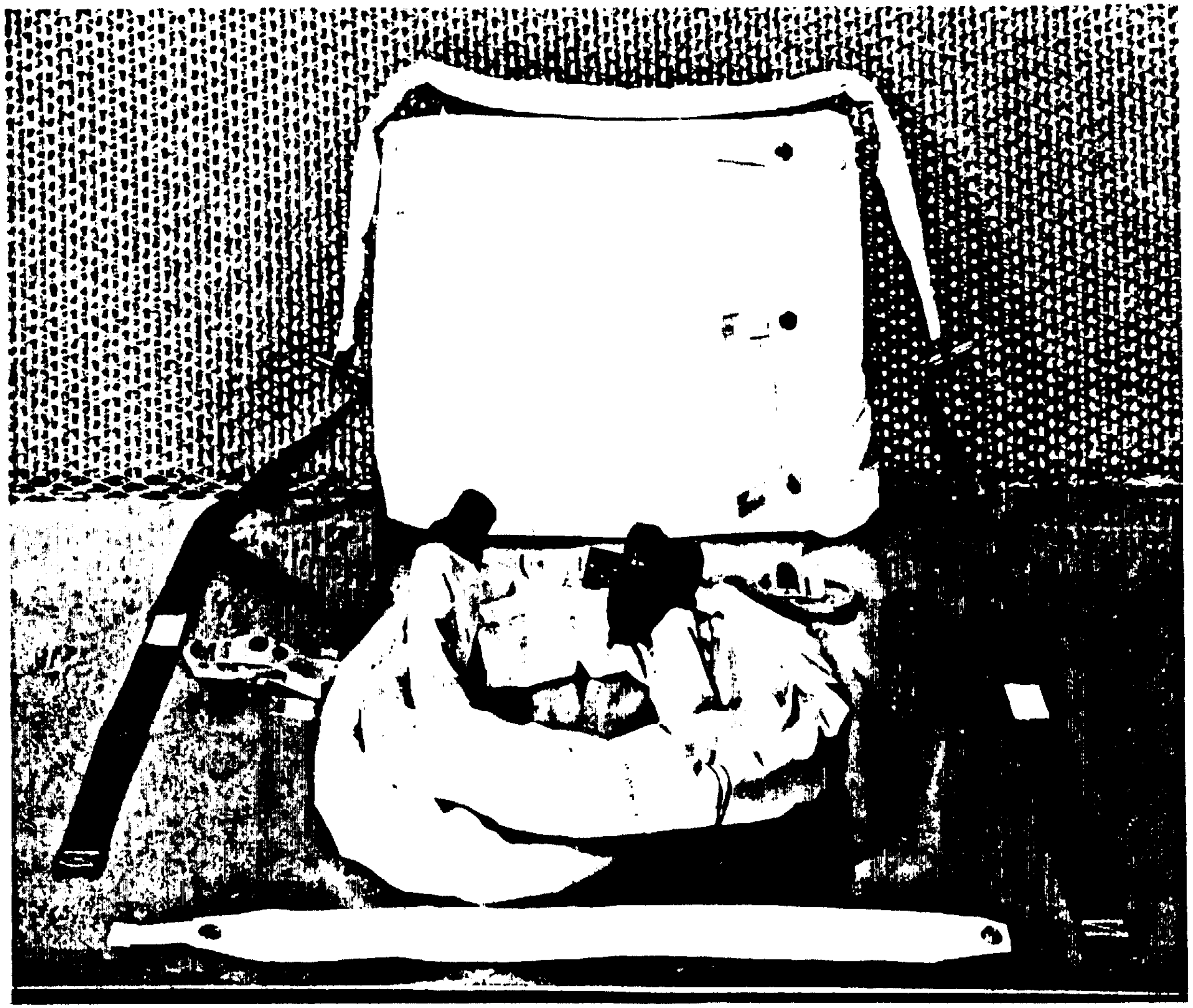

Figure 4-30.- Buddy secondary life support system.

4.10.2.1 Command module crew station and equipment.- Figure 4-31 shows the general arrangement of the command module crew station. Changes and additions to the crew station and crew equipment were continuous throughout the Apollo program. The development of the couch, restraint and impact attenuation systems are discussed in section 4.4.4. The development of displays and controls are discussed in section 4.4.10. The problems associated with the development of the crew equipment items were discovered from use and comments by crewmen. Prior to the approval of a design for flight, the items were subjected to hardware design reviews, bench evaluations, mockup evaluations, zero-gravity water tests, high-fidelity fit and function tests, and, finally, manned-chamber evaluation under simulated altitude conditions. During the early crew interface tests, the design remained fluid and changed, as required, with each review.

Crew equipment engineers learned to remain closely involved with the equipment from the time of initial design concept until completion of the postflight analysis. After the Apollo I fire, it became mandatory to make spacecraft cabin materials less flammable. This new emphasis completely changed the design philosophy of the crew equipment. The design process began with new ground rules and new restrictions that required the use of nonflammable materials.

As experience increased, changes to the equipment decreased. Designers were better able to anticipate the requirements of the Apollo missions. Eventually, a point of minimum change and maximum efficiency was attained, this being a fine blend of design intuition and crewman participation in the development effort.

As the program advanced, additional mission activities included wide-ranging scientific endeavors. This change was reflected into the crew station/crew equipment systems. For example, the addition of the scientific instrument module bay in the service module resulted in the requirement for transearth extravehicular activities. Film magazine retrieval was accomplished through crewman extravehicular activity via side-hatch egress and body translation to and from the scientific instrument module bay. The crewman was aided in this endeavor by equipment such as restraints, tethers and umbilicals.

Stowage items used most during a mission (clothing, food, bags, etc.) received prime consideration with respect to optimum stowage locations. Stowage volumes were made as uniform as the vehicle configuration would allow and common mounting designs were utilized. Every effort was made to understand the crew station environments during launch, orbit, return, and ground handling activities because stowage designs based on unrealistic design loads have proven to be troublesome. Except for a very few unique situations, return stowage did not present a problem. Since the couch stroking envelope for a water-landing was much less than for a land-landing, the amount of available stowage volume was adequate for return items.

It became obvious as Apollo neared the end of the program that certain stowage concepts were proven from both an operational and budgetary standpoint. Specifically, the basic concepts were:

a. Provide specific stowage locations and arrangements for all items of loose equipment, to be determined based on mission time lines and crew operational requirements.

b. Provide individual structural restraints for high density and fragile items to preclude stowed items from being supported by other stowed items.

c. Provide individual zero-gravity restraints for all stowed loose equipment in such a way that any one item can be removed without adjacent loose equipment floating away.

d. Utilize stowage provisions (bags, cushions, brackets, and straps) as required to prevent contact of the equipment to the metal stowage lockers, thus meeting vibration and shock protection requirements.

e. All materials that support combustion must be stowed in a closed metal locker or inside a double layer of fiberglass material (Beta cloth) containers. Also, these materials cannot be stowed near potential ignition sources even though they are in metal lockers or Beta cloth containers.

f. Clearances must be maintained outside the couch loading (stroking) envelope for land-landing pad abort and water-landing return. Some exceptions can be allowed if the material is crushable, (i.e., liquid cooling garment, some food items, etc.).

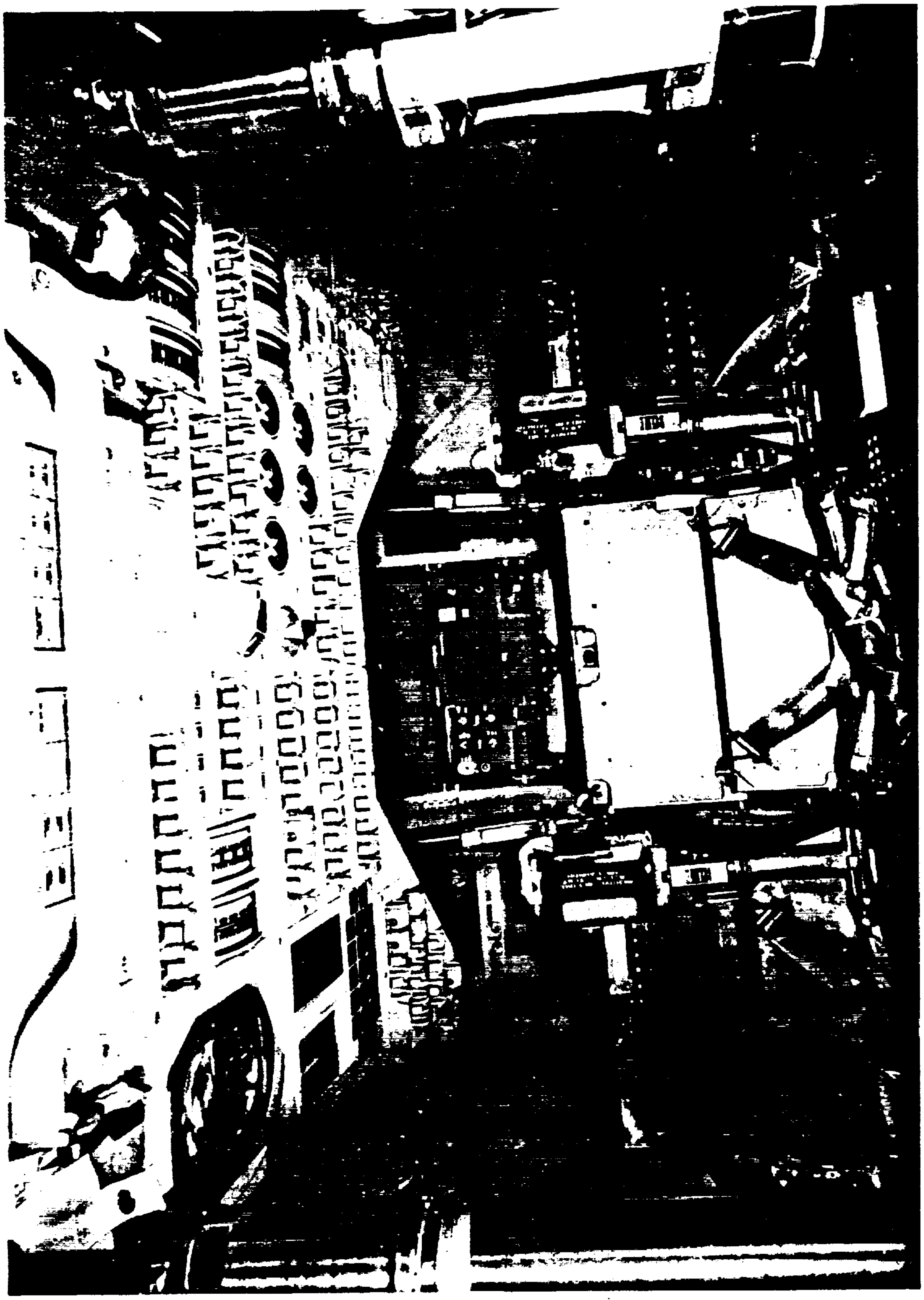

Figure 4-31.- Command module interior view, looking through side hatch.

High fidelity mockups and trainers were invaluable in evaluating stowage configurations. They were also used continuously by many other Manned Spacecraft Center elements to develop procedures, equipment modifications, and to demonstrate new concepts. Any program in the future should be well equipped with this type of hardware and every effort should be made to keep it current through all phases of the program.

Additional information on command module crew provisions and equipment is contained in reference 4-82. Stowage is discussed in references 4-82 and 4-83.

4.10.2.2 Lunar module crew station and equipment.- A number of lunar module crew station and equipment configurations were developed as earth orbit experience from previous programs and analysis of lunar gravity and acceleration profiles were introduced.

Initially, conventional crew seating at the controls was provided in the early lunar module concept. This concept was changed in favor of the crew standing at the control station. Acceleration loads less than one-g during lunar descent and ascent on the crewmen allowed minimal body restraints, thus providing the capability of crew viewing out the windows along the module thrust axis with minimum window area (fig. 4-32).

Operational procedures developed in full-scale mockups provided insight in problem areas of crew mobility in pressurized suits. Egress and ingress through the forward hatch proved to be a laborious task while pressurized. As a result, the forward hatch was modified and enlarged, and the docking procedure was changed from using either the forward or top hatch to using the top hatch only.

For the first manned lunar landing, cabin stowage was limited to equipment necessary to support life, lunar sample containers, and photography equipment. A modular pallet in one sector of the descent stage contained some equipment to be deployed by the crew in addition to television for the historic first step onto the lunar surface. After return of the Apollo 11 crew, specific vehicle and equipment changes were identified. Sleeping hammocks were added, additional cameras and film were provided, and lunar surface equipment was changed and increased to provide for more efficient operation.

The retrieval of Surveyor III components on the Apollo 12 mission required the development of special tubing cutters, wire cutters, sampling methods, safety lines, and equipment necessary for expanded scientific operations. In conjunction with the Surveyor hardware retrieval, lunar samples were gathered, and scientific lunar experiments were deployed.

After the Apollo 12 mission, it became evident that no two lunar landing missions were going to be alike. Therefore, the crew station for each succeeding vehicle was custom designed. Stowage, both internal and external to the cabin, became more complex to facilitate handling of the increased quantity of equipment required to accomplish the mission objectives.

The Apollo 13 lunar module was configured for the maximum lunar stay time (2 days) of the H-series missions. When this spacecraft became the life support system for a circumlunar flight, it brought the crew safely to the point where command module entry was assured.

The lunar module configuration was revised, beginning with the Apollo 15 vehicle, to provide capability for the longer duration J-series missions. The cabin stowage concept was changed to a semi-modularized configuration to allow more flexibility of loading. The descent stage modular equipment stowage assembly was enlarged to carry more equipment, and potential growth capability was provided, which became of great value later in providing stowage space for new mission equipment with a minimum expenditure of funds. In addition, stowage pallets were added to quadrant III of the descent stage to carry the large scientific payloads being identified. The lunar roving vehicle, which also required a stowage interface on the lunar module, was being designed in parallel.

All these changes were identified and a detailed design was initiated using the experience gained on previous lunar missions. For the first time, on the J-series spacecraft, allowance was made in the design of the crew station and the exterior crew-operated stowage areas for expected programmatic changes. Indeed, the full capability of the lunar module was used for the final three missions.

Additional information on stowage may be found in references 4-82 and 4-83.

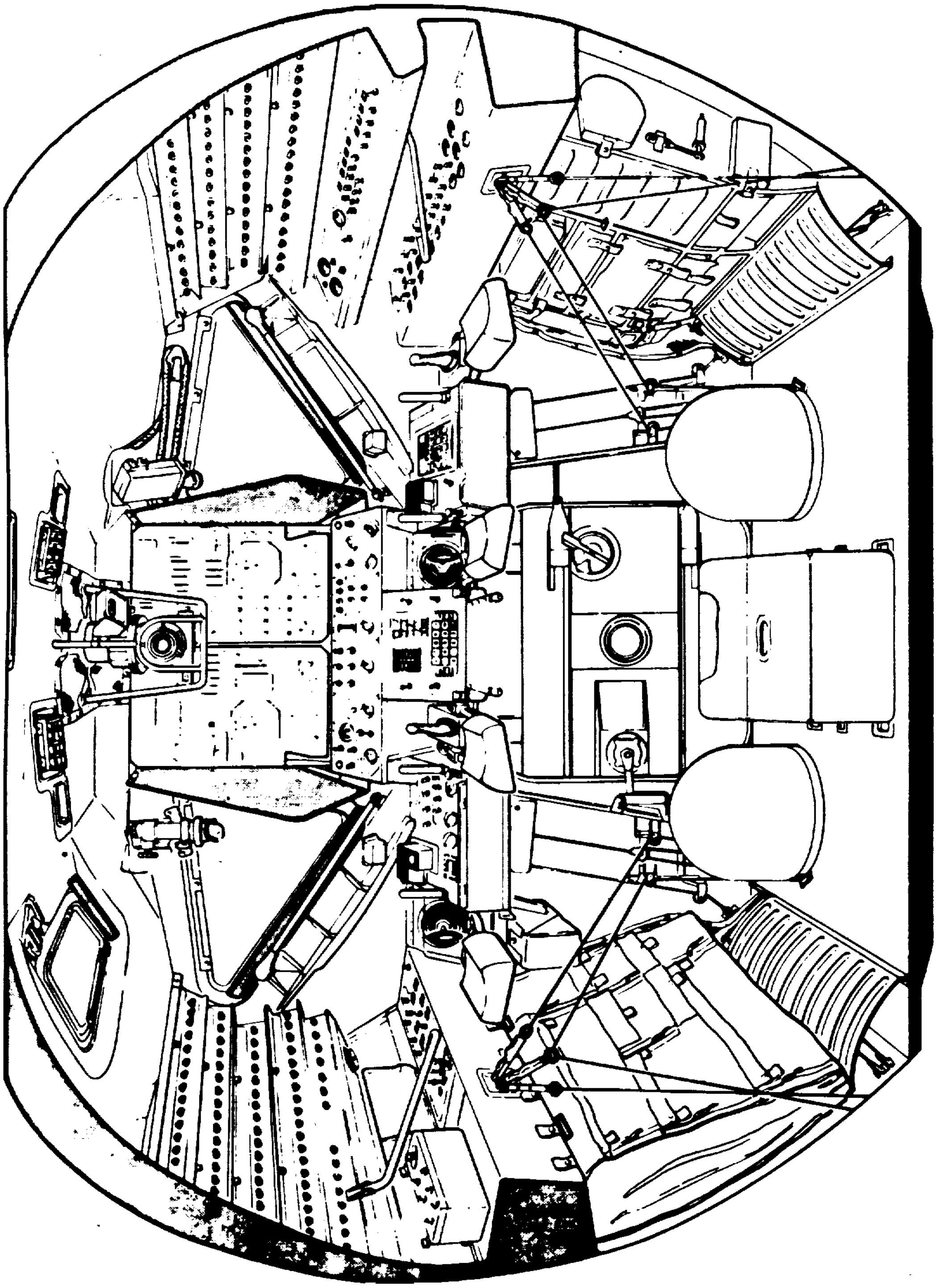

Figure 4-32.- Lunar module ascent stage interior view, looking forward.

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5.0 SPACECRAFT DEVELOPMENT TESTING

5.1 INTRODUCTION

The development of the Apollo spacecraft and associated flight equipment required extensive testing. A large part of the command and service module and the lunar module testing, especially at higher levels of assembly, was conducted at the White Sands Test Facility and the Manned Spacecraft Center.

5.2 WHITE SANDS TEST FACILITY

The White Sands Test Facility operates as an element of the Manned Spacecraft Center and is devoted to propulsion and power systems development and certification testing, and special testing of materials, components, and subsystems used with propellants or other hazardous fluids or environments. The facility has five operational propulsion test stands located in two separate areas. Three of the stands have altitude simulation capabilities (up to approximately 140 000 feet for 12 000-pound-thrust engines). Each test stand is essentially self-contained and is separately maintained and controlled.

Testing accomplished at the White Sands Test Facility consisted of integrated systems ground testing of the following service module and lunar module systems:

Service Module	Lunar Module
Service propulsion system	Ascent propulsion system
Reaction control system	Descent propulsion system
Electrical power system (fuel cells and cryogenic storage subsystem)	Reaction control system

Screening of a wide variety of Apollo program materials for ignition and combustion hazards, toxicity, and odor outgassing required the development of new "standardized" test methods and test devices. The White Sands Test Facility took the lead in developing these tests and, as a result, has become an "industry-standard" test agency for this type of testing. Standard tests now capable of being performed at the White Sands Test Facility satisfy all of the requirements as specified by NASA Handbook 8060.1 "Flammability, Odor and Offgassing Requirements, and Test Procedures for Materials in Environments that Support Combustion." The testing includes combustion propagation rate tests, thermogravimetric analysis, flash point and fire point determination, offgassed and combustion products analysis, odor evaluations, mechanical and pneumatic impact ignition sensitivity tests, and vacuum stability tests. Tests can be performed in gaseous and liquid oxygen, in hydrogen, and in earth storable propellants.

5.3 MANNED SPACECRAFT CENTER

Testing accomplished at the Manned Spacecraft Center included vibration, acoustic, and thermal-vacuum tests of the command and service module and the lunar module; water- and land-landing impact tests of the command module; and lunar landing impact tests of the lunar module. Command module and lunar module docking simulations were performed as well as modal surveys of the docked configuration. Numerous other tests at various levels of assembly were also conducted on Apollo program hardware. These tests are documented in summary form in references 5-1, 5-2 and 5-3. A description of the test facilities used in this testing can be found in reference 5-4.

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6.0 FLIGHT CREW SUMMARY

Considering the available resources and the time spacing for launches, each Apollo mission represented a considerable increase in sophistication and complexity from the standpoint of crew performance. The mission reports (refs. 6-1 to 6-11) for 11 manned missions show a continual improvement in flight crew performance. This improvement was possible because each mission supported the next one with a wealth of pertinent crew experience. The increased complexity in the objectives of each mission was possible, in part, because new operational experience was used where appropriate to standardize and revise crew operations as each mission was flown, especially in the areas of preflight training, flight procedures, and equipment operation. This standardization allowed follow-on crews to concentrate on the development and execution of those flight phases which were new.

An important factor in the demonstrated success of each flight crew, especially in view of additional operational and scientific requirements for each mission, was the continually increasing effectiveness and validity of crew training, particularly training conducted in the mission simulators.

The 22 three-man flight crews (primary and backup) assigned for the 11 manned Apollo missions are listed in table 6-I. Thirty-two different astronauts received assignments to this team. Of 29 astronauts who flew Apollo missions, four flew two missions each. Twenty-four different crewmembers participated in the lunar missions, and 12 men landed on the lunar surface.

6.1 CREW REPORT

This section summarizes and presents an overview of the significant contributions and experiences of all crewmen during the flight program, particularly in areas where flight crew experience was used to improve performance for subsequent missions. Attention is directed primarily to lessons learned, both in flight and on the lunar surface.

6.1.1 Training

Training for the early manned flights (Apollo 7 through 10) leading to the first lunar landing concentrated on continuous in-depth reviews of the command and service module and lunar module systems, with major crew participation in nearly every phase of spacecraft test and checkout. This involvement was necessary because total vehicle systems performance, both for normal and abort operations, was neither well understood nor well documented. Preflight training usually began with the checkout, integration, and verification of the command and service module and lunar module simulators because the availability and effectiveness of these simulators was a major crew concern. In every case, however, the simulators supported each mission effectively and provided the most valuable crew training for the dynamic phases of the mission for spacecraft system operating procedures and for simulations of integrated time-line activity with the flight controllers in the Mission Control Center.

Crews participated only in major spacecraft test and checkout activities during training for the lunar landing missions and devoted proportionately more time to training on new scientific mission activities with the attendant development of new procedures and checklists. Much wider use was made of such specialized training devices and techniques as the lunar landing training vehicle (fig. 6-1), high-fidelity stowage mockups, 1/6-earth-gravity and zero-g aircraft training flights, the zero-g water tank, and suited training for the lunar surface and transearth extravehicular activity phases. The increasing effectiveness of standardized crew training for operational mission aspects, the continuous addition of crew experience, and the greater spacing between launches permitted the crews of the later science-oriented missions to devote 30 to 40 percent of their time to the development of, and training for, lunar orbital and lunar surface science procedures. The effectiveness of the standardized training program was dramatically demonstrated during the aborted Apollo 13 flight. Furthermore, mission results showed that substituting the backup Apollo 13 Command Module Pilot for the prime crew Pilot 2 days before flight was practical and effective, even under conditions of stress.

TABLE 6-I.- APOLLO FLIGHT CREW ASSIGNMENTS

Apollo mission	Prime crew (a)	Backup crew (a)
7	Walter M. Schirra, Jr. Donn F. Eisele R. Walter Cunningham	Thomas P. Stafford John W. Young Eugene A. Cernan
8	Frank Borman James A. Lovell, Jr. William A. Anders	Neil A. Armstrong Edwin E. Aldrin, Jr. Fred W. Haise, Jr.
9	James A. McDivitt David R. Scott Russell L. Schweickart	Charles Conrad, Jr. Richard F. Gordon, Jr. Alan L. Bean
10	Thomas P. Stafford John W. Young Eugene A. Cernan	L. Gordon Cooper, Jr. Donn F. Eisele Edgar D. Mitchell
11	Neil A. Armstrong Michael Collins Edwin E. Aldrin, Jr.	James A. Lovell, Jr. William A. Anders Fred W. Haise, Jr.
12	Charles Conrad, Jr. Richard F. Gordon, Jr. Alan L. Bean	David R. Scott Alfred M. Worden James B. Irwin
13	James A. Lovell, Jr. [b]John L. Swigert, Jr. Fred W. Haise, Jr.	John W. Young Thomas K. Mattingly II Charles M. Duke, Jr.
14	Alan B. Shepard, Jr. Stuart A. Roosa Edgar D. Mitchell	Eugene A. Cernan Ronald E. Evans Joe H. Engle
15	David R. Scott Alfred M. Worden James B. Irwin	Richard F. Gordon, Jr. Vance D. Brand Harrison H. Schmitt
16	John W. Young Thomas K. Mattingly II Charles M. Duke, Jr.	Fred W. Haise, Jr. Stuart A. Roosa Edgar D. Mitchell
17	Eugene A. Cernan Ronald E. Evans Harrison H. Schmitt	John W. Young Stuart A. Roosa Charles M. Duke

[a] Listed in order of Commander, Command Module Pilot, and Lunar Module Pilot.

[b] Backup Command Module Pilot Swigert replaced prime crewman Mattingly 2 days before flight.

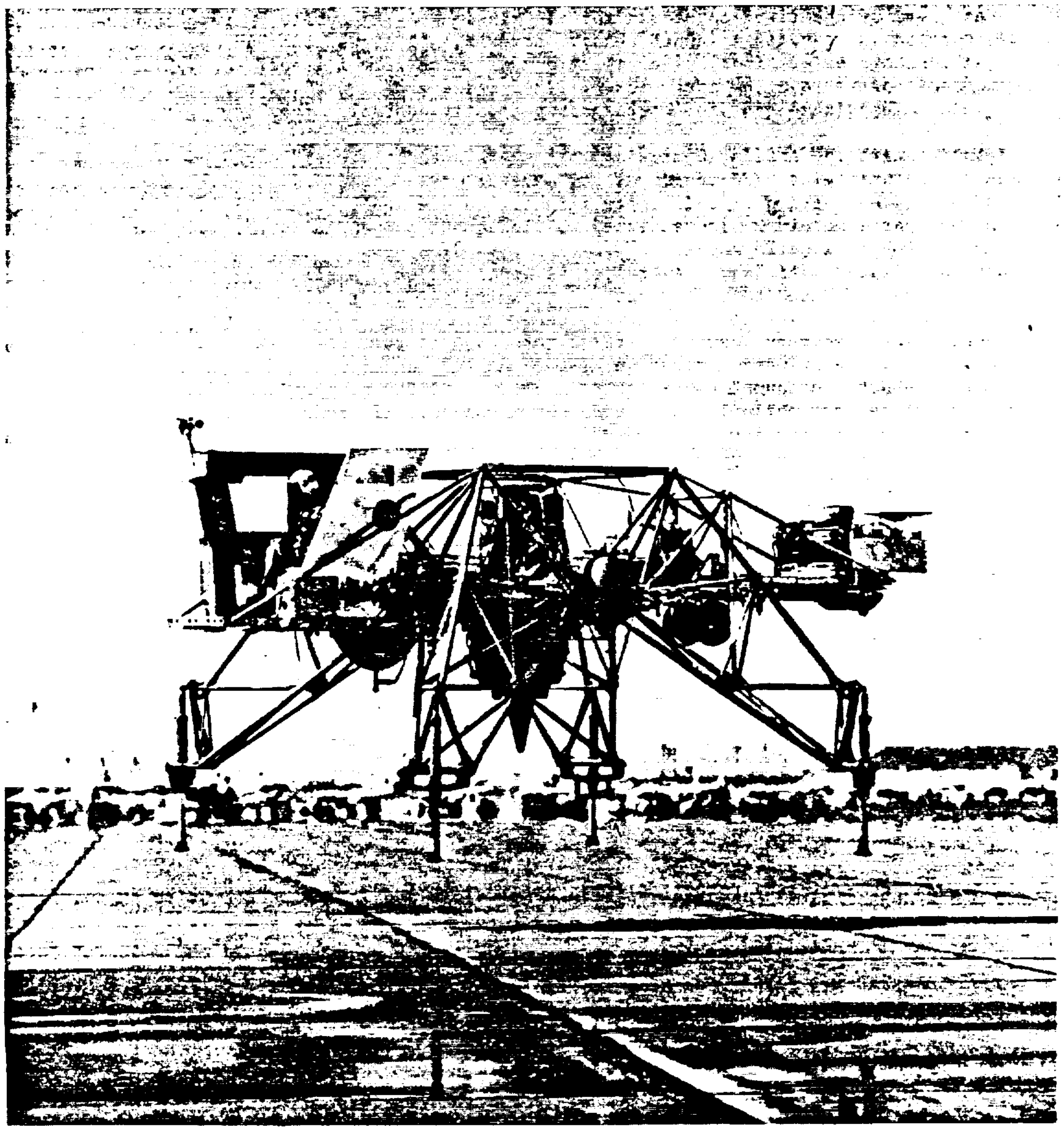

Figure 6-1.- Lunar landing training vehicle.

6.1.2 Mission Experience

6.1.2.1 Launch through docking.- The crew and the spacecraft test team were normally 10 to 20 minutes ahead of the final countdown for all missions. The Apollo 7 crew, launched on a Saturn IB, reported an uneventful launch phase. However, all crews launched aboard a Saturn V reported varying degrees of first-stage vibration and noise from lift-off through the region of maximum dynamic pressure. The most unusual first-stage experience was the Apollo 12 lightning strike, which caused the loss of onboard backup booster control capability.

Beginning with the Apollo 10 mission, all crews noted the rapid fore-and-aft longitudinal oscillations occurring at S-IC shutdown, and several crews commented on small longitudinal vibrations in the latter portion of S-II stage flight. On the Apollo 13 mission, S-II center engine shutdown was approximately 2 minutes early, but adequate compensation was made through outboard engine and S-IVB stage performance. Positive suppression of S-II longitudinal oscillations was incorporated on later vehicles. Several crews commented on a small high-frequency S-IVB vibration, which was attributed to valve chatter and which was not really objectionable.

Except for a temporary loss of inertial reference on the Apollo 12 mission because of the lightning strike, the primary navigation system enabled the crew to monitor booster-steering performance throughout the launch phase and to confirm satisfactory orbit insertion conditions. During simulations for Apollo 10 and subsequent missions, all crews demonstrated a satisfactory backup capability for steering the booster, in the event of a Saturn platform failure, into an acceptable orbit using the independent command module inertial measurement unit. The flight-crew backup steering mode was included in the training program because a less precise orbit was preferable to a launch phase abort in case a launch vehicle platform failed.

An unexpected phenomenon reported by the Apollo 7 crew was the gravity-gradient effect on the command and service module when the perigee was between 90 and 120 miles. Similarly, the Apollo 9 crew reported that, in drifting flight, the longitudinal axis of the two docked spacecraft tended to align with the orbital plane with the lunar module closest to earth. This crew also reported that the autopilot was effective in rotating the spacecraft about any axis while holding attitude about all other axes. This feature later became a major factor in the accurate positioning of the spacecraft in lunar orbit for service module experiments, thus freeing the Command Module Pilot to perform other experiments and observations.

The Apollo 9 crew experienced the first of several instances of propellant valve closure in the reaction control system because of shock during launch or pyrotechnic firings. After the Apollo 9 mission, the standard crew procedure was to check all valve positions following any pyrotechnic system firings.

Although several different manual control techniques were used for transposition and docking, maximum use of the digital autopilot both in simulations and in flight proved to be the most satisfactory technique for frugal propellant usage. The Command Module Pilot executed the docking maneuver by manual activation of the reaction control thrusters in an attitude-hold mode and by aligning the two spacecraft optically with a sight in the command module and a target cross on the lunar module. As a result, docking misalignments never exceeded 5°, lateral velocities were generally less than one-tenth of a foot per second, and closing rates ranged from one-tenth to three-tenths of a foot per second. Six contacts of the probe and drogue were made during the Apollo 14 mission before docking was successfully achieved. The crew was unable to discover any obvious contamination or mechanical problems with the docking system, which later functioned properly during lunar orbit docking. Several crews reported that as many as three of the 12 docking latches showed lack of closure, thus requiring the latches to be manually recocked and triggered. A design improvement in the probe capture-latch mechanism was incorporated in the Apollo 15 and subsequent spacecraft to eliminate this problem.

The Apollo 9 crew reported that the docking hardware and hatches could be removed from the tunnel in 5 to 7 minutes. Movement of large masses from the tunnel to a stowage position in the command module, such as the 84-pound tunnel hatch and the 80-pound probe, was found to be easy to control in zero gravity.

6.1.2.2 Translunar and transearth coast.- A passive thermal control mode was established for translunar and transearth coast, wherein the spacecraft was rotated about its longitudinal axis at a rate of 3 revolutions per hour. The attitude deadbands for the Apollo 8 spacecraft using this mode were quite restrictive; however, the procedures were modified for the Apollo 10 mission by opening the allowable deadbands. This change saved considerable reaction control system propellant, and the crew's sleep was not continually interrupted by thruster firings. On Apollo 12 and subsequent missions, an improved computer routine and revised crew procedures resulted in no thruster firings once the passive thermal control mode was initiated. When the spacecraft were in the docked configuration, all crews noted that small ripplelike oscillations were introduced into the spacecraft structure while the service module reaction control system thrusters were firing.

Star and horizon navigation sightings were made during the translunar phase of all lunar missions and during the transearth phase of all lunar landing missions through Apollo 14. On several flights, the auto-optics control mode would not position the star properly with respect to the sextant horizon fiduciary marks. When this deficiency occurred, the minimum-impulse controller was used to position the star on the horizon. Since the optical viewing axes were between the service module reaction control system roll and yaw thruster firing axes, this control mode was expensive in terms of both time and propellant.

The failure of cryogenic oxygen tank 2 during translunar coast on the Apollo 13 mission resulted in an abort of the lunar landing mission into a lunar flyby mission. This aborted mission required the use of the lunar module to supply power, oxygen, water, and attitude control. In addition, the lunar module descent propulsion system was used to place the docked combination into a free-return trajectory and to speed up the return to earth. The crew efficiently exercised onboard contingency procedures for fast powerup of the lunar module in preparation for the first descent propulsion firing. Also, following ground instructions, the crew used command module lithium hydroxide cartridges in the lunar module to remove carbon dioxide from both spacecraft. A manual descent propulsion midcourse correction was also conducted on the Apollo 13 mission using the cusps of the earth terminator in the optical alignment sight to align the docked configuration for a maneuver which corrected the entry angle. Before entry, the lunar module batteries were used to recharge the command module entry batteries while supplying power to the lunar module systems. The ability of the crew to handle the time-critical phases of this aborted mission demonstrated successful crew performance of complex tasks while under stress in a space environment.

6.1.2.3 Command and service module thrusting maneuvers.- The Apollo 7 crew verified the performance of the service propulsion system, including manual thrust-vector control, using the backup stabilization and control system, and minimum-impulse velocity changes. The Apollo 9 mission further verified service propulsion system performance, this time in the docked configuration where inflight bending response (stroking tests) and manual thrust-vector control were evaluated. After the Apollo 9 mission, there were more than 60 service propulsion maneuvers using the primary guidance and navigation system for thrust-vector control with excellent results. On each lunar mission, at least one translunar midcourse correction was made using the service propulsion system for a combined trajectory change maneuver and performance verification test.

Although service propulsion system maneuvers normally demanded the attention of the entire crew, the Command Module Pilots of Apollo 12 and subsequent missions performed them by themselves during lunar orbital solo operations. Such a maneuver normally requires, among other tasks, positioning 72 switches and circuit breakers. Major factors in the successful conduct of these maneuvers by only one crewman were the abbreviated checklist cards attached to the main display control panel and more intensive Command Module Pilot preflight training.

Once the inflight performance of the propellant utilization and gaging system was understood, crews had no trouble limiting fuel and oxidizer imbalance. Because of an open circuit in the secondary gimbal rate-feedback loop during the Apollo 16 mission, the lunar-orbit-circularization maneuver was delayed, causing a major change in the crew procedures and mission time line. As a result, onboard techniques for troubleshooting this kind of malfunction were incorporated in the Apollo 17 training.

The descent orbit insertion maneuver using the service propulsion system was initiated for the Apollo 14 mission to conserve lunar module propellant. Crew monitoring of this maneuver was critical because a 1-second overthrust could have placed the docked spacecraft in a moon-impacting trajectory. The crew, therefore, used an accurate prediction of firing duration from the Mission Control Center as the cue for a possible manual shutdown, thereby virtually eliminating the possibility of an unacceptable deorbit condition. The excellent performance of the service propulsion system in the minimum-impulse mode relegated the reaction control system to only the smaller velocity changes, such as orbit trim, lunar-orbit-phase ullage maneuvers, transearth midcourse corrections, and lunar module extraction and separation maneuvers.

6.1.2.4 Lunar module checkout.- The preliminary lunar module communications and telemetry checks and the stowage transfers were routinely made during translunar coast and in the initial phases of lunar orbit. In addition, several early entries were made into the lunar module because of ground instructions to verify systems performance, such as a systems verification check after the Apollo 12 lightning strike and a battery-data check on the Apollo 15 mission. These early entries were factors in the decision to make the entire preliminary lunar module checks earlier in a more leisurely phase of translunar coast to permit an early identification and collection of trend data on potential systems problems.

Activation of the lunar module was essentially an inflight operational checkout procedure. The Apollo 9 crew verified the lunar module powerup and checkout procedures in earth orbit. The Apollo 10 crew demonstrated these systems checkout activities in a period beginning 6 hours before undocking in lunar orbit. On several missions, because of various systems or procedural problems, crews were required to reverify checks or rearrange activities in real time to complete lunar module checkout on time. For example, during the Apollo 10 mission when the tunnel would not vent before undocking, the lunar module crewmen modified the hatch integrity check in real time. Also, the Apollo 12 crewmen modified their pressure suit donning sequence in real time to provide sufficient clearance at the lunar module navigation station for landmark tracking. Approximately 2 hours was deleted from the lunar module activation and checkout sequence during the Apollo 16 mission to shorten that workday to a more reasonable 22 hours. All lunar module systems were verified as satisfactory within the shortened time line, even with an S-band antenna failure (which required extensive manual updates to the computer), a double failure in one reaction control system, and several real-time revisions and repetitions of checkout procedures.

All crews reported that reaction control firings were much more audible in the lunar module than in the command module. Crews also reported hearing the sharp shotgunlike report made by the closure of the cabin repressurization valve, the glycol pump whine, the grinding of the S-band antenna, and several pyrotechnic firings. Although sometimes annoying, these noise cues were often helpful as indications of proper system functioning.

All Apollo crews required almost 10 minutes to vent the tunnel for the hatch integrity check before lunar module undocking. The Apollo 10 crew could not vent the tunnel for lunar module jettison. Because of the sharp pyrotechnic report at jettisoning, this crew recommended that future crews wear helmets and gloves to guard against a possible loss of cabin pressure caused by increased pyrotechnic shock with an unvented tunnel. As a result of this recommendation and because of a Soviet Soyuz accident in which cabin pressure was lost, the procedure was implemented for the Apollo 15 and subsequent crews.

6.1.2.5 Lunar module thrusting maneuvers.- Manual throttling of the descent propulsion system was first tested on the Apollo 9 mission in both the docked and undocked configurations. Manual control was used for the descent propulsion thrusting during descent orbit insertion for the Apollo 11 and 12 lunar missions and for the three descent engine firings of the Apollo 13 mission. Automatic throttle control and throttle-up were used during powered descent initiation for every landing mission except Apollo 14. The crews reported no vibrations except for a short period of roughness during the phasing maneuver throttle-up on the Apollo 9 mission. In 16 descent engine firings, the physiological cue of throttle operation was always noticeable. All lunar module crews commented on small lateral oscillations in the attitude control deadbands. These oscillations were attributed to propellant slosh. For all landings, the rate-of-descent throttle control mode was used to specify altitude rate. This control mode was easy to operate and allowed the Commander to concentrate on landing in the area of his choice.

Crew firing of the ascent engine was first performed on the Apollo 9 mission, and the system subsequently performed flawlessly in the automatic control mode during the 12 firings in the flight program. Considerable training time was spent in maintaining pilot proficiency in manually controlled ascent thrusting profiles using the rate-command attitude-hold, rate-command, and direct control modes. While the first two control modes, which were semimanual in operation, were quite practical, the latter, a completely manual mode, was very difficult to perform but was still preferable to the final alternative of being stranded on the lunar surface. Manual attitude control of the unstaged lunar module, using either the primary guidance system or abort guidance system, in the rate-command, pulse, or acceleration (direct) mode was responsive and precise. For example, the pulse mode was used to position stars in the one-power telescope in aligning the inertial platforms. Small star-angle measurement differences during these alignments proved the precision of this control mode technique.

The ascent stage thrusting maneuvers using the reaction control system were performed manually for the rendezvous maneuvers of concentric sequence initiation, constant differential height, terminal phase initiation, midcourse corrections, and final braking. The precision of this manual control technique was first noted during the Apollo 9 mission, and all crews commented on the control of the light ascent stage in response to the 100-pound thruster firings.

6.1.2.6 Lunar module landings.- For the Apollo 11 mission, visual checks by the lunar module crew showed the spacecraft to be 2 to 3 seconds early over known landmarks. After these checks, the lunar module was yawed to a faceup position approximately 4 minutes after powered descent initiation. For subsequent missions, powered descent was begun in the faceup position to accommodate S-band antenna acquisition and landing radar lockup. To maintain S-band antenna acquisition with earth during the Apollo 17 mission, various yaw angles of as much as 70° were used, but these angular shifts had only a slight effect on the crew's ability to monitor descent parameters.

For the Apollo 12 vehicle to land acceptably near the Surveyor site, all docked maneuvers were made using balanced thrust coupling, and a soft undocking was performed in a radial attitude with respect to the lunar surface. This procedure eliminated the possibility of orbital perturbations from reaction control maneuvers that could have compromised the accuracy of the state vector. After undocking, maneuvering was held to a minimum to avoid further affecting the established orbit. All crews after the Apollo 12 mission conscientiously followed this minimum-maneuver requirement, since the precision landing requirement became a factor in surface operations. The precision landing capability for these missions was further increased by permitting computer entries after powered descent initiation.

A series of alarms during the Apollo 11 descent indicated a computer overload which occasionally precluded computer monitoring of descent trajectory information. During the Apollo 14 mission, the landing radar circuit breaker had to be recycled to enable landing radar lockup. Neither of these unexpected procedural changes affected crew performance appreciably. At pitchover during the Apollo 11 descent, the crew prediction that the landing point was down range of the target location was confirmed. The Commander transferred from the automatic to the attitude-hold control mode to extend the range beyond a boulder field in which the automatic guidance program would have placed the vehicle. For Apollo 12 and subsequent missions, planned landmark recognition was instituted as soon after pitchover as possible so that manual redesignations of the landing site could be made to allow landing either near the target point or in a more suitably flat area.

The Apollo 11 crew reported that lunar surface dust began to move noticeably when the spacecraft was at an altitude of 100 feet and became increasingly dense as altitude decreased. The Apollo 12 crew noted dust motion at an altitude of 175 feet and reported that the surface was completely obscured at 50 feet. Dust was not detrimental to out-the-window visibility cues during the Apollo 14, 16, and 17 landings, but it completely obscured visibility from 60 feet to the surface during the Apollo 15 landing. The effect of dust on the Commander's ability to judge and control altitude, altitude rate, and lateral velocities was a function of such factors as the sun angle at landing, the cohesiveness of the surface regolith, and the presence of blocks or shadowed crater rims on the surface, which might be seen through the dust.

All lunar module crews noted that the lunar module simulator and the lunar landing training vehicle control system responses were representative of the flight hardware. The simulator and the training vehicle (figs. 6-1 and 6-2), together with the high fidelity of the visual landing and ascent television presentation, proved to be excellent training devices for the manually controlled final portion of the landing.

Commencing with the Apollo 15 mission, the angle of the final descent trajectory after pitchover was changed from 14° to 25°. This modification allowed for improved clearance over the Apennine Mountains and provided better visibility of the landing site after pitchover. For the Apollo 16 and 17 missions, the steeper descent angle permitted the crews to assess landing site targeting while still well above the nominal 7200-foot pitchover altitude. In training simulations, crews repeatedly demonstrated the ability to land safely using manual throttle, landing radar, and the abort (backup) guidance system from altitudes above 20 000 feet. In addition, by using the lunar module shadow on the surface as a descent altitude and altitude-rate indicator, crews demonstrated the capability to land safely without landing radar and within the 3-sigma altitude/targeting dispersion criteria of the Mission Control Center.

6.1.2.7 Lunar surface operations.- As experience was gained, the time required for extravehicular activity preparation was considerably shortened. For the Apollo 11 simulations, 2 hours had been allocated for extravehicular activity preparation, which consisted of film transfer, portable life support system (backpack) donning, and remote control unit attachment as well as checkout and pressure integrity checks of the extravehicular mobility unit. The close confinement imposed by backpack/suited work in the lunar module cabin and the less-than-orderly configuration of various items resulted in exceeding the planned preparation time on that mission. The Apollo 12 crew devoted more training time for extravehicular activity preparation than did the Apollo 11 crew; and, because of a very detailed high-fidelity cabin-stowage configuration, both crewmen prepared for egress in a rather routine fashion. On the Apollo 15 mission, the first of the 3-day lunar stay missions, the crew found that, with donning practice in the 1/6-earth-gravity environment and the confidence developed in extravehicular mobility unit performance, egress preparation times were consistently shorter than planned. Later crews confirmed that preparation times were considerably shortened after the initial extravehicular preparation. After each mission, preparation difficulties were quickly corrected. For example, a problem in mating the electrical remote control unit cable connector during the Apollo 11 mission resulted in the use of a more easily mated connector for later flights. Also, the preparation checklist was changed to eliminate communications checkout problems encountered during the Apollo 12 mission.

The Apollo 11 crew reported that preflight training at simulated 1/6-earth-gravity was reasonably adequate in preparing the crew for lunar module egress. Body-positioning techniques were necessary to prevent the backpack from engaging the instrument panel and the upper portion of the hatch frame. The Apollo 11 crew noted that egress operations around the hatch, porch, and ladder were performed easily without losing body balance. This crew found that they could jump vertically up the ladder to the third rung, thereby facilitating ingress past the high first step. They also noted the requirement to arch the back when halfway through the hatch to keep the backpack from snagging on the hatch frame. On subsequent missions, crewmen talked each other through the egress and ingress activity to minimize the snagging possibility.

A typical example of the evolution of lunar surface activity techniques resulting from 1/6-earth-gravity experience was the method of equipment transfer. Initially, a pulleylike double-strap conveyor was used to lower equipment to the surface and raise it into the cabin. The Apollo 11 crew found that, when the straps became heavily coated with dust, the dust fell on the suit of the surface crewmember and was also deposited in the lunar module cabin. The dust ultimately seemed to bind the pulley so that considerable force was required to operate the conveyor. A single-strap conveyor was used for Apollo 12 operations, but the crew reported that this conveyor also collected dust which was subsequently deposited in the cabin. In lieu of using a conveyor system, the Apollo 14 crew reported that stability and mobility on the ladder, maintained by using only one hand for support, seemed adequate to allow carrying equipment up the ladder. For Apollo 16 and subsequent missions, sample container bags, sample return containers, and pallets were quite easily hand-carried up the ladder, thus alleviating the dust problem with the conveyor. The conveyor had been further modified to a single short strap (which retained the camera/film/map equipment transfer bag) and was easily hoisted by one hand.

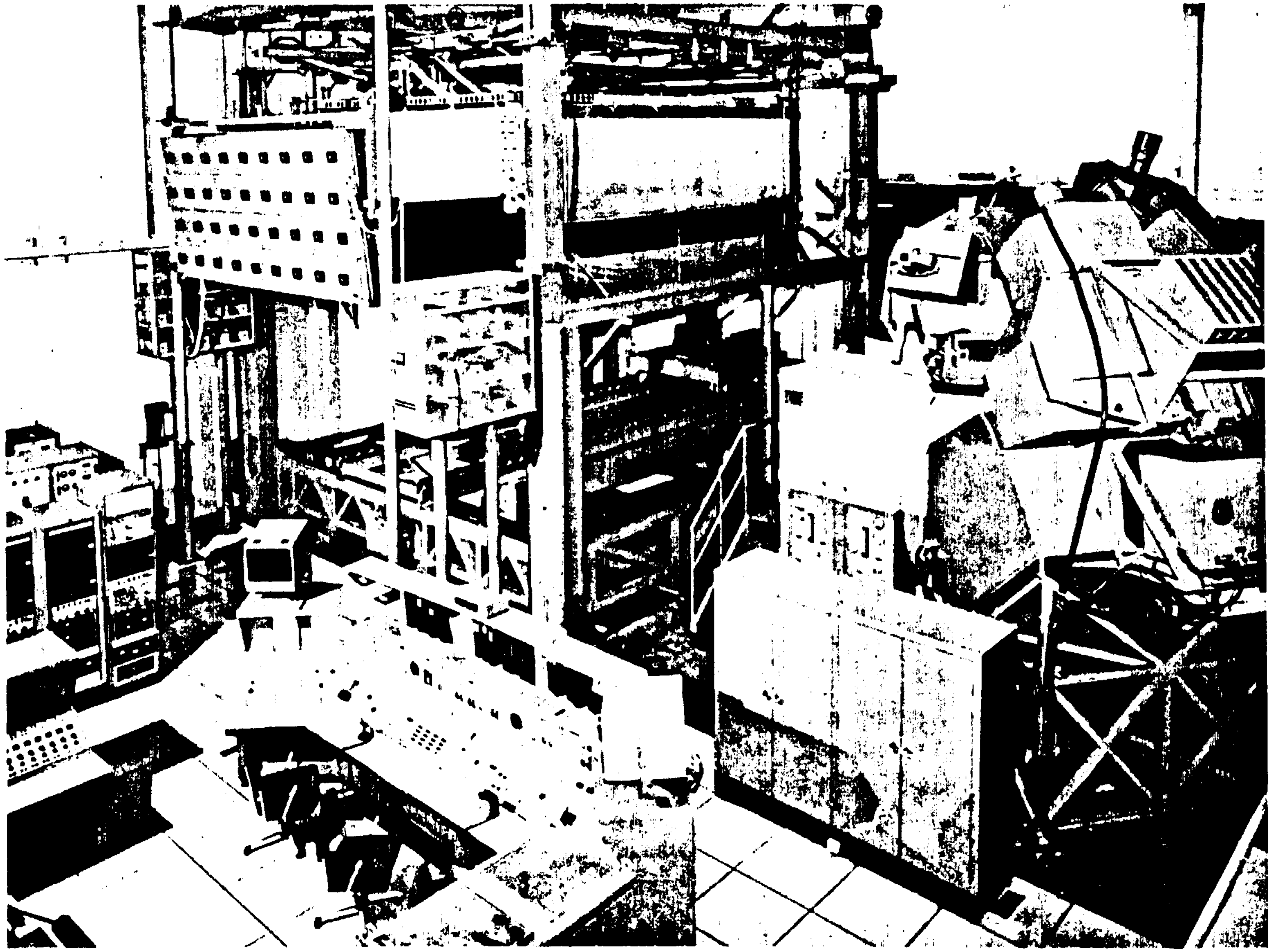

Figure 6-2.- Lunar Module simulator.

As first reported by the Apollo 11 crew, working in the 1/6-earth-gravity environment was not difficult and adaptation was quite natural. Movement was facilitated by using either a natural loping gait in which both feet were briefly off the surface or by using an earth-type running gait. Most crewmen preferred the loping movement. When the loping movement was used, the inertia of the crewman wearing the extravehicular mobility unit (representing an earth weight of 360 pounds) and the sometimes slippery effect of the lunar regolith required the crewman to plan for a finite stopping distance in advance of the selected point.

No crew reported significant discomfort because of insufficient heat removal by the liquid-cooling system in the backpack, even under the high surface temperatures encountered in the latter part of the lunar day and after some degradation of the suit heat-rejection capability because of lunar dust. The gradual increase in suit temperatures during the three long-duration extravehicular activities, first reported on the Apollo 15 mission, was handled by increasing the control setting to intermediate cooling and, occasionally, during high workload conditions, to maximum cooling.

With the outer visor down, the Apollo 11 crewmen noted that a brief period of dark adaptation was required when walking from sunlight into shadow. The Apollo 12 crewmen commented that the brightness was extreme when looking toward the sun while the sunlight was at low incidence angles, and they recommended an opaque upper visor in addition to the two side-shield visors. The sun elevation also affects the color of rocks and lunar soil. All crewmen noted washout of horizontal terrain and reduced visibility of vertical features when looking directly away from the sun while the sunlight was at low incidence angles. Crewmen frequently raised the outer visor for better viewing in shadowed areas and to compensate for the effect of the sun angle on mineral colors in rocks. As noted during the Apollo 17 mission, raising this visor greatly improved rock composition descriptions under some sunlight conditions and in the shadows.

The Apollo 11 crewmen recommended that future crewmen should consider kneeling and working with their hands to increase productivity on the surface. The Apollo 12 crewmembers reported that the efficiency of lunar surface work could have been increased by 20 to 30 percent if they had been able to bend over at the waist to retrieve surface samples. The capability for bending was made possible on the last three missions after the pressure suits were modified with a waist joint which was required to allow the crewmen to sit in the lunar roving vehicle. The improved waist flexibility permitted static kneeling for retrieval of samples during the Apollo 15 lunar surface activities and single-motion dynamic retrieval of samples during the Apollo 16 mission. Several falls to the surface were experienced and, on earlier missions, one crewman usually assisted the other in regaining his footing. With the improved-mobility pressure suits of later missions, footing was frequently regained without assistance.

Hand fatigue was the only memorable fatigue from lunar surface operations. The Apollo 12 crewmen reported that carrying the Apollo lunar surface experiments package was tiring to the hands because the carry bars had to be gripped tightly. Also, the Apollo 16 crewmen commented that the pressure suit glove required the crewman to maintain pressure on an object to grip it. A crewman's hand strength could not be relied on to apply the required pressure to grasp, hold, or manipulate objects on a continuous basis.

The Apollo 11 crewmen reported some physical exertion while transporting the lunar sample return container to the lunar module but indicated that tasks requiring greater physical exertion could have been undertaken. Both Apollo 12 crewmen believed, in general, that they were working at the maximum practical level needed for lunar surface activities. As a result of the successful 4-hour extravehicular activities during Apollo 12, the crewmen suggested that extravehicular periods could be extended to periods lasting as long as 8 hours without causing excessive fatigue. Thus, beginning with Apollo 15, three 7-hour extravehicular activities were scheduled. The Apollo 17 crew completed more than 22 hours of extravehicular lunar surface operations without apparent detriment to their working efficiency or well-being.

The methods of transporting samples, tools, and equipment on the lunar surface were continually improved. The Apollo 11 crew reported that 20 trips were required to fill up one sample return container positioned on the lunar module worktable. For the longer traverse of Apollo 12, a portable handtool carrier for geology tools and samples was taken to the lunar surface. However, the crewmen reported that holding the carrier at arm's length for rapid movement became tiring after a number of samples had been collected and later recommended attaching the carrier to the backpack in a manner similar to that used for carrying parts collected from Surveyor III.

Rock-sample bags were mounted on the backpack beginning with the Apollo 15 mission. The Apollo 14 crewmen used the modular equipment transporter to haul the tool carrier, lunar samples, and a portable lunar magnetometer. The transporter was reported to be stable and easily pulled; far less dust was kicked up by the wheels than had been anticipated before flight.

Beginning with the Apollo 15 mission, a lunar roving vehicle was taken to the moon for transportation on the longer traverses. The Apollo 15 crewmen reported that the steering of the lunar roving vehicle was quite responsive below a speed of 5 kilometers per hour but that sharp turns at 10 kilometers per hour resulted in breakout of the rear wheels. Incorporating a more positive seat restraint was recommended to minimize the effects of motion feedback to the directional hand controller. The crewmen noted that forward visibility was excellent except when driving away from the sun, which caused image washout and made obstacle avoidance difficult. With an improved seat restraint system, the Apollo crew drove the lunar roving vehicle over very hummocky and blocky terrain and up slopes in excess of 20°. They reported that the dynamics of the vehicle suspension system were excellent. The Apollo 17 crew traversed the same type of terrain while the lunar roving vehicle was loaded with a traverse gravimeter, a surface electrical properties experiment, and explosive packages for a lunar seismic profiling experiment. They reported a top speed of 17 to 18 kilometers per hour and covered a total distance of approximately 34 kilometers.

The Apollo 12 crew believed that efficiency on the surface would be enhanced by performing actual traverses under simulated lunar conditions during preflight training. As a result, later crews devoted the maximum practical amount of time to lunar surface science training, particularly geology. The crews of the last three missions devoted an average of 2 days per month to field geology training at lunarlike sites to sharpen their observational techniques and to become familiar with the mechanical aspects of collecting and documenting samples. On the last three missions, the character of lunar surface exploration changed drastically because of the capability for longer stay times on the surface and the availability of the lunar roving vehicle.

In an effort to obtain maximum scientific return from surface operations, the surface science time lines were generally overcrowded, especially when unforeseen equipment deployment problems were encountered. Although all crews trained with high-fidelity lunar surface hardware and tools, every lunar crew had to solve unanticipated problems. For example, the Apollo 12 fuel element for the experiments package became stuck in its cask, and the crew was required to hammer the cask to free it. During Apollo 14 surface activities, the Lunar Module Pilot's right glove developed an anomalous condition of assuming a neutral position to the left and down, thus requiring this crewman to perform geologic sampling tasks essentially with one hand during the second extravehicular period. On Apollo 15 operations while holes were being drilled for the heat flow experiment probes, the drill chuck became bound to the stem because of high torque levels. The stem had to be destroyed to remove the chuck for later deep-core drilling. A pair of pliers was used during the Apollo 16 activities to free the cosmic ray experiment when the experiment unexpectedly stuck in its frame. Finally, during Apollo 17 activities, both crewmen were able to retrieve the deep core only after considerable effort and after using a real-time-developed 1/6-earth-gravity "fall" upon the extraction tool.

Science return was improved by using crew experience to benefit follow-on crews. On the Apollo 11 mission, for example, the core sample tube could be forced to a depth of only 4 or 5 inches by hand and driven only 6 inches with a hammer. The tubes were redesigned for Apollo 12 activities; the crew reported that the tubes were easy to drive but that space remained in the tube because of soil compaction. For Apollo 14 operations, the tubes were plugged with caps to help retain the cores. The Apollo 14 crew reported that finding rocks small enough to fit in the small bags was difficult; therefore, the Apollo 15 crew was given larger sample bags. The Apollo 15 crew reported that collection of the deep-core sample was difficult and required far more time and effort than was anticipated; thus, the Apollo 16 crew was given a redesigned extraction tool that was excellent in aiding deep-core recovery. The Apollo 16 crew experienced numerous equipment problems which were corrected for the Apollo 17 mission.

The Apollo 11 crewmen reported that their sleep on the lunar surface was a complete loss because of light leakage into the cabin, excessive cabin noise, and an uncomfortably cool cabin temperature. The Apollo 12 crewmen, who slept in their pressure suits in sleeping hammocks, noted that the cabin noise was loud, but not loud enough to prevent adequate sleep. The Apollo 14 crew reported that very little sleep was obtained on the surface, primarily because they were uncomfortable in the suits, and recommended that crews remain unsuited during sleep periods. When this recommendation was adopted for Apollo 15 and subsequent missions, crews obtained adequate sleep. Also, a correlation was noted between the ability of the crews to sleep soundly and their increasing confidence in the proper operation of lunar module systems, based on proven performance.

All crews reported that food preparation and waste management functions were easier to perform in the lunar gravity field as compared to the zero-gravity conditions of flight. On the lunar surface, for example, food bags conveniently stayed where they were placed. also, air bubbles in water, permanent in zero gravity, automatically floated out of the in-suit drink container and the hydrated food bags.

A troublesome and ever-present problem that was corrected only partly during lunar surface missions was that of dust. On all missions, large amounts of floating dust were present in the lunar module cabin after insertion into lunar orbit. The Apollo 12 crew noted that dust made breathing without helmets both difficult and hazardous. Although all crews, before entering the lunar module, spent considerable time removing dust from their shoes, legs, arms, pressure suits, and lunar surface equipment, the cohesive nature of the dust prevented its complete removal. During the Apollo 17 mission, dust on the lunar module floor was swept into floor receptacles which were sealed before lift-off, but some dust was still present in the cabin atmosphere after lunar orbit insertion. Because of dust, the Apollo 16 crew had difficulty with the installation of their pressure gloves, and the surface equipment locks and handles on Apollo 17 equipment were barely operating by the end of the last extravehicular activity.

6.1.2.8 Rendezvous and docking.- Rendezvous of the Apollo 7 command and service module with the S-IVB booster stage was the first rendezvous performed in the Apollo program. The crew reported that the manually controlled braking maneuver was very discomfiting because no reliable backup ranging information was available to compare with computer solutions as was the case for a lunar module rendezvous. The first rendezvous of the command and service module and the lunar module was performed in earth orbit on the Apollo 9 mission. A similar rendezvous was demonstrated on the Apollo 10 mission in lunar orbit to check the maximum range performance of the rendezvous sensors. In this latter mission, the lunar module was visually tracked through the command module sextant against the lunar surface to a distance of 125 miles in daylight, above the horizon in daylight to 275 miles, and at night to 230 miles. In earth orbit, the Apollo 9 crew visually acquired and tracked the jettisoned lunar module, again using the sextant, at a range of 2500 miles.

Rendezvous thrusting maneuvers in the lunar module were protected by "mirror image" readiness in the command and service module to perform a backup thrusting maneuver in case the lunar module propulsion system failed. This backup technique was initiated for the Apollo 9 mission and was continued for all subsequent rendezvous operations.

For rendezvous missions through Apollo 12, the lunar-orbit-rendezvous sequence consisted of concentric sequence initiation, a possible plane change, and constant-differential-height maneuvers before a terminal phase initiation. These maneuvers allowed the proper correction of sizable trajectory dispersions. However, beginning with Apollo 14, the precision of rendezvous maneuver calculations and performance analyses made possible the deletion of the three smaller maneuvers before terminal phase initiation by substituting a ground-calculated trajectory-adjustment maneuver shortly after lunar module ascent stage orbit insertion. The terminal phase initiation maneuver was then performed with the ascent propulsion system. Any midcourse corrections performed during the several lunar rendezvous sequences were conducted manually using the lunar module reaction control system. The braking phase was also performed manually in a rate-command attitude-hold mode, with the rendezvous radar supplying accurate range, range-rate, and inertial line-of-sight data to reveal any dispersions in maneuver calculations or in the performance of previous maneuvers.

For the Apollo 16 mission, a "brute force" re-rendezvous was conducted with the command module active to bring the two spacecraft back together after an aborted command and service module circularization maneuver. In this case, the lunar module radar was used to supply accurate range, range-rate, and line-of-sight data, which were conveyed to the Command Module Pilot through crew radio coordination using instructions similar to those of a ground-controlled approach aircraft landing. These data allowed the Command Module Pilot to maintain the planned range rate and to null the line-of-sight rates using the more accurate lunar module data.

Lunar module crews were trained to be proficient in using the backup maneuver charts, which permitted semi-independent checks of maneuver calculations and actual performance in case a critical computer failure occurred. Use of the charts was based on range, range-rate, and angular-rate data provided by the lunar module radar.

All reasonably high velocity braking phases were performed comfortably by all lunar module crews during simulations, as were the actual flight braking phases, because of the optimum lunar module reaction control system thrust-to-weight ratio using the lunar module reaction control system. However, rendezvous simulations showed the command and service module performance to be marginal during dispersed braking thrusting in excess of 40 feet per second.

At the completion of lunar-module-active rendezvous on the Apollo 9 mission, the lunar module was used as the active docking vehicle. Review of this procedure indicated that docking would be easier, more accurate, and less time-consuming if the command module were the active vehicle. Thus, for subsequent missions, the lunar module was maneuvered to the docking attitude and the command and service module was used to complete final approach and docking. One factor in the difficulty of controlling the lunar module for final docking was the 90° mental reorientation of the translation axis required of the Commander. This axis reorientation and the 90° body/head rotation required for overhead viewing of the docking aids relegated the lunar-module-active docking maneuver to a backup procedure, even though excess reaction control propellant was aboard the lunar module on every flight.

6.1.2.9 Lunar orbit operations.- The Apollo 8 crew reported that groundtrack determination on the far side of the moon was more difficult than expected because of the large uncertainty in the accuracy of the preliminary maps of that region. Maps of the far side were improved throughout the program as a result of Apollo lunar-orbit photography and landmark tracking.

The Apollo 10 crew conducted lunar surface photography of proposed Apollo landing sites and landmark tracking of the proposed Apollo 11 landing site. On Apollo 11, selected landmarks were tracked from the command module while the lunar module was still docked. In addition, the Command Module Pilot tracked selected landmarks during solo flight and searched for the lunar module on the surface, examining an estimated 1 square mile on each overhead pass. During Apollo 12 solo operations, with the lunar landing site being northwest of the recognizable Surveyor crater, the Command Module Pilot was able to locate the lunar module on the surface by using the sextant. He reported the lunar module as a bright object with a long, pencil-thin shadow and also observed the Surveyor III spacecraft as a bright spot in the crater. During Apollo 17 solo operations, the Command Module Pilot's low-altitude landmark tracking data for the Taurus-Littrow site was incorporated into lunar module targeting and was a factor in the precision of the actual landing.

The Apollo 14 spacecraft was equipped with a large, high-resolution topographic camera for so-called bootstrap photography of Descartes, the Apollo 16 landing area. (Data from the photographs were to be used for the selection of landing sites.) Although the high-resolution camera malfunctioned, the Command Module Pilot was still able to record more than 120 pictures of the proposed Descartes site using another camera with a 500-mm lens in support of the site selection analysis for Apollo 16.

For Apollo 15 and subsequent missions, the Command Module Pilot had to time the operation of scientific instrument module experiments. The crewmen developed various reminder techniques for performing the required operations. The computer timer was used for Apollo 15 operations. During Apollo 16 operations, the Capsule Communicator provided ground voice assistance, and the Command Module Pilot used a "kitchen timer" onboard.

Because the ability to make accurate observations of surface features during lunar orbit was demonstrated on early lunar landing missions, the Command Module Pilot of each later mission devoted considerable training time to preparing for lunar geology observations, including flying over and describing selected earth analogs. Their flight performance indicated that this training was extremely effective. For Apollo 16 and 17 activities, the Command Module Pilots spent considerable time reviewing lunar orbit flight plans in the simulator before flight to verify such items as the adequacy of planned maneuver times, maneuver gimbal lock avoidance, the feasibility of dim-light photographic techniques, and the proper time line integration of scientific instrument module operating procedures. Thus, the use of simulators to verify and correct lunar orbit time lines before flight relieved the Command Module Pilot of the need for continual maneuver monitoring and provided time for the important lunar orbit photography and surface observations.

6.1.2.10 Command Module extravehicular activity.- The command module cabin depressurization systems were exercised for the first time on the Apollo 9 mission, including hatch opening and closing. The Apollo 9 Command Module Pilot was able to move easily within the open hatch and center couch envelope. (The center couch was stowed.) For Apollo 15 and subsequent missions, the Command Module Pilot performed an extravehicular activity during transearth coast to retrieve film from the scientific instrument module and to operate certain experiments directly. An oxygen purge system (retained from lunar surface operations) was installed in the "helmet-mounted" mode behind the Command Module Pilot's shoulders to provide backup breathing oxygen and cooling in case the umbilical line failed. In zero gravity, the oxygen purge system tended to hang up on the many protrusions in the center couch envelope and hatch area during egress and ingress. Generally, comments from the other two crewmen on the Command Module Pilot's body-positioning aided his egress and ingress.

On Apollo 15, 16, and 17, each Command Module Pilot moved from the command module to the scientific instrument module bay along a handrail traverse path and returned the film cassettes without incident. All pilots reported that the handrails were excellent as mobility aids, allowing for flexibility in body orientation and in operation sequence.

6.1.2.11 Crew accommodation to zero gravity.- The Apollo 7 crew reported that they adjusted to zero gravity quickly and completely. They stated that at no time was intravehicular activity a problem, although suited movement was awkward as compared to unsuited motion. The main physical problem encountered during Apollo 7 operations was the extreme discomfort caused by head colds. The crew noted that the mucus did not leave the head area but congested and filled the sinus cavities.

Adaptation to zero gravity varied widely from one crewman to another. Some crewmen noted a temporary fullness of the head, others noted a desire to move slowly at first, and still others commenced immediate and rapid body movements without adverse effects. Most crewmen reported that the adaptation to body maneuvering in zero gravity could be speeded considerably by conducting vigorous aerobatics before flight in a T-38A jet aircraft which was provided for astronaut flight proficiency training.

Sleep habits in zero gravity also varied widely among the Apollo crewmen. For example, some crewmen thought that they slept best when they were restrained in the sleeping bag or when they were strapped in the couches. Others found that they could sleep soundly while floating freely in the cabin. Some crewmen, however, slept too well. For example, the Apollo 17 crewmen were difficult to awaken on several occasions during their mission. Other crewmen slept fitfully one night and well the next. The general subjective opinion was that not nearly as much sleep was required in zero gravity as was required on earth unless a crewman was particularly fatigued from the day's activities.

Food preparation in zero gravity was a time-consuming process because of prelaunch package stowage, package control, use of package overwraps, manual mixing of water and food in the rehydratable packages, and the requirement to restow the used food packages in a small volume. In zero gravity, when the food packages were rehydrated with water containing gas bubbles, the bubbles could not be removed from the food. The hydrogen gas separator used on lunar flights did not successfully remove the gas from the water on every occasion. Gas bubbles in the food and water contributed to intestinal problems experienced by the crewmen during the last two missions.

The Apollo 15 crew reported that more time than had been anticipated was required for normal housekeeping functions. This condition was attributed to the fact that additional equipment from the lunar surface (such as experiments and rock bags) and the new bulkier pressure suits crowded the crew compartment. The Apollo 16 crew noted the same problem and recommended that additional time be allotted for stowage and for personal hygiene.

6.1.2.12 Guidance and navigation systems.- All flight crews reported great confidence in the performance of the primary guidance and navigation systems in both spacecraft. Power permitting, crews unanimously chose to keep the inertial measurement unit (platform) powered up and aligned because the unit would permit very rapid and accurate response to every conceivable abort situation requiring immediate velocity changes. The platform was not powered down on the lunar landing missions until the power requirements for the 3-day surface stays dictated the necessity for conserving power.

Alignment of the platform in the command module was readily achieved. Commencing with the Apollo 7 mission, all crews reported that several minutes were required for the eyes to adapt to the recognition of constellations when the command module telescope was used at night in either earth orbit or lunar orbit and in earthshine light conditions. With the lunar module attached during translunar coast, sun reflections from the lunar module into the optics prevented any but the brightest stars from being seen with the telescope. During transearth coast, constellations could usually be recognized when the telescope was pointed away from the sun, earth, or moon. In general, to maintain platform alignment during translunar coast, the Command Module Pilot relied on automatic optics positioning to place reference stars in the field of view of the 28-power sextant.

Upon activation of the docked lunar module, initial alignment was accomplished by transferring the command module platform angles to the lunar module platform. (Initially, ground-computed angles had been used to correct the angular platform misalignments between the two vehicles.) For Apollo 15 and subsequent missions, the lunar module telescope was used for fine alignments of the platform while docked. The Apollo 9 crew reported that visibility through the lunar module telescope was adequate to identify bright stars and the more prominent constellations at night.

Every flight crew was concerned with the prospect of losing inertial attitude reference when maneuvering to an attitude in which the yaw angle exceeded 85°. This condition was called gimbal lock. Many simulations of dynamic flight situations showed that maneuvers leading to gimbal lock could have been hazardous under certain conditions, such as postatmospheric launch abort (possibly causing an aft-end-forward entry). Therefore, many autopilot maneuvers had to be stopped before completion and the spacecraft maneuvered manually to avoid gimbal lock. The Apollo 9 crew commented that greater-than-desired amounts of time and propellant were required to keep the docked configuration out of gimbal lock in drifting flight. The Apollo 11 platform was inadvertently placed in gimbal lock when the lunar module was maneuvered to avoid bright sunlight in the forward window. Just before entry of Apollo 13, close cooperation between the Command Module Pilot and Lunar Module Pilot was required to avoid gimbal lock in the platforms of both vehicles. This procedure used considerable lunar module reaction control fuel and still placed the command module platform close to gimbal lock. The command module platform was placed in gimbal lock during drifting flight of Apollo 17 while a waste-water dump was being performed. The possibility of platform gimbal lock thus restricted many spacecraft maneuvers.

Crew/computer operational compatibility improved continuously throughout the Apollo missions. Computer programs were changed to delete extraneous displays; to eliminate unnecessary delays; and to provide the crews with meaningful monitoring capability of computer navigation computations, autopilot operations, and velocity changes. The Apollo 11 Command Module Pilot recalled that he had little time to analyze off-nominal rendezvous trends or to cope with system malfunctions because he was busy with hundreds of computer entries and numerous lunar module tracking marks. For Apollo 15 operations, an automatic sequencing computer program, designed to relieve the Command Module Pilot's workload, was available for the rendezvous phase. The program was functional as designed and allowed the Command Module Pilot much more time for optics tracking and systems monitoring.

Because of a malfunction during the Apollo 14 mission, an abort discrete signal was set in the lunar module computer before powered descent. Such a signal during powered descent would automatically initiate an unwanted abort. To prevent an abort, ground personnel devised a real-time workaround erasable memory program which inhibited the abort capability of the primary guidance system, and the program was entered in the computer. This abort discrete was inhibited on subsequent missions. Although no major changes in computer programs were made on the last three missions, erasable memory programs were devised for many critical guidance and navigation system failure possibilities. In fact, one such program was used during the Apollo 16 mission to prevent recurrence of a loss in platform reference and to correct an intermittent, and apparently erroneous, indication of failure of the coupling data unit. The operational requirements for designing flexibility into future spacecraft computers and for having a better balance between fixed and erasable memories were demonstrated by the sweeping revisions made to the Apollo computer programs until late in the Apollo missions and by the extensive development of the erasable memory programs to correct potential hardware and computer software failures.

The abort guidance system was an efficient backup system to the primary guidance and navigation system. On all lunar flights, good agreement was achieved between the abort and the primary guidance systems in the solutions for ascent stage orbit insertion and terminal phase initiation. A feature of the abort guidance system was that there was no gimbal lock to restrict lunar module maneuvering or cause loss of attitude reference.

6.1.2.13 Entry and landing.- The Apollo 7 crew performed entry while suited but with helmets and gloves removed. The crewmen had developed head colds, and removal of the helmets provided a means of clearing the sinus and inner ear cavities. Follow-on crews entered the earth atmosphere with their suits stowed under the couches.

The Apollo 8 and 10 crews reported that the appearance of the ionization envelope around the spacecraft preceded the 0.05g indication of entry by approximately 15 seconds. These crews also noted that the ionized plasma streaming by the windows bathed the cockpit in light that was as bright as normal daylight. All entries were flown using the entry autopilot or the primary guidance and navigation system. Crews verified that the primary guidance system never violated the skip-out tangency lines of the entry monitor system. Because of thunderstorms in the primary recovery area, the Apollo 11 crew made a long-range entry of 1500 miles instead of the planned 1285 miles.

Crew training for supercircular entry was initially accomplished through closed-loop centrifuge runs using the entry monitor system. The crews felt confident (and the simulations demonstrated) that they could monitor and take over the control of entry for a wide range of failure conditions in the primary guidance and navigation system. In the simulators, supercircular entries could be flown fairly accurately to landings near the recovery ship when using the secondary (entry monitor system) displays and to a safe landing in the ocean using only the gravity meter.

When one of the main parachutes failed during the Apollo 15 parachute descent, the resulting increased descent rate caused a landing that was 32 seconds early, but the crew felt no physiological effects from the harder landing impact. A considerable variation in the force of the landing impact was subjectively described by each crew. The hardest landing probably occurred during the Apollo 12 mission, in which an impact acceleration of 15g was produced. The impact jarred a 16-millimeter camera loose from its mounting bracket, and the camera hit the Lunar Module Pilot's head.

Of the 11 landings, five resulted in the spacecraft coming to rest in the stable II position (heat shield up), but the spacecraft was always righted without problems by inflating the uprighting bags. When the Apollo 11 crew donned the biological contamination garments required for the initial lunar landing missions, their visibility was substantially degraded because of condensation on the faceplates. The contamination-prevention procedures were modified to include the use of a portable face mask for the Apollo 12 and 14 missions, after which the requirement for the procedures was eliminated.

The thorough egress and recovery training program provided each crew by qualified landing and recovery personnel was a major factor in the satisfactory recovery of all crews.

6.2 FLIGHT CREW TRAINING PROGRAM

The fidelity of crew training improved with each mission as the flight results and crew experience provided the necessary feedback to the training program. Through this process, crew procedures, flight plans, and checklists that had once required an appreciable amount of crew time to develop and verify became standardized. With this maturity and standardization in the program, crew training time for the later missions could be more heavily focused on scientific aspects.

The training of flight crews may be conveniently divided into five major categories: simulators, special-purpose activities, procedures, briefings, and spacecraft tests. A delineation of the activities for each category and a summary of the hours logged by the assigned crewmembers are presented in table 6-II. The 37 953 hours of operations in the command module and lunar module simulators, with briefings, represents 45 percent of the total training time expended. As

TABLE 6-II.- TRAINING TIME SUMMARY

Type of training	Number of hours
Simulator	
Command module	
Command module simulator	17 605
Command module procedures simulator	1 204
Simulator briefings	1 195
Contractor evaluations	866
Dynamic crew procedures simulator	741
Other simulators	156
Rendezvous and docking simulator	87
Centrifuge	58
Massachusetts Institute of Technology hybrid	48
Subtotal	21 960
Lunar module	
[a]Lunar module simulator	13 317
[b]Lunar landing training vehicle	1 130
Lunar module procedures simulator	770
Simulator briefings	533
Full mission engineering simulator	179
Translation and docking simulator	64
Subtotal	15 993
Total	37 953
Special Purpose	
[c]Lunar science	11 408
Water immersion facility checkout	1 248
Stowage	993
Extravehicular mobility unit checkout	919
Egress	820
Bench checks	802
[d]Walkthroughs	719
Medical	601
Water immersion facility (zero g)	516
Planetarium	448
Fire	174
Total	18 648

[a] Includes lunar roving vehicle navigation simulator.

[b] Includes lunar landing training vehicle flights (at 2 hours per flight), vehicle systems briefings, lunar landing research facility, and lunar landing training vehicle simulator time.

[c] Includes briefings, geology field trips, lunar surface simulations, and lunar roving vehicle trainer operation.

[d] Related to zero-g flight operations.

TABLE 6-II.- TRAINING TIME SUMMARY - Concluded

Type of training	Number of hours
Procedures	
Mission techniques	2 730
Checklist	2 334
Flight plan	1 987
Mission rules	1 039
Design, acceptance	1 011
Test reviews	814
Team meetings	541
Training meetings	393
Rendezvous	288
Extravehicular contingency transfer	88
Flight readiness reviews	48
Total	11 273
Briefings	
Command and service module	4 060
Guidance and navigation	2 397
Lunar module	2 130
Lunar topography	1 458
Launch vehicle	656
Photography	405
Total	11 106
Spacecraft tests	
Command and service module	3 332
Lunar module	1 759
Total	5 091
Program total	84 071

pointed out in other sections, the Apollo simulators provided the most valuable source of crew training for each mission. A description of these simulators is provided in reference 6-12. The time listed for lunar science training, shown in table 6-II as a special-purpose activity, is the third highest total behind command module and lunar module simulator training. Science training included geology field trips, lunar surface activity simulations, extravehicular preparation and postactivity operations, and lunar roving vehicle trainer operation.

Table 6-III shows these same training data grouped into three different mission categories: missions before lunar landing (C-, D-, and F-series missions), the first four lunar landing missions (G- and H-series missions), and the final three lunar landing missions (J-series missions), The trend in training emphasis across the three categories is interesting. Simulator training, besides being the largest single training activity, increased significantly for the early lunar landing missions and then decreased for the J-series missions. The special-purpose training steadily increased in its percent of the total, with lunar science activities for the J-series missions making up more than one-third of the total training effort. The training categories of briefings, procedures, and spacecraft tests exhibited a decreasing level of training effort. These decreases are, indeed, signs of maturity and standardization of flight procedures.

A further delineation of the training accomplished by the crews of the lunar landing missions is provided in tables 6-IV and 6-V, which summarize the number of lunar surface simulations and geology field trips. The lunar surface exercises in table 6-IV include training for operations before, during, and after extravehicular activity. Lunar surface training made use of a full-scale, high-fidelity, lunar module mockup and actual lunar surface equipment. Training exercises commenced after egress through the hatch and terminated before ingress, following closely the planned lunar surface time lines. The training for the periods before egress and after ingress provided rehearsals for the necessary crew procedures before and after the lunar surface activities. Major tasks in this training included backpack donning and doffing, cabin decompression and repressurization, lunar surface sample stowage, and equipment cleaning. The geology field trips presented in table 6-V, especially for the J-series missions, generally followed an order of increasing complexity. Earth features analogous to certain lunar geologic formations were studied on the early field trips. These trips were followed by field exercises of lunar surface traverse simulations using some of the lunar surface sampling and geologic equipment. The latter field trips rehearsed a nearly complete mission simulation and included the science support teams in the Mission Control Center working with the suited astronauts on location.

For each mission, full dress rehearsals of the various flight phases were accomplished where integration of the crew, the flight plan, and the ground support elements was an essential part of the preflight preparation. These simulations were as valuable in preparing the ground crews as they were for the flight crews. The scope of this phase of the simulation training program is presented in table 6-VI in which the days spent conducting full-scale mission simulations for the flight crew and Mission Control Center personnel are listed.

6.3 FLIGHT PLANNING

Any major manned spaceflight project requires a documented flight plan which brings man, machine and operational techniques together to execute a mission. The need was particularly important in the complex Apollo program. Among the factors considered and eventually integrated into the Apollo flight plans were:

a. Mission objectives and their related constraints

b. Vehicle system constraints and operations

c. Crew and ground procedures and their relationships

d. Duration and sequence of crew activities

e. Division and interaction of onboard tasks

f. Consumable constraints

g. Alternate and contingency plans

TABLE 6-III.- APPORTIONMENT OF TRAINING ACCORDING TO MISSION TYPE

Training category	Missions before first lunar landing (Apollo 7 through 10)		Early lunar landing missions (Apollo 11 through 14)		Final lunar landing missions (Apollo 15 through 17)	
	Hours	Percent of total	Hours	Percent of total	Hours	Percent of total
Simulators	11 511	36	15 029	56	11 413	45
Special purpose	4 023	13	5 379	20	9 246	36
Procedures	7 924	25	2 084	8	1 265	5
Briefings	5 894	18	3 070	11	2 142	9
Spacecraft tests	2 576	8	1 260	5	1 255	5
Total	31 928	100	26 822	100	25 320	100

TABLE 6-IV.- LUNAR SURFACE ACTIVITY SIMULATIONS

(Number of training sessions)

Apollo mission	Surface operations	Operations before and after extra-vehicular activities	Total per mission
11	20	10	30
12	31	4	35
13	42	11	53
14	43	18	61
15	91	20	111
16	67	10	77
17	47	20	67
Total	341	93	434

TABLE 6-V.- GEOLOGY FIELD TRIPS[a]

Apollo mission	Number of trips
11	1
12	4
13	7
14	7
15	12
16	18
17	13

[a] Each field trip lasted from 1 to 7 days.

TABLE 6-VI.- INTEGRATED CREW/GROUND MISSION SIMULATIONS[a,b]

(Number of days)

Apollo mission	Command module simulator	Lunar module simulator	Command module and lunar module simulators	Total per mission
7	18	0	0	18
8	14	0	0	14
9	10	2	8	20
10	11	0	7	18
11	6 (1)	4	7	17 (1)
12	10	3	12	25
13	13	5	9	27
14	12 (3)	5 (2)	12 (1)	29 (6)
15	13 (6)	5	7	25 (6)
16	16 (5)	7 (1)	10	33 (6)
17	13 (2)	6	9	28 (2)
Total	136 (17)	37 (3)	81 (1)	254 (21)

[a] Includes participation of Mission Control Center personnel.

[b] Numbers in parentheses indicate simulations accomplished by follow-on or support crewmen.

By the interaction of the preceding factors, the flight plan ultimately communicated to project participants their roles and responsibilities, served as a guide for mission execution and, in the end, was the means by which performance was measured.

6.3.1 Flight Plan Development

Flight plans, in a variety of forms and for a variety of purposes, were required from the embryonic program definition stage through the culmination of the program with the lunar landing missions. Through early experience, flight plan concepts matured and the flight plan became recognized as a valuable tool in integrating many disciplines.

Apollo flight plans varied in complexity from that of the relatively simple Apollo 7 mission, involving one spacecraft in earth orbit, to those of the lunar landing missions, wherein two spacecraft were active simultaneously in a fully integrated time line. Flight plans, tried and proven from each mission were progressively improved so that, even though flights became more complex, the crews became more efficient.

6.3.1.1 Flight planning techniques.- All activities identified for Apollo flights were scheduled in the flight plan in a sequence required to accomplish certain objectives. The activity sequence fell into two basic categories:

a. Consecutive activities — These consist of a series of related activities which must be performed in a fixed sequence to accomplish a desired goal. Lunar module activation fell in this category. Consecutive flight plan activities have the advantage of changing very little from mission to mission and, therefore, provide the crew with tried and proven sequences during critical mission phases.

b. Non-consecutive activities — These consist of a series of activities which need not be performed in a fixed sequence to accomplish a desired goal. Lunar orbit science activities fell in this category. Non-consecutive flight plan activities have the advantage of allowing the crewman, from his vantage point, to select the best activity sequence to optimize a particular situation.

Within each category, certain activities are necessarily dependent on time and place of execution. These activities are called dependent activities. Activities which are not constrained by time or place are called independent activities. "Padding" was allowed in consecutive flight plans to ensure that dependent activities would be performed at the appropriate time or place. For non-consecutive flight plans, dependent activities were easily schedulable since the activity sequence was flexible.

6.3.1.2 Alternate and contingency flight plans.- Apollo flight plans were constructed to provide a maximum accomplishment of mission objectives assuming no major off-nominal situations. These were called prime flight plans and one was generated for each mission. Unfortunately, because of the complexities of vehicle systems and operational constraints, no Apollo flights were executed exactly as planned preflight.

In addition to the prime flight plan, two other types of flight plans were developed to support probable and/or predictable off-nominal situations. Each flight plan attempted to optimize the mission based on the given off-nominal situations.

a. Alternate flight plans — In the event the launch could not occur on the planned day and time, alternate launch day flight plans were developed. Each flight plan was highly dependent on a detail trajectory. Because the lunar trajectory is influenced by time and launch data, a great deal of effort was spent developing unique trajectories and flight plans for each launch opportunity. The alternate flight plans were equal to the prime flight plan in mission objectives.

b. Contingency flight plans — Flight plans were developed to support missions brought about by the failure of some critical system. While it was difficult to plan for all situations, only those system failures which could radically affect the completion of the mission were considered (e.g., no translunar injection; no transposition, docking and extraction; lunar module failure; etc.). Contingency flight plans attempted to glean as much as possible from the given situation but fell far short of the objectives of the prime or alternate flight plans. By the time of the Apollo 17 mission, five distinct alternate mission plans, 20 contingency plans, and eight lunar orbit alternate plans were developed.

6.3.1.3 Flight plan verification using simulators.- Early flight experience indicated that the portions of a mission that were simulated most thoroughly were those that were best executed and virtually free of unexpected situations except for systems anomalies. Consequently, more emphasis was placed in later missions on simulating as much of the mission as possible. In fact, for the Apollo 16 and 17 missions, virtually the entire mission was being verified in the simulators.

Crew simulations were very important to the flight planning and procedures development process. Simulations provided a near-actual flight environment using equipment that closely matched actual vehicle performance. In this situation the crew could execute portions of the flight plan and could verify the sequence of activities, the length of activities, and the activity interaction with trajectory and systems. The flight plan was tested and consequently optimized from these simulations.

6.3.2 Flight Plan Execution

The onboard flight plan served as a crew guide in the execution of a mission. In some mission phases, the flight plan provided all of the execution data required to perform that phase. In other phases, especially those that were critical and complex, the flight plan served as an index to checklists required in that phase by providing book names and page numbers where procedures were to be found. In these cases, the flight plan would set the sequence of activities but checklists provided the actual procedural information.

Major emphasis during the Apollo program was placed on the execution of the mission exactly as planned. In general, flight crews executed their flight plans with few missed activities. The major contributors to off-nominal activities were equipment malfunctions. In order to prevent major deviations from the prime flight plan, a close interface between the flight crew and ground support team was required to quickly provide alternatives or solutions to problems. This cooperation yielded a near-normal flight plan execution and, at the same time, optimized the mission.

Changes to the flight plan during a mission were communicated by voice to the crew. The crew would then work the changes on the prime flight plan. This technique was somewhat cumbersome since it required much crew time, and was inherently confusing. It was therefore important that the execution of the flight plan be as close to the preflight plan as practical.

6.3.3 Change Control

The Apollo flight data file consisted of documents placed aboard the spacecraft for crew reference in flying a mission. In addition to the flight plan, the following types of documents were included.

a. Integrated flight procedures checklists (generally providing all information required to conduct specific phases of a mission)

b. Systems checklists (procedures for operating specific systems)

c. Malfunction checklists (procedures for isolating and correcting certain failures)

d. Systems data book

e. Graphics and maps

f. Cue cards (abbreviated procedures for crew use during time-critical high-density activities)

At the beginning of the Apollo program, the crew procedures control process was intended to cover system operating procedures documents acquired from the hardware suppliers and internally generated procedures documents which were not used in flight. As the program developed, it became obvious that attempting to control crew procedures through documents that were not used directly by the crews was difficult and expensive. The interrelationships between the various control documents and the onboard documents were not adequately defined, nor was the purpose of control documentation well understood. During the course of the program, procedural change control gradually evolved until on Apollo 17 all procedures change control was directed toward the flight data file. In general, in the latter stages of the program, the change control techniques were to maintain overall cognizance and control of the flight data file contents and schedules. Requirements for new flight data file articles or procedures were reviewed by the crew procedures control board. Mature articles or procedures remained under direct control from mission to mission, thereby requiring that change control procedures be followed for all changes. New articles or procedures normally came under direct control after the basic article was published. Items that were highly trajectory dependent were updated to the new trajectory without a requirement for crew procedures control board concurrence.

Additional information on flight planning for Apollo missions is given in reference 6-13.

6.4 OPERATIONAL PHOTOGRAPHY

In the course of the Apollo program, a varying complement of photographic equipment was carried aboard each spacecraft to perform operational documentation, record crew observations, and accomplish many scientific objectives. This photographic equipment most often consisted of a 16-millimeter sequence camera system, two 70-millimeter still camera systems, and a 35-millimeter still camera system. A 127-millimeter lunar topographic camera was used to a limited extent. The equipment complement also included a light-metering system and various brackets and filters to meet the required photographic objectives. The photographic equipment used on each flight through Apollo 13 is tabulated in reference 6-14. The reference also contains a discussion of equipment hardware and operational development for three manned programs. Further details on equipment characteristics can be found in reference 6-15. This report deals primarily with photographic equipment and use for Apollo missions 14 through 17, thereby supplementing the contents of reference 6-14.

6.4.1 Equipment Summary

A typical complement of photographic equipment and accessories is listed in table 6-VII and depicted in figure 6-3. Miscellaneous operational equipment is also included in the figure. The three camera systems identified in the table are illustrated individually in figures 6-4, 6-5, and 6-6. Table 6-VIII lists crew-operated photographic equipment used for Apollo missions 14 through 17 and includes the types of lenses and film and a brief statement of usage for each item. These missions were characterized by an increasing scientific emphasis which resulted not only in the addition of new photographic equipment but also in a more diverse use of equipment. The expanded use is reflected in table 6-VIII.

6.4.2 Photographic Results

Photographs taken under operational conditions supported postflight anomaly analyses, vehicle documentation and inspection requirements, crew mobility studies, scientific evaluations, and equipment evaluations. Perhaps the most important photographs supported lunar sample documentation, lunar experiments location, and lunar terrain description, since photographs were the primary data source for satisfying lunar exploration objectives in these areas. The photographs also served the function of relaying to the scientific community and the public at large the exploration results in space and on the lunar surface, thereby sharing Apollo achievements with people throughout the world. Early photographs of the lunar surface during the lunar landing development missions served to update existing lunar maps. The revised maps were used extensively for crew familiarization and training in the actual types of lunar terrain that would be encountered. The improved maps were also used in selecting landing sites.

TABLE 6-VII.- TYPICAL PHOTOGRAPHIC EQUIPMENT
COMPLEMENT FOR LATER APOLLO MISSIONS

Item	Quantity	
	Command module	Lunar module
16-mm sequence camera system:		
Data acquisition cameras	1	[a]2
Film magazines	10	[b]3
75-mm lens	1	
18-mm lens	1	
10-mm lens	1	1
Right-angle mirror	1	
Power cable	1	
Remote control cable	1	
Spare fuse	1	2
Mounting bracket		1
70-mm still camera system:		
Electric camera	1	
Electric data cameras		[c]3
Film magazines	8	[b]15
60-mm lens		2
80-mm lens	1	
250-mm lens	1	
500-mm lens		1
20-sec intervalometer	1	
8-sec intervalometer	1	
Polarizing filter		1
[d]Ring sight		1
35-mm still camera system:		
Camera body	1	
Film cassettes	8	
Film canisters	7	
55-mm lens	1	
Polarizing filter	1	
Red filter	1	
Blue filter	1	
Mounting bracket		
[e]Spotmeter	1	

[a] Stowed in lunar module and transferred to lunar roving vehicle.

[b] Stowed in command module and transferred to lunar module.

[c] One long-focal-length camera used with a 500-mm lens; two electric data cameras used for lunar geology and crew operations documentation.

[d] Aiming device for long-focal-length camera.

[e] Light-measuring system.

Figure 6-3.- Typical Apollo photographic equipment complement.

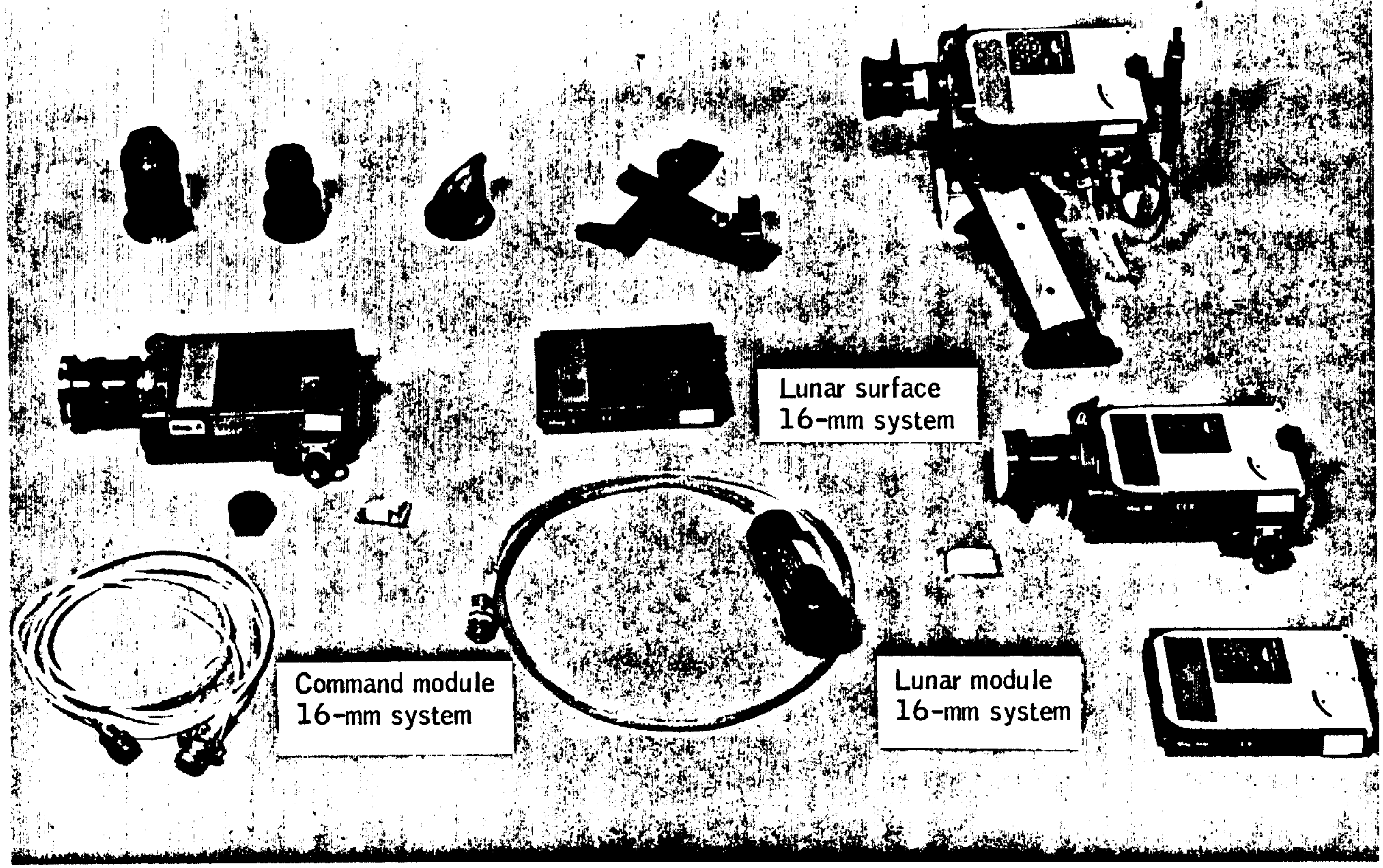

Figure 6-4.- The 16-mm sequence camera system.

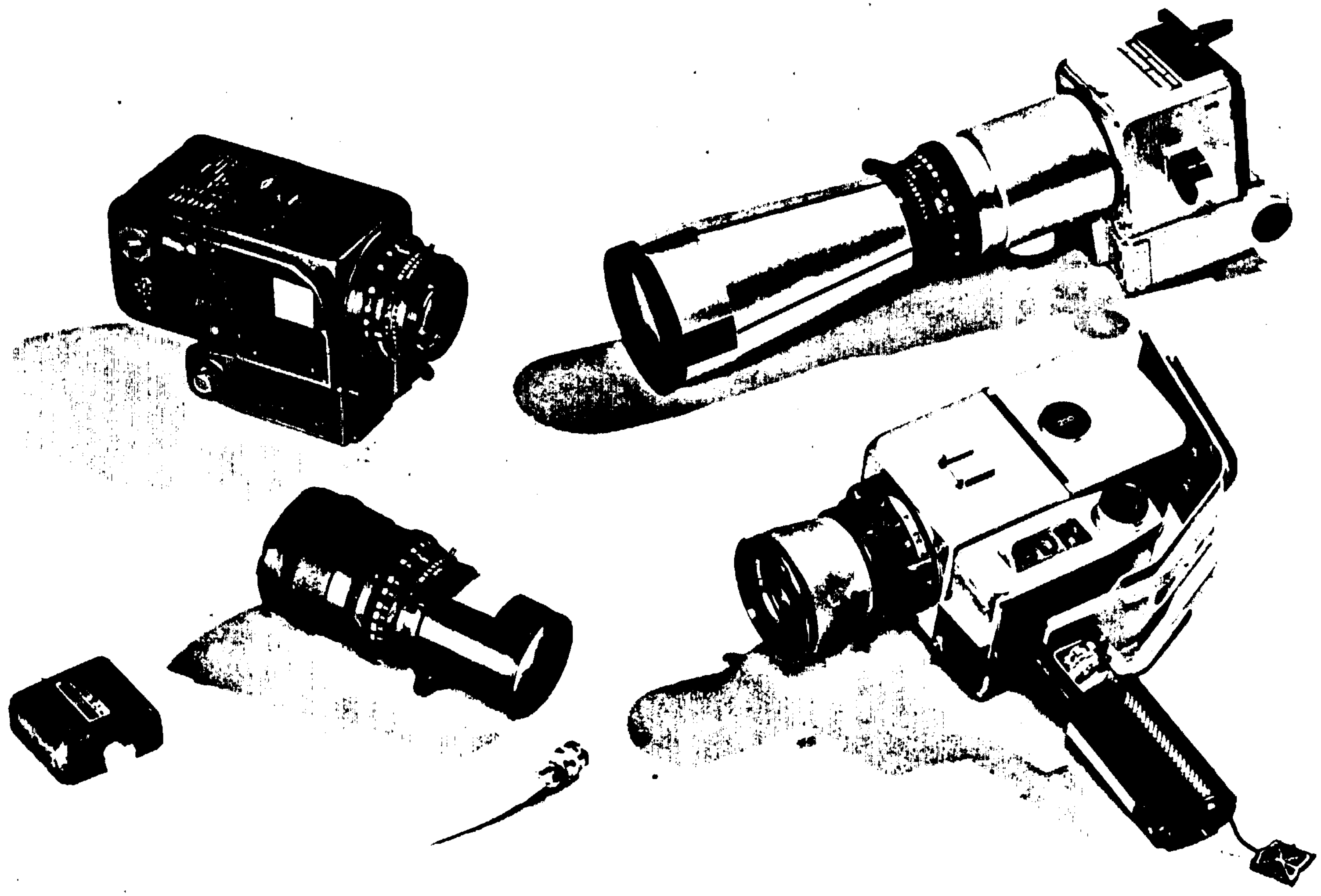

Figure 6-5.- The 70-mm still camera system.

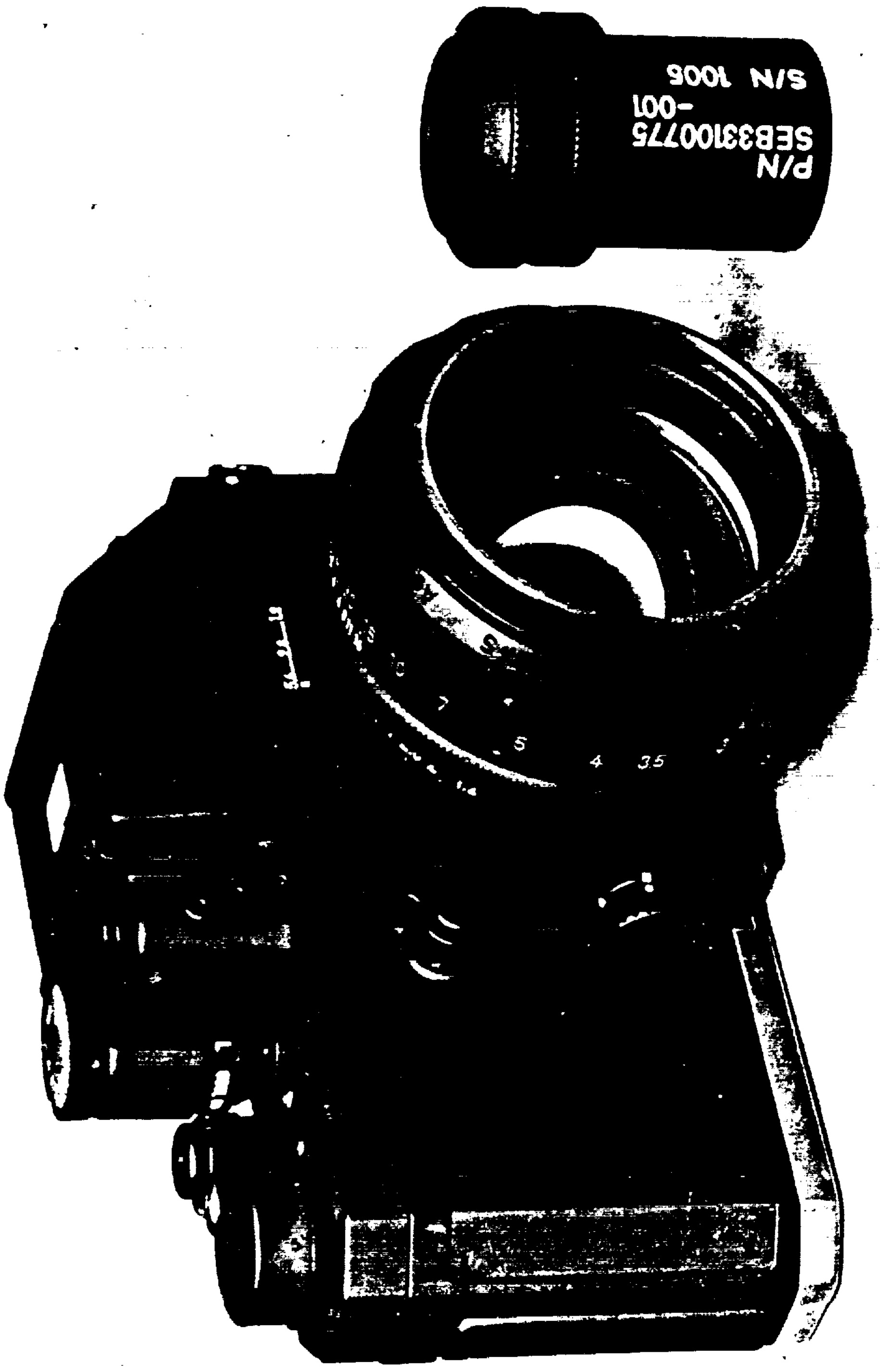

Figure 6-6.- The 35-mm still camera system.

TABLE 6-VIII.- PHOTOGRAPHIC EQUIPMENT USAGE (APOLLO 14 THROUGH 17)

Camera	Lens focal length, mm	Film type (a)	Usage or target
Apollo 14			
Command module 70-mm electric	80 500 250	3400 S0368 3400	Transposition, docking, and undocking; inflight demonstrations; orbital science; landing sites; earth and moon
Command module 70-mm electric data	80	3400 S0349 2485	Zero phase; earthshine; stereographic strip of moon; visibility study
Command module 16-mm data acquisition	18 5 10	S0368 S0168 2485	Transposition, docking, and undocking; landmark tracking; spacecraft interior; lunar dark side; Gegenschein; zodiacal light; galactic survey; earth entry
Command module 127-mm lunar topographic	18 in.	S0349 3400	Landing sites of follow-on missions
Lunar surface 70-mm electric data	60	S0168 3400	Lunar geology documentation, lunar surface documentation, lunar module on surface, crew operations
Lunar module 16-mm data acquisition	10	S0368	Lunar descent and ascent
Lunar surface 16-mm data acquisition	5	S0368	Modular equipment transfer evaluation and lunar surface experiments traverse
Apollo 15			
Command module 70-mm electric	80, 250 500, 250 [b]105	S0368 3414 2485 IIa-0	Lunar eclipse; earth and moon; stereographic strip; solar corona; terminator; Gegenschein; transposition and docking; rendezvous; lunar orbit science; ultraviolet clouds, land, water, and earth; lunar horizon and features
Lunar surface 70-mm electric	500	3401	Panorama; geology and sample documentation; distant surface features
Lunar surface 70-mm electric data	60	3401 S-168	Geology and sample documentation; docking; panorama; lunar surface experiment documentation; lunar module; crew; scientific instrument module
Command module 35-mm	55	2485	Lunar surface in earthshine; terminator; zodiacal light; Milky Way; Gegenschein; lunar eclipse; lunar libration point
Command module 16-mm data acquisition	18	2485 S0168 S0368	Solar corona; contamination; twist of mass spectrometer boom; transposition and docking; rendezvous; entry
	Sextant adapter	S0368	Lunar surface from orbit
Lunar module 16-mm data acquisition	10	S0368	Undocking; descent; lunar surface; ascent
Lunar surface 16-mm data acquisition	75 10	S0368 S0368 S0168	Jettison of scientific instrument module door; launch of subsatellite; lunar roving vehicle traverse and evaluation; surface geology

[a] 3414 and S0349	Slow-speed black and white.
3400 and 3401	Medium-speed black and white.
2485	Very-high-speed black and white.
S0168	High-speed color exterior.
BW168	High-speed black and white exterior.
S0368	Medium-speed color exterior.
IIa-0	Ultraviolet spectroscopic.

[b] Ultraviolet.

TABLE 6-VIII.- PHOTOGRAPHIC EQUIPMENT USAGE (APOLLO 14 THROUGH 17) - Concluded

Camera	Lens focal length, mm	Film type (a)	Usage or target
		Apollo 16	
Command module 70-mm electric	80 250 [b]105	2485 3401 S0168 S0368 IIa-0	Window calibration for solar corona; moon; earth; electrophoresis; orbital science; lunar module inspection; ultraviolet earth and moon; lunar terrain, maria, and horizon
Lunar surface 70-mm electric data	60 500	S0168 3401	Geology sample documentation; lunar surface experiment layout data; lunar module; distant lunar features
Command module 35-mm	55	2485 S0168	Gegenschein; galactic; Gum Nebula; zodiacal light; earthshine; contamination; light flash moving emulsion detector position data
Command module 16-mm data acquisition	18 10 18 75	BW168 S0168 2485 S0368	Twist of mass spectrometer boom; food evaluation; intravehicular transfer; solar corona; contamination; transearth extravehicular operations; transposition and docking; lunar module inspection; rendezvous; landmark tracking; entry
Lunar module 16-mm data acquisition	10	S0368	Lunar module descent, ascent, and docking
Lunar surface 16-mm data acquisition	10	S0368	Lunar roving vehicle traverse; crew mobility; soil dynamics
		Apollo 17	
Command module 70-mm electric	80 250	S0368 2485	Undocking; ejection; lunar module inspection; rendezvous; docking; earth and moon; orbital science; solar corona; stereographic strip; contamination
Lunar surface 70-mm electric	60 500	S0368 3401	Geology sample documentation; surface panorama; lunar surface experiment deployment; soil mechanics; lunar module inspection; distant features
Command module 35-mm	55	S0168 2485	Light flash moving emulsion detector position data; zodiacal light; galactic; lunar libration point; lunar surface in earthshine; dim-light phenomena
Command module 16-mm data acquisition	75 18 10	S0368 S0168 2485	Transposition and docking; undocking; rendezvous; lunar module inspection; scientific instrument module door jettison; Command Module Pilot extravehicular activity; heat flow demonstration; comet; contamination; intravehicular operations; lunar strip photography; entry; parachute deployment
Lunar module 16-mm data acquisition	10	S0368	Lunar descent; surface activity; lunar ascent; rendezvous

[a]3414 and S0349	Slow-speed black and white.
3400 and 3401	Medium-speed black and white.
2485	Very-high-speed black and white.
S0168	High-speed color exterior.
BW168	High-speed black and white exterior.
S0368	Medium-speed color exterior.
IIa-0	Ultraviolet spectroscopic.

[b]Ultraviolet.

On each of the lunar landing missions, an average of approximately 3400 frames of 70-millimeter film, 2000 feet of 16-millimeter film, and 250 frames of 35-millimeter film were exposed. The 35-millimeter photographs supported, primarily, dim-light phenomena for the Apollo 16 and 17 missions, and a limited number of 127-millimeter photographs were taken for the Apollo 14 mission.

Several examples of crew photography are included in this section. In addition, crew photographs are used in other sections of this report. Of the many examples of long-range photography from lunar orbit that are available, figures 6-7 and 6-8 were selected as being typical. Figure 6-9 was taken of the fully illuminated moon just after the Apollo 17 transearth injection.

6.4.3 Conclusions

Crew photography was a primary source of data for the Apollo program and provided documentation of vehicle conditions and dynamics, crew operations, celestial phenomena, lunar surface features and geology, and surface experiment location data. The following conclusions are drawn from the Apollo experience.

With one exception, all photographic objectives were met with the operational camera systems even though occasional problems required a second attempt in obtaining the data. The exception was an instance in which high-resolution photographs of Descartes were not obtained because of a transistor failure in the primary camera system seconds before the primary photographic site was reached. The Descartes data, however, were obtained with a backup camera and were of sufficient resolution to meet minimum objectives.

The complement of camera equipment and lenses was properly selected to meet mission requirements and was obtained within budget guidelines. The use of professional quality commercial equipment, when available in the format sizes required and with minor modification to meet space environmental criteria, was an adequate approach which resulted in quality photography at minimum cost.

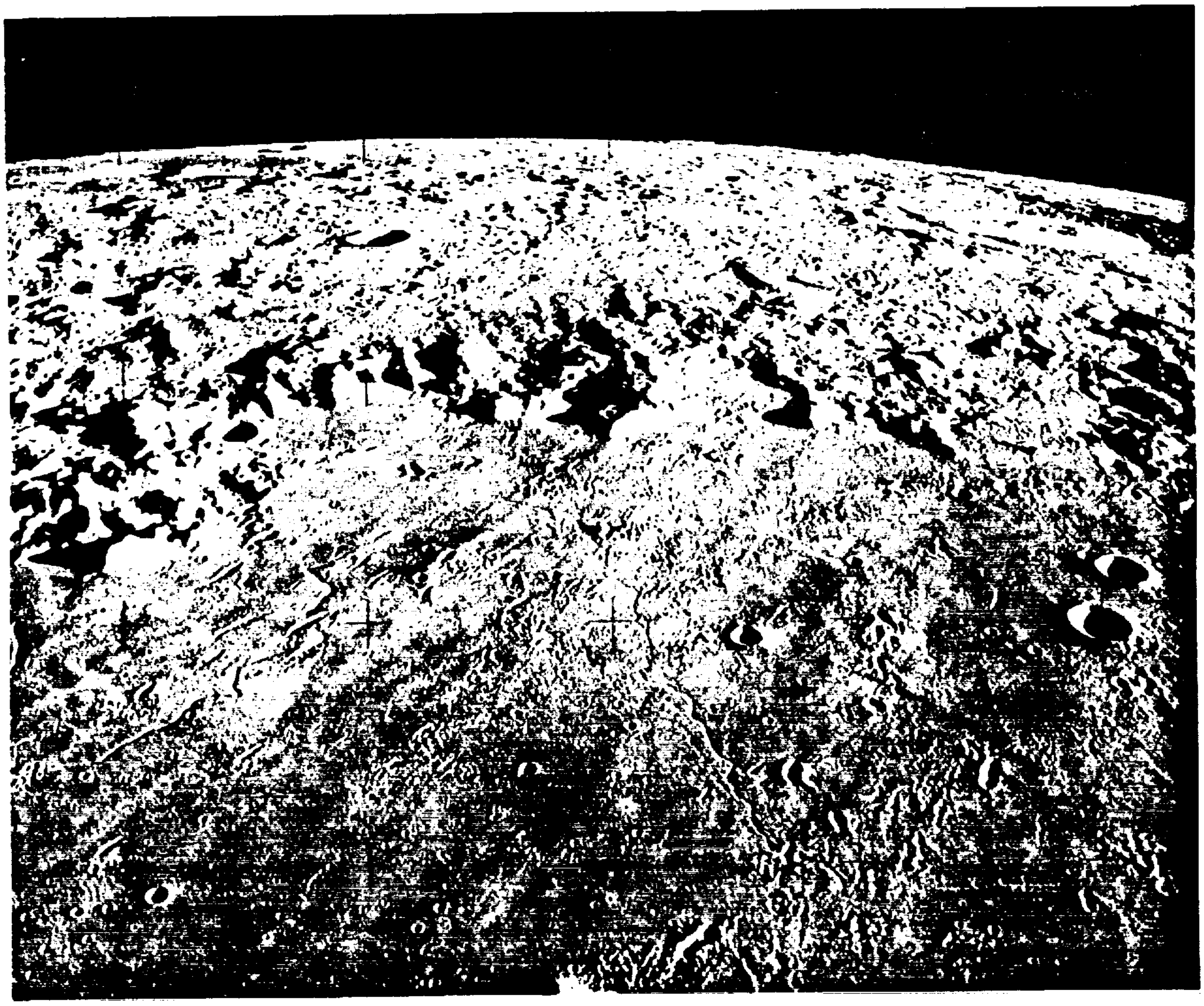

Figure 6-7.- View of lunar surface taken from command module on Apollo 17.

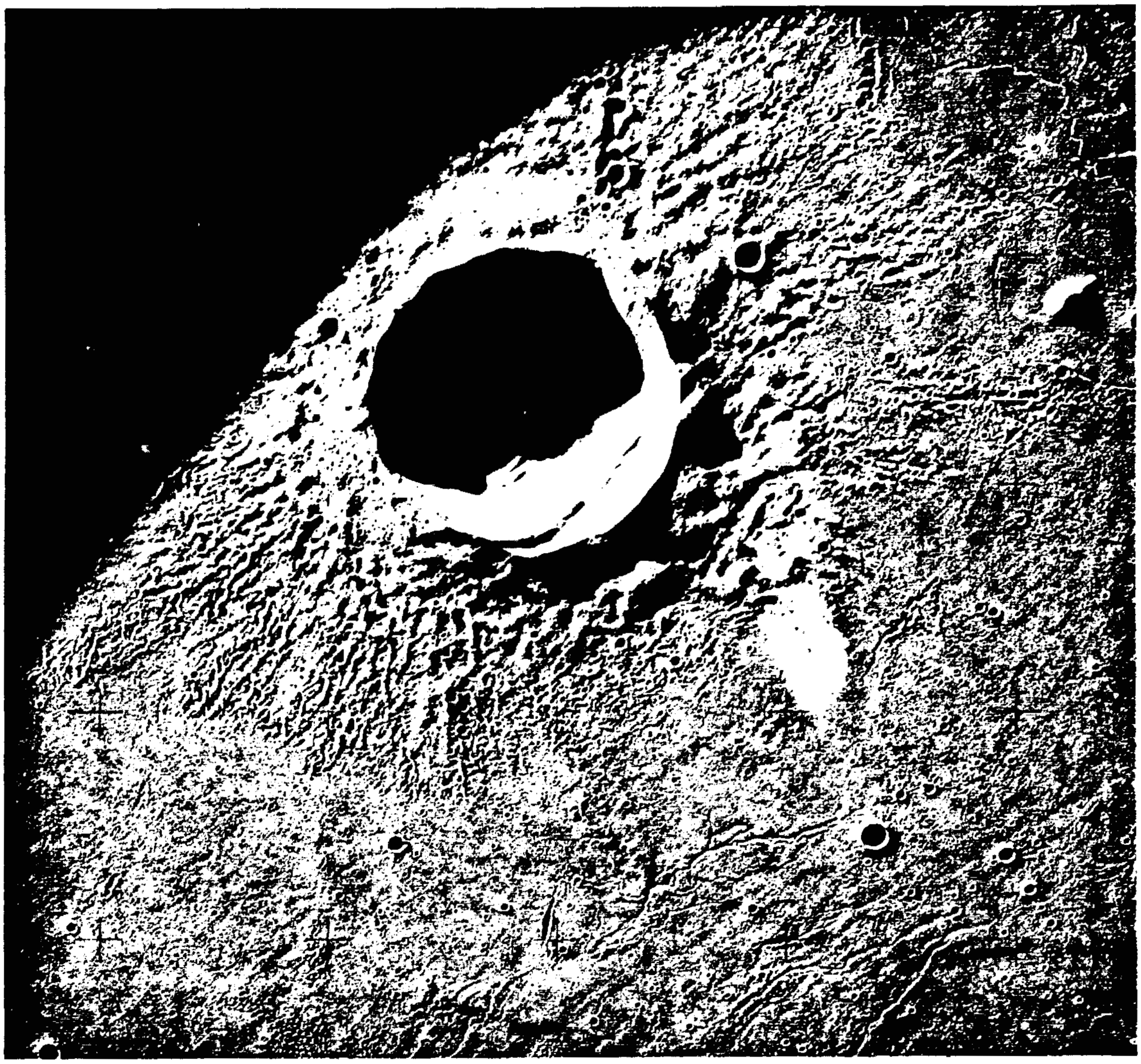

Figure 6-8.- View of lunar surface as taken from command module.

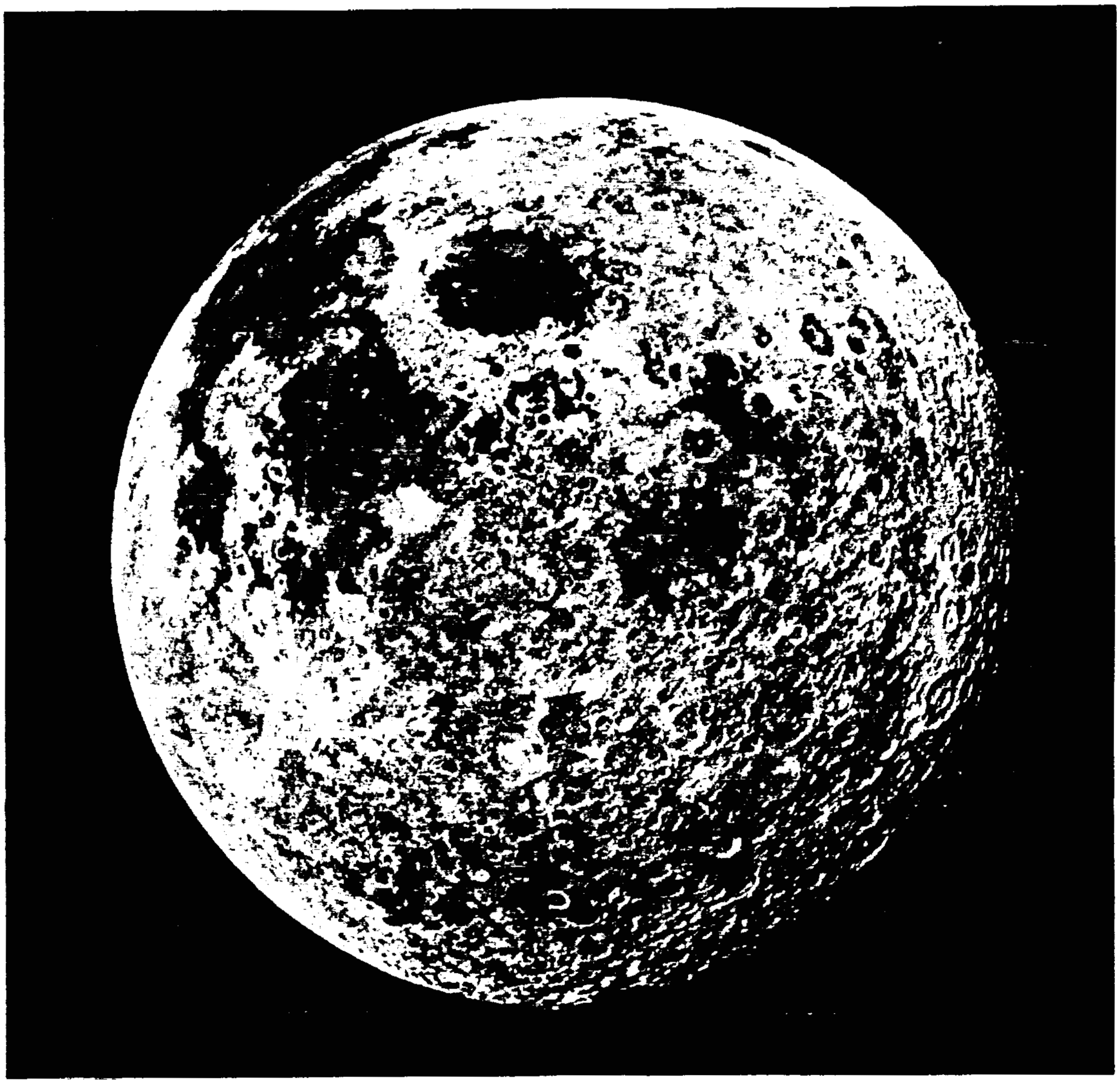

Figure 6-9.- View of fully illuminated moon taken after transearth injection on Apollo 17.

6.5 REFERENCES

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7.0 MISSION OPERATIONS

Apollo mission operational activities encompassed several diversified support disciplines. The largest number of supporting personnel were located at the NASA Manned Spacecraft Center in Houston, Texas; numerous other supporting organizations were located throughout the United States and the world. All organizational elements functioned as a unified team during a mission, with some elements remaining active until a postflight report of the mission had been published and all conditions causing anomalous performance of the mission hardware had been resolved. This section summarizes the activities of the major support disciplines and gives examples of the problems encountered.

7.1 MISSION CONTROL

The basic objectives and responsibilities of mission control were established in previous manned space flight programs. In the Apollo program, the flight control team continued its primary role in trajectory determination, maneuver computation, overall spacecraft systems evaluation, and crew assistance as required. The capabilities involved in mission control were intended to aid the crew in accomplishing the mission objectives and to preserve crew safety under normal and contingency conditions. Even though the objectives remained unchanged, the role and capability of mission control increased throughout the program to meet the additional requirements of each new mission.

7.1.1 Mission Control Center

The focal point for ground-based Apollo mission operational activities was the Mission Control Center located at the NASA Manned Spacecraft Center. The Mission Control Center contains two identical mission operations control rooms (fig. 7-1). Either can be used, or in some circumstances, they can be used simultaneously. The mission operations control room provided the working space for three basic groups of flight controllers: mission command and control, systems operations, and flight dynamics. Each group was assigned a nearby staff support room (fig. 7-2) where data on the missions were monitored and analyzed in detail. Other support areas within the facility included a meteorological room, a spacecraft planning and analysis room, a recovery operations control room, and a lunar surface experiments package support room. The consoles at which the flight controllers worked in the mission operations control room, and those in many of the support rooms, included one or more television screens and the necessary controls to display data on a number of different channels. The data could be the same as that displayed on large screens on the front wall of the mission operations control room, or other data could be "called up" by changing channels. Static information was obtained from a library of reference data, while digital-to-television display generators provided constantly changing data.

A real-time computer complex on the first floor of the Mission Control Center processed incoming tracking and telemetry data and compared actual mission conditions with predetermined parameters. Of five primary computers in the real-time computer complex, two were used to support one mission operations control room, and two were used for the other. The fifth served as a backup, or could be used to develop and perfect computer programs.

Another facility on the first floor that was essential to the success of a mission was the communications, command and telemetry system. The system processed the incoming digital data and distributed it on a real-time basis to the mission operations control room and support rooms for display. The system also handled the digital command signals to the spacecraft.

Another important facility was the voice communications system. It enabled the flight controllers to talk to one another without having to leave their consoles, and it connected them to the specialists in the support rooms, to flight crew training facilities where specific procedures could be tried out on spacecraft simulators before they were recommended to the mission crew, and to personnel along the Manned Space Flight Network. It also provided the voice link between the control center and the spacecraft.