honeycomb splice joint.

The experiences associated with this anomaly indicate that, in the design of honeycomb panel structures, avoiding overlapping edges and splices and making the structure easy to inspect should be strong design considerations. The possible detrimental effects of entrapped moisture in honeycomb core cells should also be considered.

CONCLUDING REMARKS

Many of the structural failures that occurred in the ground test program were caused by inaccurate predictions of load paths and load distribution. Two examples of these are the failures of the Block I and Block II service module aft bulkheads and the failure of the single sway brace. The ability to make accurate mathematical models of the structure and to predict load distribution progressively improved during the Apollo Program. This ability will be useful in providing more accurate analyses for future programs. However, a rigorous test program should be conducted to uncover any design or manufacturing weaknesses.

The use of honeycomb sandwich structure has some inherent difficulties that should be considered for future programs. The inspection of honeycomb structure is extremely important, and every effort should be made to avoid a design that may complicate the inspection. For example, in the design of joints, overlapping core and face sheet splices and doublers should be avoided. Good inspection methods are now available, and the use of honeycomb should not be excluded on future spacecraft. The use of perforated core should be avoided on future spacecraft because of the possibility of moisture being absorbed by the honeycomb cells.

No major schedule perturbations were caused by structural problems. Even the one flight structural failure on Apollo 6 did not prevent the success of that mission. Modifications to the structure required by test failures were made without major redesign. The axial-torsional coupling discovered during the Marshall Space Flight Center dynamic tests showed the torsional loads to be almost an order of magnitude greater than those used for design; however, loads were reduced simply by installing additional aluminum tube sway braces at the command module/service module interface.

The testing of components requires extreme care to assure that the proper boundary conditions are imposed on the component. For example, problems that occurred with the service module service propulsion system tank skirts and aft bulkhead would have been avoided had the proper tanks been used in the first command-and-service-module-type static test. Whenever possible, test hardware should be structurally similar to flight hardware to eliminate this type problem.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, March 1, 1974
914-50-31-00-72

REFERENCES

1. Anon.: Structural Analyses of Apollo Block II Spacecraft. Rept. SD67-1103, North American-Rockwell Corp. (Downey, Calif.), Dec. 1968.

2. Anon.: Postlaunch Report for Mission AS-201 (AS-009). NASA TM X-59649, 1966.

3. Anon.: Postlaunch Report for Mission AS-202 (AS-011). NASA TM X-60788, 1966.

4. Anon.: Apollo 4 Mission Report. NASA TM X-61639, 1968.

5. Anon.: Apollo 6 Mission Report. NASA TM X-62567, 1968.

6. Anon.: Apollo CSM 105-AV Acoustic and Vibration Test Program. Rept. SD68-466, North American-Rockwell Corp. (Downey, Calif.), Sept. 1968.

APPENDIX A

DEVELOPMENT TESTS SUMMARY

LAUNCH ESCAPE TOWER

ATR[1] 502-3 — Structural Tubing Test

Tests were conducted to evaluate the ability to fabricate welded tube joints for tower use.

BOOST PROTECTIVE COVER

ATR 131005 — Boost Protective Cover Static Structural Test

Tests were conducted to determine the maximum load-carrying capability and mode of failure of the typical lap joint sections of the soft boost protective cover (BPC).

ATR 391013 — Apollo Boost Protective Cover Crew Hatch Window Panel Structural Test

Tests were conducted (1) to determine the load-deflection characteristics of the window panel assembly under critical Apollo mission aerodynamic pressure, (2) to provide structural verification of the window panel assembly to withstand critical Apollo mission requirements without failing at ultimate loading conditions, and (3) to determine the ultimate strength of the window panel assembly and failure mode caused by mission aerodynamic pressure.

ATR 391020 — Nomex-Layered Aft Boost Cover

Tests were conducted (1) to demonstrate the structural integrity of the BPC on the command module (CM) for the normal and backup tower-jettison mission under conditions of 250° F temperature and simulated inertial loading, and (2) to determine the load-deflection characteristics of the aft boost cover under the two tower-jettisoning conditions.

---

[1] Apollo Test Requirement.

COMMAND MODULE

ATR 112-B — Main Parachute Riser Attachment Test

Tests were conducted to verify the structural integrity of the parachute riser attachment assembly for the boilerplate CM when loaded by riser harness at critical angles.

ATR 112-1 — Main Parachute Riser Attachment Test

Tests were conducted to determine failure loads of the parachute riser attachment assembly for the boilerplate CM when loaded by the tension strap at critical angles.

ATR 208-2.2 — Command Module Reentry Heat Shield Component Test

Tests were conducted to determine the structural and thermal characteristics of ablator and honeycomb.

ATR 211-5 — Main Longeron to Parachute Typical Attachment Test

Tests were conducted to determine the ultimate strength of a typical longeron-to-parachute attaching lug.

ATR 212-1 — Property Tests of Candidate Apollo Observation Window Materials

Tests were conducted (1) to determine the effects of vacuum, cryogenic temperatures, and charged-particle radiation on various glass materials, together with the thermal and mechanical properties of the materials, and (2) to investigate optimum methods for sealing and protecting window panels.

ATR 212-4 — Thermal Test of Sample Command Module Heat Shield Window Glass

A test was conducted to determine the thermal gradient through the glass under a simulated, front-face, temperature-time history.

ATR 331030 — Meteoroid Shielding Tests

Tests were conducted (1) to develop and verify empirical formulas for the response of the command and service module (CSM) to meteoroid impact, and (2) to verify the integrity of these structures.

ATR 214-2A — Aft Heat Shield Flexibility

These tests were conducted (1) to verify analytical methods for predicting the stresses and deflections of a hemispherical sheet under localized unsymmetrical loads, and (2) to support the sphere and the sphere-toroid programs used for the aft heat shield.

ATR 471001 — General Instability of Sandwich Cylinders Subjected to Pure Axial Compression and Pure Bending

These tests were conducted to verify the analytical methods for predicting general instability failure of sandwich cylinders subjected to axial compression or bending.

ATR 471002 — General Instability of Sandwich Cones Subjected to Pure Axial Compression

These tests were conducted to verify analytical methods for predicting general instability failure of sandwich cones subjected to axial-compression load. These tests supported the methods prepared for use on the CM and spacecraft/lunar module (LM) adapter (SLA).

ATR 214-3A — Evaluation of Mechanical Properties of Some Rigid Foams

The test was conducted (1) to determine the mechanical properties of rigid foam and (2) to determine the feasibility of using a rigid foam as core material in later sandwich cylinder tests. This test supported ATR 471001.

ATR 217 — Command Module Bulkhead Component Test - Tee and Beam Configuration

The test was conducted to determine the strength characteristics of tees with different flange thicknesses when bonded to aluminum alloy honeycomb beams.

ATR 218 — Apollo Steel Honeycomb Joint Test

This was a proof test of Apollo joint designs; it also verified analytical methods. These data verified the load-carrying ability of typical Apollo joints. Design variations were tested to verify analytical methods for joint design.

ATR 220 — Steel Honeycomb Foundation Modulus Test

This test was conducted to establish the honeycomb core foundation modulus that describes the load response of the face sheets. This test, in support of ATR 218, was conducted (1) to permit design of ATR 218 test specimens and (2) to verify test methods.

ATR 223 — Command Module Penetration Seal Leak Tests

These tests were conducted (1) to determine the helium leakage rates of butyl rubber O-rings and molded-in-place butyl rubber gaskets proposed for sealing inner structure penetrations, and (2) to determine the sealing properties of reused O-rings and the compression set of the gaskets.

ATR 331034 — Aft Heat Shield Water Impact Test

This test was conducted to determine the dynamic effect on a composite structure from water impact.

ATR 331035 — Impact Load Test - Command Module Aft Heat Shield Quarter Panel

The impact load test was conducted (1) to determine the structural response of a modified aft heat shield quarter panel to impact loading, (2) to determine the stress, load or pressure, and acceleration characteristics of the test panel under impact conditions, and (3) to develop a method to determine load and impact pressures for other test series.

ATR 331036 — Aft Heat Shield Component Test - Pyrotechnic Pressure

The test was conducted (1) to evaluate the structural integrity of the proposed aft heat shield configuration for water impact, and (2) to verify the analytical stress analysis for impact loading.

ATR 331037 — Apollo Brazed Steel Honeycomb Repair Test

The test was conducted (1) to verify existing repair design criteria and (2) to establish design data for new repair methods.

ATR 252 — Particle Impact Test of Two-Sheet Structures

This test was conducted (1) to investigate the resistance of two-sheet structures to penetration by hypervelocity projectiles to extend and verify analytical methods, and (2) to investigate parameters and structural configurations of interest to Apollo that were not included in ATR 331030.

ATR 291 — Hatch Window Breakage Feasibility

This test was conducted to determine the feasibility of, and the effort required for, breaking and removing the hatch window glass to provide ventilation for the crew after landing.

ATR 321013 — Fasteners and Joint Tests

These tests were conducted to obtain design allowables for various types of joints in honeycomb structure.

SERVICE MODULE

ATR 304 — Aft Bulkhead Attachments

Tests were conducted on attachments of the radial beam shear webs to the aft bulkhead and the service propulsion system (SPS) tank support structure. A failure during this test required rework and a repeat of the test as ATR 304-2.

ATR 301-5 — Radial Shear Web

Tests were conducted to verify the design approach for an extremely light, partial-tension field beam. This beam was manufactured by machining integral stiffeners, webs, and caps from a thick aluminum plate.

ATR 301-3 — Aft Bulkhead

Tests were conducted to verify the design approach on a section of the aft bulkhead under simulated spacecraft loading.

ATR 301-1 — Outer Panel

This test was conducted on a typical outer panel under axial and simulated air loads. to verify the design approach.

ATR 301-12 — Outer Panel Joint

Tests were conducted to verify the adequacy of blind attachments to honeycomb panels.

ATR 304-2 — Aft Bulkhead Components

Additional testing of local attachments on the aft bulkhead was performed because of a failure on ATR 304.

ATR 301-7 — Friction Joint

Tests were conducted to determine the local characteristics associated with attaching the outer panels to the radial shear webs and bulkheads with oversized holes.

ATR 301-9 — Panel Edge Member

This test was conducted to determine the basic load path from honeycomb panel through an extruded edge member to the support structure.

ATR 321013 — Fasteners and Joints

These tests were conducted to determine design allowables on methods of fastening clips, brackets, and supports to honeycomb structure.

ATR 304-1 — Service Module Aft Bulkhead Splice and Shear Panel Test

Tests were conducted to evaluate the bonded splice and shear panel tie of the service module (SM) aft bulkhead.

ATR 309-1 — Joint Tests; SM to SLA

Tests were conducted (1) to determine the structural integrity of the barrel nut/ epoxy-filled joint design, and (2) to determine the limit and ultimate load-carrying capability of the joint.

ATR 309-2 — Fasteners and Joint Tests

Tests were conducted (1) to determine design allowables for spacecraft (SC) joints such as angles, tees, channels, et cetera, and (2) to determine ultimate load-carrying capabilities for spacecraft joints.

ATR 321007 — Adjustable Radial Beam Pads

This test was conducted to verify a late design change, made after initial testing of ATR 301-5. This test was performed on the subcomponent level because the change went into effect after SC-004 was built.

SPACECRAFT/LM ADAPTER

ATR 402-1 — Panel Thermal Tests

These tests were conducted on 21 small honeycomb panels representative of the SLA shell structure. The panels were tested to failure at elevated temperatures to substantiate design allowables.

ATR 402-2 — Joint Tests

Tests on these joints were conducted to verify the design approach on 12-inch-wide sections of each SLA joint at elevated temperatures.

ATR 403-2 — Lunar Excursion Module Support Structure

Tests were conducted on two specimens, representative of the LM (formerly LEM) attachment area of the SLA, (1) to verify the design approach and (2) to supplement the stress analysis.

ATR 322012 — The SM/SLA Joint

Tests were conducted on a small section of the SM/SLA joint to limit and ultimate tensile loads.

APPENDIX B

COMPONENT TESTS SUMMARY

LAUNCH ESCAPE TOWER

ATR[1] 500-1 — Launch Escape Tower Separation Fitting Test

Tests were conducted to verify the structural integrity of the launch escape tower (LET) attachment housing for design loads.

ATR 502-2 — Launch Escape Tower Attachment Fitting Test

Tests were conducted (1) to determine the strength and failure mode of the attachment between the LET and tower skirt, and (2) to verify stress analysis methods.

BOOST PROTECTIVE COVER

ATR 505-1 — Boost Protective Cover Panel Fastener Test

Tests were conducted (1) to determine the shear characteristics of the boost protective cover (BPC) panel fastener, (2) to determine if the BPC fastener joint could sustain the following ultimate design loads without failure: configuration A - 75 lb/in. (150 pounds per fastener), and configuration B - 125 lb/in., and (3) to determine the failure load and mode of failure of each specimen.

ATR 391008 — Boost Protective Cover Longitudinal Splice

Tests were conducted (1) to determine the shear strength and deflection characteristics of the longitudinal splice joint, and (2) to determine the failure load and mode of failure of the longitudinal splice joint.

---

[1] Apollo Test Requirement.

ATR 331022 — Static Test of Base Section Subassembly, Inner Structure and Aft Heat Shield Substructure

Tests were conducted (1) to demonstrate the strength of the command module (CM) heat shield for the 20g reentry condition, (2) to determine load-deflection data, and (3) to verify analysis methods. After these tests, the aft heat shield was used in conjunction with boilerplate elements for a water impact test.

ATR 331023 — Static Test of Typical Inner Structure to Heat Shield Attachment, Station X_c 42.67

Tests were conducted (1) to determine the joint shear strength and deflection characteristics and (2) to determine the failure load and mode of failure of the typical inner structure to heat shield slip joint at station X_c 42.67.

ATR 331024 — Static Test of Support Brackets of the CM Helium, Potable Water, and Fuel Tanks

Tests were conducted (1) to demonstrate by a static test the the support-bracket assembly and installations could sustain limit-design loads without yielding and could sustain ultimate-design loads, and (2) to verify the analysis methods.

ATR 331025 — Test of Modular Element of the CM Lower Equipment Bay

Tests were conducted (1) to demonstrate by a static test that the individual electronic compartments would sustain limit-design loads without yielding and would sustain ultimate-design loads without failure of the mounting-clamp assemblies, and (2) to obtain load-deflection data.

ATR 331026 — Static Test of Typical Section of the CM Lower Equipment Bay

Tests were conducted (1) to determine whether the action of the attachment clamp is affected by boost loads, (2) to determine whether the lower equipment bay (LEB) section would sustain limit-design loads without yielding of the mounting assemblies, (3) to determine whether the LEB section would sustain ultimate-design loads without failure of the mounting assemblies, and (4) to obtain load-deflection data.

ATR 331027 — Typical Attachment Test, Launch Escape System Tower and Forward Heat Shield to Inner Structure

Tests were conducted (1) to determine LET bolt torque requirements for obtaining a specified bolt preload, (2) to determine the effects of axial preloading in the bolt during application of critical mission condition loading, (3) to demonstrate that the joint could sustain limit-design loads without yielding and ultimate-design loads without failure, and (4) to determine load versus deflection characteristics and strain characteristics of the joint.

ATR 331029 — Test of CM Inner Cabin Window Panels and Seals

Tests were conducted (1) to determine the validity of the window seal configuration, (2) to ascertain that the leak rate was within acceptable limits, (3) to determine the ability of the inner cabin window assembly to sustain limit-design loads without yielding and ultimate-design loads without failing, (4) to determine deflections at selected locations, and (5) to find maximum load capabilities and mode failures.

ATR 331041 — Test of CM and Heat Shield Window Panel and Seals

Tests were conducted (1) to verify the ability of the window glass, retainer, and panel to sustain the ultimate-design aerodynamic pressure without failing, (2) to define the airload versus deflection and strain characteristics of the heat shield window panels, (3) to verify the ability of the heat shield window assemblies to sustain the most critical entry heating environment without failing, and (4) to evaluate thermally induced stresses and deflection characteristics of window glass and retainers.

ATR 219 — Structural Test of Crew Compartment Heat Shield Stringer

Tests were conducted (1) to determine the spring rate of the heat shield stringer under transverse loading when fully compressed, half extended, and fully extended, (2) to determine the allowable tensile load of the assembly, and (3) to determine the mode of failure under transverse loading.

ATR 331042 — Test of CM Crew Hatch Tongue and Groove Edge Members, Heat Shield

Tests were conducted (1) to evaluate the structural integrity of joint edge members under loads, (2) to determine design-limit and ultimate-load values under the Apollo mission environment, and (3) to determine the mode of failure in tension and compression.

ATR 331033 — Command Module/Service Module Compression Shear Tie

Tests were conducted (1) to demonstrate that the command module/service module (CM/SM) interface shear compression and tension tie could sustain ultimate-design loads without failing, (2) to verify analytical-loads analysis of the compression-shear pad, and (3) to determine the mode of failure of the CM/SM interface.

ATR 331054 — Forward Cylinder/Longeron Gusset Assembly, Static Structural Tests

Tests were conducted to demonstrate that the forward cylinder gusset assemblies would sustain limit-design loads without yielding and ultimate-design loads without failing when subjected to drogue or main parachute wraparound loads.

ATR 391022 — Frangible Nut, LET/CM Interface Joint

Tests were conducted to verify the structural integrity of the frangible nut and LET/CM interface joint for spacecraft (SC) 011 and subsequent spacecraft.

ATR 321011 — Reaction Control System Engine and Tank Supports

Tests were conducted on the tank support structure to simulated dynamic loading using equivalent static loads.

ATR 131004 — The CM/SM Fairing

Tests were conducted to verify the adequacy of the CM/SM fairing for the ultimate boost differential pressure and umbilical disconnect loads.

SPACECRAFT/LUNAR MODULE ADAPTER

No component tests were conducted on the spacecraft/lunar module adapter.

APPENDIX C

COMPLETE MODULE TESTS SUMMARY (BLOCK I)

LAUNCH ESCAPE TOWER

ATR[1] 500 — Structural Test of Launch Escape Tower

Tests were conducted (1) to verify the structural integrity of the launch escape tower (LET) for critical flight loading conditions, (2) to determine the ultimate strength and failure characteristics of the tower, and (3) to determine the deflection characteristics of the tower.

COMMAND MODULE

ATR 131003 and ATR 131006 — Combined Module Static Tests - Command Module and Service Module

Tests were conducted (1) to evaluate the integrity of the command module (CM) interface structure for critical maximum $q\alpha$ and end-boost first-stage loading, (2) to evaluate the integrity of the CM structure in the tension-tie area for critical tension loading at lift-off, and (3) to verify the analytical loads and stress analysis.

ATR 251001 and ATR 251002 — Command Module Static Structural Tests

Tests were conducted (1) to demonstrate by a series of static tests simulating various flight environments that the CM or component assembly of the CM would sustain ultimate test loads without failure, (2) to obtain load-deflection data, and (3) to verify analysis methods. Test conditions included three main parachute load conditions, pilot parachute mortar loads, drogue parachute deployment load, crew couch attach loads, abort loads, and 165 percent of abort loads.

ATR 251003 — Command Module Static Structural-Thermal Test

Tests were conducted (1) to perform a design evaluation of the CM heat shield system under Block I heat load trajectory 3A overshoot entry, trajectory-simulated environment, (2) to verify the ability of the heat shield strain isolation support system to function properly during entry without jeopardizing the integrity of the ablative thermal-protective system, (3) to evaluate the structural-thermal characteristics (deflection, stress, gaps, misalinements, and temperature) of heat shield components

---

[1] Apollo Test Requirement.

under entry conditions, and (4) to evaluate the performance of the thermal-protective (insulation) system to limit the inner-structure outer-surface temperature to 200° F

ATR 111014 — Command Module Static Tests, Forward Section

A series of tests was conducted to demonstrate that the CM Earth-landing system support structure would sustain limit-design loads without yielding.

SERVICE MODULE

ATR 131007 — Engine Mount Stiffness Test

Tests were conducted to determine the stiffness of the Block I service propulsion subsystem (SPS) engine mounting. Ultimate engine thrust loads were also applied.

ATR 131003 — Service Module Static Structural Test

Tests were conducted that subjected the service module (SM) structure to the critical Saturn V limit and ultimate boost loads. Thermal environments were not applied.

ATR 321082 — Service Module Aft Bulkhead Test

Tests were conducted to demonstrate the structural capabilities of the modified Block I SM aft bulkhead and SPS propellant tanks with skirts representative of spacecraft (SC) 020 to the loading environment of the Saturn V end-of-first-stage boost condition.

SPACECRAFT/LUNAR MODULE ADAPTER

Tests (ATR 321031 and ATR 321033) were conducted that subjected the spacecraft/lunar module (LM) adapter (SLA) structure to the critical Saturn I-B and Saturn V limit and ultimate maximum $q\alpha$ loads. The test for the Saturn I-B loads used a flight stiffener, and the test for the Saturn V loads used LM test article 10 (LTA-10). Tests with LTA-10 also were conducted to demonstrate the structural compatibility of SLA-2 and LTA-10 and to determine the interaction loads between LTA-10 and SLA-2.

APPENDIX D

DYNAMIC TESTS SUMMARY

COMMAND MODULE DEVELOPMENT TEST

ATR[1] 205 — Vibration and Acoustic Tests of Typical Command Module Panels

These tests were conducted (1) to determine acoustic transmissibility and sonic-induced vibration of complex structural panels when subjected to narrow- and broad-band random vibration as well as reverberant and progressive wave acoustic excitation, (2) to evaluate the response of complex panels to narrow- and broad-band random vibration excitation, (3) to determine natural vibration response modes and structural damping coefficients of complex panels, (4) to determine natural response modes and damping coefficients of ablative-covered heat shield panels and to evaluate the fatigue strength of ablative material bonding methods at the predominant panel response frequency, and (5) to evaluate the effect of elevated temperatures (entry heat loads) on vibration response characteristics of ablative-covered heat shield panels.

COMMAND MODULE COMPONENT TEST

ATR 321025 — Dynamic Tests of Support Brackets of the Command Module Helium, Potable Water, and Fuel Tanks

These tests were conducted (1) to determine the structural response under sinusoidal excitation (mechanical vibration), and (2) to determine the structural integrity under random vibration.

ATR 331053 — Dynamic Test of Typical Section of the Command Module Lower Equipment Bay

This test was conducted (1) to evaluate the lower equipment bay (LEB) structural response in the dynamic environment, (2) to appraise the vibration input to the individual electronic components when mounted in the LEB, (3) to evaluate coldplate response when mounted in the LEB and subjected to a dynamic environment, and (4) to appraise the response of the electronic unit attachment clamps when mounted in the LEB and subjected to a dynamic environment.

---

[1] Apollo Test Requirement.

SERVICE MODULE COMPONENT TEST

ATR 321011 — Reaction Control System Engine and Tank Support Test

This test was conducted to simulated dynamic loading using equivalent static loads.

ATR 311002 — Reaction Control Subsystem Module Acoustic Test

This test subjected a reaction control system (RCS) quadrant on a large panel and a complete RCS module and service module (SM) panel to an acoustic environment.

COMMAND MODULE TEST

ATR 121006 — Spacecraft Acoustic Environmental Test

This test was conducted on spacecraft (SC) 007 to verify the structural integrity of the spacecraft when subjected to a laboratory simulation of the maximum acoustic environment anticipated during launch. Acoustic attenuation and vibration response characteristics of the structure were determined.

SERVICE MODULE TEST

ATR 121006 — Service Module Acoustic Tests

These tests were conducted on SC-007 to verify the adequacy of the spacecraft when subjected to acoustic environments with simulated subsystems installed.

APPENDIX E

STATIC STRUCTURAL TESTS SUMMARY (BLOCK II)

LAUNCH ESCAPE SYSTEM COMPONENT TEST

ATR[1] 392002 — Apollo Launch Escape Tower Static Structural Test - Block II

Tests were conducted to demonstrate the ability of the Block II launch escape tower (LET) and LET/command module (CM) joint structure to sustain Saturn V abort condition ultimate loads without failure.

ATR 332117 — Boost Protective Cover Tower Leg Fairing

Tests were conducted (1) to evaluate the structural integrity and to establish the mode of failure of the boost protective cover (BPC) tower leg fairing, and (2) to demonstrate the failure modes resulting from the Saturn V maximum $q\alpha$ abort pressure loading.

COMMAND MODULE COMPONENT TESTS

ATR 332172 — Main Display Console Static Structural Test

Tests were conducted to demonstrate that the main display console panels and supporting structure could sustain a vertical inertia load of 78g.

ATR 332113 — Command Module Thermal Isolator Ring Static Test

Tests were conducted to verify the structural integrity of the CM forward tunnel isolation ring.

ATR 332204 — Static Test of Nylon Sea Hoisting Sling Assembly, CM-108 and Subsequent Vehicles

Tests were conducted (1) to verify the ability of the nylon sea hoisting sling assembly, its attaching hardware, and CM backup structure to sustain ultimate design load without failing, (2) to determine the ultimate capability and failure mode of the nylon sling, and (3) to determine the amount of degradation caused by salt water soaking of the nylon sling.

---

[1] Apollo Test Requirement.

COMMAND MODULE TESTS

ATR 222003 — Spacecraft 2S-2 CM Static Structural Test

Tests were conducted (1) to verify the adequacy of the CM structure to withstand design-ultimate loads simulating the critical flight-loading environment without failing and design-limit load without yielding, and (2) to determine stress levels, load distributions, and deformations of the structure under loads.

ATR 222015 — Block II CM (2S-2) Static Test in Support of Command and Service Module 103 and Subsequent Spacecraft

Tests were conducted (1) to verify that the CM structure could withstand design-limit and ultimate loads, and (2) to determine stress levels, load distributions, and deformations of the structure under load. Test conditions were at room temperature and included three main parachute deployment load tests, drogue parachute wraparound load (abort case) (both repeats of ATR 222003), docking ring separation reaction load on the CM tunnel, CM cabin burst pressure test (repeat of ATR 222003 on new combined hatch), and docking ring interface point contact load.

ATR 222020 — Block II CM Parachute Load Static Test in Support of Command and Service Module 109 and Subsequent Spacecraft

Tests were conducted (1) to verify that the CM structure could withstand design-limit loads without yielding and ultimate loads without failing, and (2) to determine stress levels, load distributions, and deformations of the structure under loads.

ATR 332141 — Apollo CM Inner Structure Crew Couch Strut Attachments Static Structural Tests

Tests were conducted (1) to demonstrate the structural integrity of the crew couch attachments to sustain design-ultimate loads without failing, and (2) to determine the maximum load-carrying capability and failure mode.

SERVICE MODULE

ATR 222005 — Apollo CM to Service Module Fairing Static Test

Tests were conducted to demonstrate that the Block II CM/service module (SM) fairing could sustain Saturn V boost-phase limit and ultimate differential pressures.

ATR 332071 — Static Test of Reaction Control System Tank (Fuel and Helium) Brackets and Mounting on SM Panel

Tests were conducted (1) to verify the structural integrity of the reaction control system (RCS) fuel and helium tank brackets for the critical mission loads, (2) to verify the structural integrity of the mounting of the RCS tank brackets to the SM panel, and (3) to determine the structural characteristics (i.e., load deflection and stress) of the RCS panel and tank brackets.

ATR 332072, 312003-2 — Static Test of SM RCS Panel and RCS Oxidizer Bracket Mounting Assembly

Tests were conducted (1) to verify the structural integrity of the redesigned RCS panel splice at station X_s 287 under combined shell and tank loads, (2) to verify the structural integrity of the SM and CM oxidizer tank brackets and the attachment of these brackets to the RCS panel under mission load environment, (3) to determine the structural characteristics of the redesigned panel (i.e., deflection and stress produced by mission loads, maximum $q\alpha$, and dynamic forces), and (4) to determine the maximum load-carrying capability of the panel/brackets.

COMMAND AND SERVICE MODULE STACK TESTS

ATR 222002 — Apollo Combined Module Static Tests (2S-2)

Tests were conducted (1) to evaluate the structural integrity of the combined modular structure for boost-phase aerodynamic and inertial loads, and (2) to determine load and stress distribution within the vehicle.

ATR 222013 — Apollo Block II CM/SM Stack Static Test

Tests were conducted to verify the structural integrity of the CM/SM interface with the SM radial beam configuration modified to the six sway braces. The latest Saturn V maximum $q\alpha$ loads were imposed for the most critical condition to demonstrate that the CM/SM structure could withstand limit and ultimate loads.

ATR 222014 and ATR 222018 — Block II CM/SM Stack Static Test - Saturn V First-Stage End Boost

Tests were conducted to demonstrate that the CM/SM structure could withstand limit and ultimate Saturn V first-stage end-boost loads.

ATR 222017 — Apollo Block II CM/SM Stack Static Test - Saturn V One-Engine-Out Condition

Tests were conducted to determine the ability of the launch escape system (LES)/CM and CM/SM interface and supporting structure to withstand the critical load orientations of the Saturn V one-engine-out condition.

NASA-Langley, 1974 S-400