Figure 7-1.- Mission operations control room during Apollo 14 docking operations.

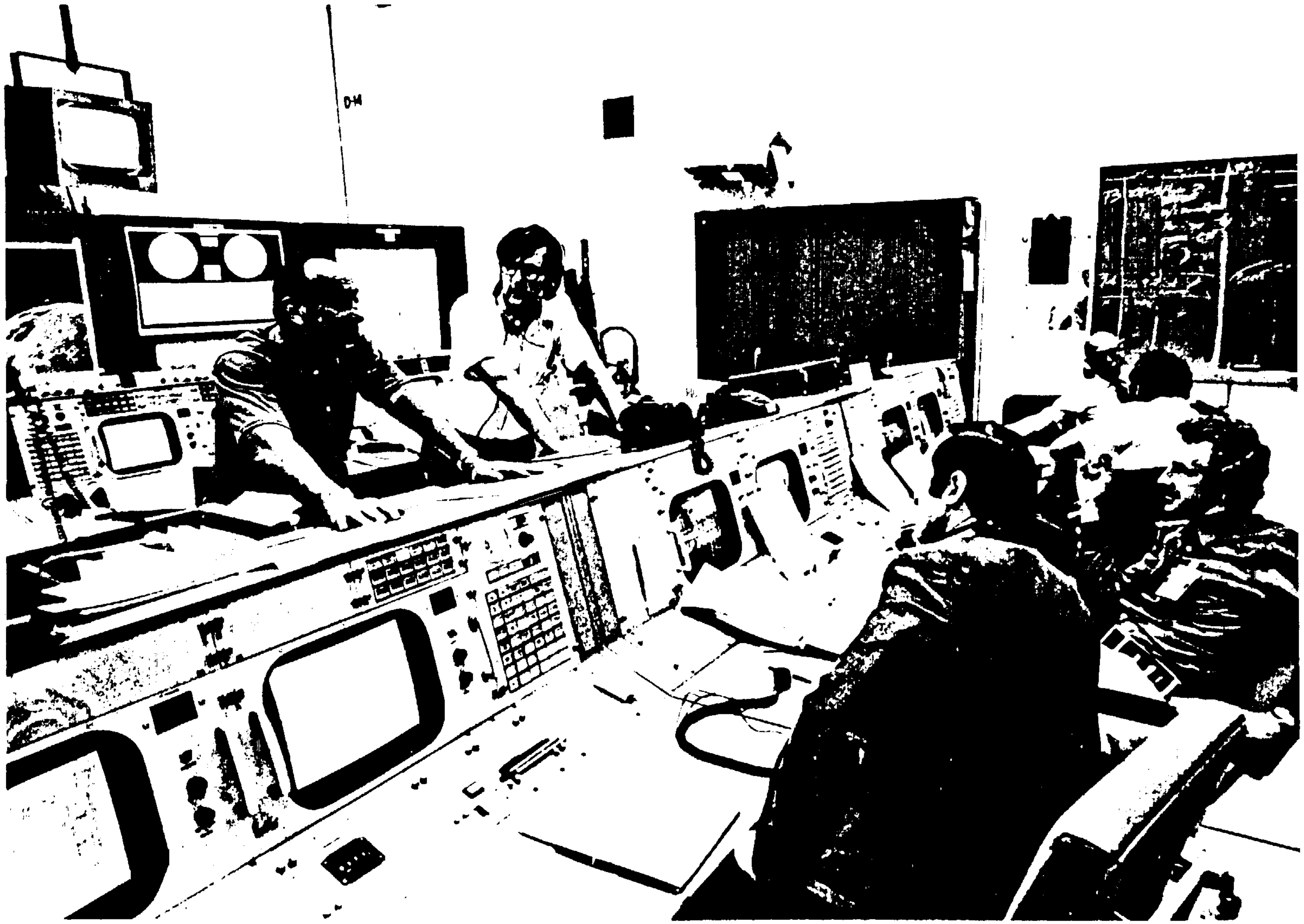

Figure 7-2.- Typical staff support room.

A separately located simulation checkout and training system enabled flight controllers in the Mission Control Center and flight crews in spacecraft simulators at the Manned Spacecraft Center and the Kennedy Space Center to rehearse a particular procedure or even a complete mission. The system even simulated voice and data reception from the far-flung stations of the Manned Space Flight Network.

7.1.2 Emergency Power Building and Backup Facility

The Mission Control Center was supported by an emergency power building which housed generators and air conditioning equipment, and was backed up by a secondary Mission Control Center at the Goddard Space Flight Center.

7.1.2.1 Emergency power system.- Electrical power is distributed to the Mission Control Center and within the emergency power building by either a "category-A" or "category-B" distribution system (fig. 7-3). Category-A power is defined as the uninterruptible power supplied to all critical loads in the Mission Control Center. The power is generated in the emergency power building for two separate electrical buses which are electrically isolated from the commercial power system and from each other. Category-B power is defined as interruptible power supplied to all loads other than the category-A power loads in the Mission Control Center. Under normal operating conditions, the category-B power is supplied by commercial power; however, when a commercial power failure occurs, the category-B power is generated in the emergency power building by two diesel generators which start picking up the load within 25 seconds after the commercial power failure. Depending upon conditions, the category-A power generating system is capable of operating in any one of three different modes.

a. Mode 1. During normal operation in which the commercial power system is intact, category-A power is obtained from a 350-kilowatt electric motor-generator and a 350-kilowatt diesel generator operating in parallel with each other. The diesel generator and motor-generator each supply approximately one-half of the load to the appropriate A bus. Either generator is capable of assuming the full load upon failure of the other. A third 350-kilowatt diesel generator acts as the standby or "swing" generator and is capable of being substituted for any of of the category-A power generators.

b. Mode 2. During periods in which the commercial power system supply has been interrupted or has failed, both electric motor-generators cease to operate and the diesel generators temporarily assume the full load for the category-A power system. As soon as the category-B power system generators have started, the category-A power system electric motor-generators are manually restarted and are operationally powered by the category-B power generators.

c. Mode 3. During periods in which one of the category-B buses has been removed from service, the respective category-A system electric motor-generator that was receiving power from the bus ceases to operate. The standby diesel generator then operates in parallel with the operating diesel generator to provide uninterruptible power to the A bus. The remaining A bus operates normally with the electric motor-generator operating in parallel with the diesel generator.

Depending upon conditions, the category-B power generating system is also capable of operating in any one of three modes.

a. Mode 1. During normal operation in which the commercial power system is intact, each of the B buses receives power from the commercial power system through step-down transformers located on a substation pad adjacent to the emergency power building.

b. Mode 2. During periods when the commercial power system supply has been interrupted or has failed, the B buses are tied together through bus-tie circuit breakers and the entire category-B system load is supplied from two 1360-kilowatt diesel generators. Each generator is capable of automatically starting and synchronizing with the other generator, and, as previously mentioned, can begin to supply system power to the B buses within 25 seconds. A third 1360-kilowatt diesel generator is provided as a standby unit capable of being substituted for any one of the 1360-kilowatt generators.

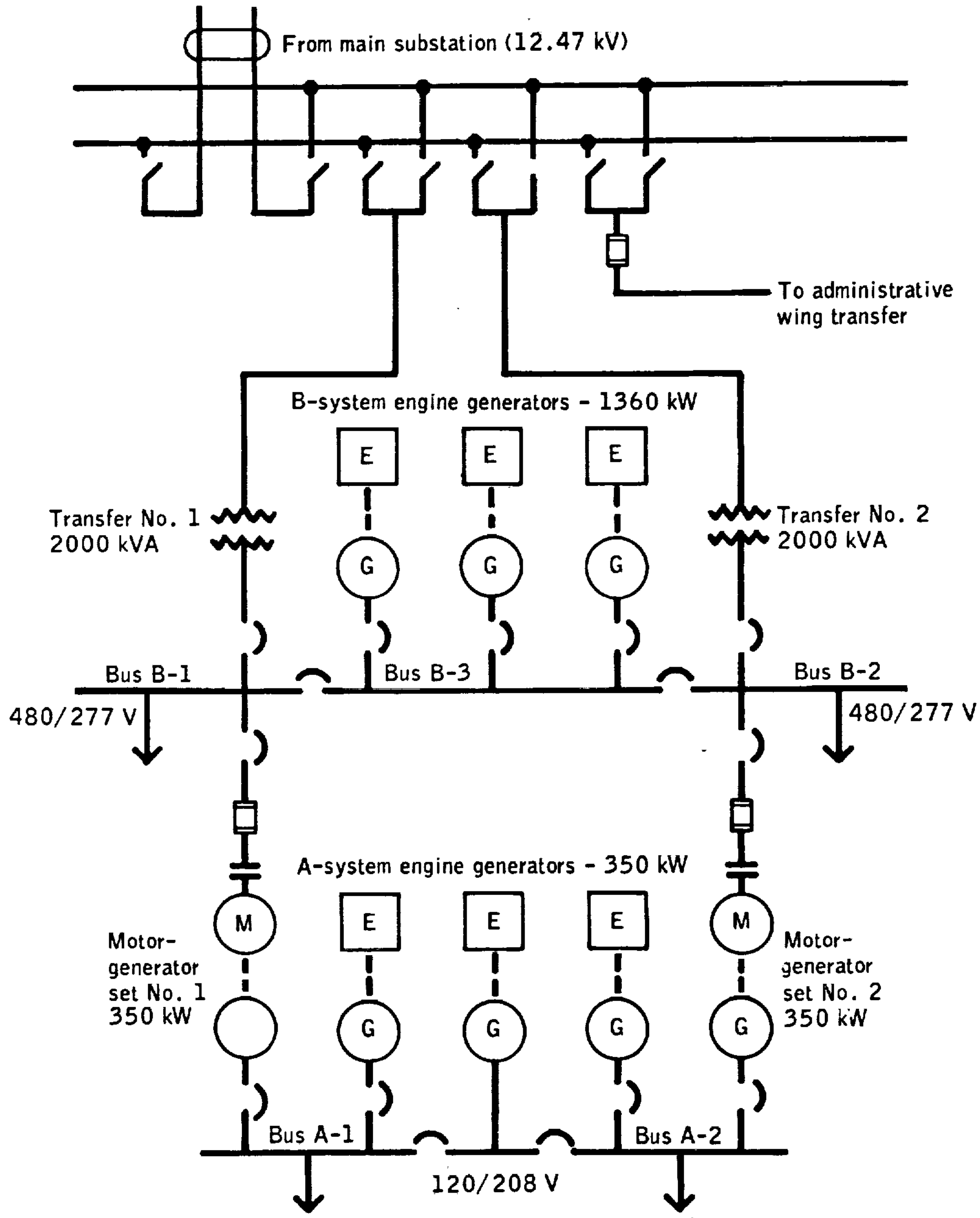

Figure 7-3.- Mission Control Center power system.

c. Mode 3. During periods when one of the substation pad transformers becomes inoperative because of failure or a maintenance requirement, category-B buses may be tied together and power supplied from the remaining transformer and one diesel generator operating in parallel. If one of the B buses is out of service, the loads on that bus may be manually transferred to the other B bus and the entire category-B power load supplied from the remaining operational transformer and one diesel generator operating in parallel.

7.1.2.2 Emergency lighting system.- A battery-operated emergency lighting system in the emergency power building is also provided for the safety of personnel in the event of a total power failure. Should a power failure occur, the emergency lighting system will automatically switch on and supply power to light fixtures strategically located in each area and in the corridors.

7.1.2.3 Emergency cooling system.- The emergency air conditioning equipment for the Mission Control Center consists of two 700-ton water chillers, a 70-horsepower heating boiler, circulating pumps, heat exchangers, automatic controls, and accessories. A cooling tower, erected adjacent to the emergency power building, provides condensing water to the chillers and jacket cooling water to the diesel engine power generators.

7.1.2.4 Secondary Mission Control Center.- If an unforeseeable failure had prevented the Control Center from continuing its support of a flight, an emergency facility at the Goddard Space Flight Center in Greenbelt, Maryland, could have been activated. The emergency center was a stripped-down version of the one in Houston, incorporating just enough equipment to let the controllers support the flight to its conclusion.

7.1.3 Mission Control Functions

7.1.3.1 Unmanned flights.- Unmanned test flights for design verification of critical flight equipment were relatively short, and only specific flight conditions had to be satisfied. Because execution of these flights was controlled mainly by the onboard guidance and navigation system, the mission control function was limited. A real-time interface, however, did exist with the Mission Control Center through the communications system, which provided up-link transmission, telemetry, and tracking capability. Thus, the flight control team had the capability to adjust flight events and control systems operation to ensure that system evaluation requirements were met. This control was used during the Apollo 6 mission when the S-IVB stage of the launch vehicle failed to restart, as planned, after achieving earth orbit. Through up-link commands, the flight control team commanded ignition of the service propulsion system to achieve an alternate trajectory that satisfied the mission objective.

7.1.3.2 Manned flights.- With the first manned flight (Apollo 7), mission complexity and duration increased. Likewise, the scope of mission control operations was expanded, and execution of additional and more complex duties demanded greater preparation and training of the flight control team. The value of this comprehensive preparation was demonstrated when development of contingency plans was necessitated by the Apollo 13 cryogenic oxygen tank failure. As the program progressed, each flight presented new objectives which required additional ground support capability. Objectives such as translunar injection and high-speed entry on Apollo 8, dual spacecraft operations and actual rendezvous on Apollo 9, lunar-orbit insertion and transearth injection on Apollo 10 and, finally, the actual lunar landing on Apollo 11 all required specialized support. Also required with each additional activity were new data computation capabilities, monitoring techniques, operating procedures for normal and contingency events, and new system operational criteria. With the successful completion of the Apollo 11 mission, all major lunar landing mission events had been accomplished; however, modifications were made to improve the execution techniques or to provide increased capability. For example, the accuracy of the Apollo 11 lunar landing was degraded by a position navigation error. To compensate for such degradation, a technique was developed to bias the Apollo 12 landing target point during the descent maneuver by a differential distance equivalent to the position error. When the mission control team observed the error from radar tracking, the required bias was provided to the crew by voice transmission.

7.1.3.3 Dual-vehicle operation.- Several new operational changes were required of the mission control team for dual-vehicle operation. Although dual-vehicle operation had been introduced on the Gemini program when two spacecraft first accomplished rendezvous, the Apollo operation was unique because the configuration of the two spacecraft was vastly different: each was designed for a special function. The vehicle differences required additional flight controller positions and modification of other positions in the Mission Control Center to accommodate data display and to allow separate systems evaluation and support for each spacecraft. The increased level of activity and the limitations in the ground data-processing equipment required a cooperative operating discipline within the Mission Control Center for the support of two active vehicles. Special procedures were adopted to maintain coordination between responsible stations for such operations as up-link transmissions to each spacecraft, high-speed data format selection, and non-real-time data retrieval. Throughout the critical phases of lunar module descent and ascent, the number of available television displays was decreased to reduce the workload on the real-time computer complex. The remaining number was allocated by console position to ensure distribution of mandatory monitoring data. Mission control was essentially split into two operational divisions to manage the high activity of dual-vehicle support. Each division had a separate flight director and spacecraft communicator supporting an individual spacecraft.

7.1.3.4 Lunar operation.- Another change in mission control for the Apollo program was the operation in the lunar environment. Because the spacecraft were operating at much greater distances from earth, emphasis was placed on maintaining the mission abort and return capability. Also, spacecraft systems management and evaluation became more critical. Before executing each major lunar mission event, the systems status was verified to satisfy required minimum capability. For example, the service propulsion system control integrity was in question before the Apollo 16 lunar orbit circularization maneuver (ref. 7-1). Consequently, a delay of the lunar landing was necessary to understand the malfunction fully and to ascertain the remaining capability, even though the landing conditions and subsequent surface activities would be affected.

Precision trajectory management was required to achieve the desired conditions for all lunar landings. The effects of spacecraft attitude thruster firings and the lunar gravitational variations introduced errors in predicted trajectories. The thruster effects were minimized by adjusting the planned spacecraft activities so that attitude maneuvers during the critical tracking intervals were avoided. The development of improved lunar gravitational potential models and navigation biasing techniques compensated for the gravitational effects. As each lunar mission was accomplished, more knowledge was gained to provide greater confidence in maintaining predicted lunar mission trajectories.

The initial lunar landing, Apollo 11, initiated still another expansion to mission control operations. In previous flights, the mission control objective had been to verify the equipment and techniques required to place man on the moon. For Apollo 11 and subsequent missions, the operational objective was expanded to include the scientific exploration of the lunar surface. To achieve the lunar surface extravehicular activity objectives, mission control served as the interface between the flight crew and the ground-based scientific investigators. In this role, mission control assumed responsibility for the real-time management of experiment deployment, traverse planning, sample collection, surface photography, and experiment data retrieval. Additional operational support was provided to monitor and evaluate the status and performance of surface equipment such as the extravehicular mobility unit and the lunar roving vehicle. This capability also provided general crew assistance in manipulating the lunar roving vehicle television camera and in recording such data as sample container numbers, film magazine codes, and crew observational comments. The management of and data retrieval from the Apollo lunar surface experiments package central station and associated experiments was unique for mission control because of this activity extended beyond the end of the mission. Between missions, a small segment of the mission control team continued active support of the Apollo lunar surface experiments from previous missions by collecting and distributing instrument observation data. In addition, up-link commands were sent to manage some of the instrument packages on the lunar surface. Beginning with the Apollo 15 mission, science support was again expanded to include operations of lunar orbital experiments. A special mission control function was established to manage the time-line execution and real-time evaluation of the crew-operated equipment. Assistance was provided to the crew in management of equipment configuration and on-off operating time.

7.1.4 Concluding Remarks

In summary, mission control maintained a flexibility of operation to support the program requirements. Although the basic intent remained constant, mission control capabilities and responsibilities expanded as required to support the variety of missions undertaken.

7.2 MISSION PLANNING

7.2.1 Trajectory Design

Initial mission planning and trajectory design early in the Apollo program transformed the broad lunar landing objectives into a standard mission profile and sequence of events against which the many spacecraft systems could be designed. Preliminary trajectory design, like the spacecraft hardware design, was developed from specified objectives within a framework of system functional characteristics and mission operational constraints. The process consisted of a series of iterative cycles in which the basic lunar mission trajectory was increasingly refined as the program progressed and as the flight hardware and operational planning became more definite.

As might be expected, incompatibilities arose between system capabilities and trajectory performance requirements which necessitated tradeoff studies so that compromises could be reached. In this respect, trajectory design activity was one of the primary means of achieving the overall systems integration on which the success of the program rested. As hardware designs became final, the trajectory design was more operationally oriented to conform to the expected capabilities of the spacecraft and ground support equipment.

The final mission design effort occurred largely in the year preceding each launch and involved the development of an operational trajectory and the associated detailed procedures, techniques, mission rules, and flight software. The operational documentation and data were used by the flight crew and ground control personnel for both nominal and contingency trajectory control and monitoring. The major problems encountered in the design of the various Apollo trajectories were not as technical as they were accommodative to the myriad user requirements, hardware and launch schedules, and the presentation of the proper data formats.

Another area in which problems were more bothersome and time consuming than they were technically difficult was that of designing the trajectory and providing associated data to overcome systems limitations, particularly those discovered immediately before launch, and accommodating last-minute changes. Trajectory engineers demonstrated a great deal of ingenuity, for example, when retargeting was required on several of the earlier missions and when a precision lunar landing was dictated on later missions. In the latter case, a new technique of updating the target vector in the onboard computer during the actual descent maneuver was very successful.

Early in the trajectory design effort, the need became apparent for some type of configuration control to ensure that all elements were using the same systems performance parameters. The proposal for a data management system to provide this necessary control was accepted and resulted in the production of the Spacecraft Operational Data Book. This document, with its continuous updates, and the data management elements in other organizations provided a common data base for all users.

In the early stages of the program, much more effort was devoted to planning for contingencies than to planning the nominal trajectory. This fact was also true for the two previous programs. As more confidence was gained in the systems performance and the basic trajectory design techniques, the concentration of effort on contingencies was somewhat reduced. The effort toward contingency planning was not wasted, however, since the ability of trajectory design engineers to respond rapidly to the Apollo 13 emergency was instrumental in returning the crew safely to earth.

7.2.2 Consumables

During the early Apollo mission planning, the need for a single authoritative consumables data source became apparent. A consumables analysis group was therefore chartered to define all major consumables data for the spacecraft. The trajectory design team was given this responsibility because of the close relationship of trajectory design to overall mission planning and systems functional performance, which included consumables usage.

7.2.3 Lunar Landing Site Selection

Lunar landing site selection was a complex process which involved technical tradeoffs among diverse interests. The scientific considerations were balanced against the system capabilities by a Site Selection Board and a recommendation was then made to agency management where the final selection was made. The trajectory design team provided inputs to the Site Selection Board on the suitability of several candidate sites for a given mission based upon operational considerations such as the translation of spacecraft performance capability into accessible areas on the lunar surface. The accessible areas were then correlated with the candidate landing sites to determine which sites were available. Reference 7-2 describes in detail the site selection process and the various trade-offs required.

Among the various organizations responding to the Site Selection Board on the acceptability of the various sites, trajectory design personnel probably appeared to be one of the least conservative. This lack of conservatism probably stemmed from the fact that numerous proven analytical tools and trajectory shaping techniques provided great confidence in the face of new mission requirement uncertainties. For example, without these tools and the wealth of mission planning experience, the scientifically valuable Taurus-Littrow site probably could not have been approved for the Apollo 17 mission. Based on the accuracy of both the lunar and the earth landings, the tools and techniques were demonstrated to be effective, and the recommendations made to the Site Selection Board regarding site accessiblity were timely and correct.

7.2.4 Documentation

Because of numerous inputs that influenced the trajectory design and because of the many users of operational trajectory data, adherence to a strict control procedure was necessary to provide the trajectory design within the time constraints of the program. To determine and define the proper input data and to provide the data on schedule, a mission documentation plan was established which integrated the various requirements of the organizations involved in the flight planning and the actual operations. This documentation plan defined the types of data required and specified the established user need dates so that publication of final trajectory data would be timely. The plan included the standard time, position and velocity trajectory information, as well as specific information such as tracking station data, attitude data, contingency data, dispersion analyses, consumables analyses, simulator input data, and onboard crew charts. References 7-3 through 7-12 are representative documents.

7.3 MANNED SPACE FLIGHT NETWORK

The initial support of the Apollo program by the Mission Control Center/Manned Space Flight Network (later called the Spaceflight Tracking and Data Network) began during the terminal phases of the Gemini program with the three short orbital flights of Apollo missions AS-201, AS-202, and AS-203. These unmanned flights were supported with the ground systems hardware and software used in the Gemini program. Systems such as the unified S-band communications equipment, which were to become well known in the Apollo program, were in their infancy and were used only on a ground systems test basis. Remote control from the Houston Mission Control Center was almost nonexistent, and the flight controllers were sent to many of the Manned Space Flight Network stations to support each flight.

7.3.1 Command Systems

The radio-frequency communications links between the ground and the Apollo spacecraft were similar to those of the Gemini program and used the 1-kilohertz/2-kilohertz phase-shift-keyed modulation techniques; however, the equipment for command generation differed. A computer-operated digital command system was used for Gemini flights and the first three Apollo flights in which command execution from the Mission Control Center was limited to special interfaces with three range stations through the use of a down-range up-link system. The commands to be transmitted to the spacecraft were transferred from the master digital command system in Houston through commercial carrier facilities to a station down-range up-link system which in turn provided the radio-frequency modulation to the spacecraft. At remote stations, such as Guaymas, Mexico, and Canarvon, Australia, flight control teams sent from Houston used station digital command systems to execute the commands.

The main-line Apollo program was to provide a different operation. The computer had matured, as had the use of digital communications. While radio-frequency modulation remained the same, modified 642B computers replaced the digital command system. Up-link commands were no longer transmitted directly from Houston. Each remote station computer was programmed with unique command words, and the execute decision from the Mission Control Center became requests for the preprogrammed command words. Additionally, the Mission Control Center was no longer limited to command execution through three stations because 13 prime range stations within the Manned Space Flight Network were linked to a 494 computer in Houston by a similar 494 computer at the Goddard Space Flight Center in Greenbelt, Maryland.

Modulation techniques remained the same; however, the radio-frequency link changed. Gemini and early Apollo missions were conducted in near-earth orbit, using an ultrahigh-frequency command system. To communicate effectively at greater than near-earth orbital distances, the Apollo program used a unified S-band system, and the up-link commands became an integral part of that system with commands modulating a 70-kilohertz subcarrier.

The practice of sending flight control teams to selected remote stations to execute commands and monitor telemetry was gradually discontinued. Confidence was established in the new system, and the Apollo 7 mission was supported with all the flight control personnel being located at the Manned Spacecraft Center and operating with a totally remote Manned Space Flight Network.

After the Apollo 7 mission, the command system configuration remained relatively unchanged. The only significant change was the adoption of the universal command system concept with the Mission Control Center complex during the later lunar missions. The universal command system increased system flexibility by providing the capability to execute real-time commands from any command panel by means of a thumbwheel selection. Until this time, real-time commands were individually selected by unique pushbutton indicators at specific consoles. Previously, if a specific console was not functioning, command capability for the discipline controlled from that console was lost. The universal command system allowed the flight controller to move to another console or to have someone else execute his command if his console malfunctioned.

7.3.2 Telemetry Systems

Telemetry, like the command system, was subjected to major changes. Only two sources of real-time digital telemetry existed at the Manned Spacecraft Center for the initial Apollo flights. The primary source came from the Kennedy Space Center and was known as the Gemini launch data system (later called the Apollo launch data system). The data were received on ultrahigh-frequency links, decommutated, sent to the data core system at Kennedy Space Center, and than transmitted to Houston at a 40.8-kilobit rate. The only other digital source was a 2.0-kilobit link from Bermuda. Real-time telemetry from the remaining Manned Space Flight Network stations was limited to critical events and was transmitted by frequency modulation on voice-quality long-line circuits. The primary method for providing telemetry data to the Manned Spacecraft Center was via teletype. Down-linked data received at the Manned Space Flight Network stations were decommutated and routed into 1218-type computers. Selected parameters were then extracted from the computer, on manual request, in teletype format and transmitted to the Manned Spacecraft Center. At the Mission Control Center, the teletype telemetry data were routed to the real-time computer complex for processing. After processing, summary messages were transmitted from Houston to the remote stations so that the onsite flight controllers would know the vehicle status before an upcoming pass over the range station.

With the availability of 642B computers, a different and more suitable system was developed. All the data were now decommutated, sent to the 642B computers, and formatted for digital output to the Mission Control Center in the same manner that commands were sent to the range stations. Two 2.4-kilobit lines from each range station to the Goddard Space Flight Center provided digital data in real time. Each line was dedicated to a selectable telemetry format. Each format contained specific data from a certain vehicle or vehicles, and the format was selectable by either the Mission Control Center or the remote station. The link between the Mission Control Center and the Goddard Space Flight Center consisted of two 40.8-kilobit lines and could provide data from multiple stations to the Mission Control Center, thereby providing either redundant data from one vehicle or data from multiple vehicles during periods when the vehicles were separated. These data were received and decommutated by 494-type computers at the Manned Spacecraft Center and transferred to either the real-time computer complex, the telemetry ground stations, or directly to console event lights. This configuration was used until the Apollo 15 mission, when the data rate of the lines was increased to 4.8 kilobits. At this time, the two telemetry formats were transmitted on one line only, and the second line was used for the transmission of digital biomedical data. Also at this point, frequency-modulated telemetry - the last of the Gemini systems - became a backup system to be used only in a contingency mode.

7.3.3 Tracking Systems

As was the case with the command and telemetry systems, tracking systems needed significant upgrading to provide adequate support for the Apollo program. Although, unlike other systems, the Gemini systems, for the most part, were retained. A significant change, however, was the use of the unified S-band system as a source of trajectory data. During the Gemini program, the primary source of trajectory data was C-band radar. To support Apollo, something else was needed because C-band radar, like ultrahigh-frequency and very-high-frequency telemetry, was serviceable only in earth orbit.

Ground systems processing of the resultant unified S-band trajectory data remained relatively unchanged. Teletype was still the method used to transmit the trajectory information and, although the computers involved were of a new generation, the software programs accomplished the same tasks.

7.3.4 Communications Systems

The communications systems, although often overlooked, probably underwent the most significant reconfiguration. The communications for the Gemini Manned Space Flight Network consisted primarily of voice and teletype circuitry used in a postpass or near-real-time fashion. The Apollo program required that digital data be routed to Houston in real time; voice communication with the spacecraft was no longer the responsibility of an on-station flight control team but required routing to a single point in the Mission Control Center; and television from the lunar surface was relayed to Houston from Madrid, Spain, Honeysuckle Creek, Australia, and Goldstone, California. Each change in a data system or the addition of a new system constituted a similar change in the communications system.

In the Gemini program, the communications network consisted of facilities leased from various commercial carrier companies. These facilities consisted of landline, submarine cable and microwave systems; the latter being avoided whenever possible because of uncertain reliability. The required circuitry, circuit reliability, and circuit quality for Apollo increased an order of magnitude over those of Gemini. Contributing to the overall improvement was the shift from the use of submarine cables to communications satellites for global communications.

7.4 RECOVERY OPERATIONS

The decision to use the water-landing mode for the Apollo program allowed the basic recovery concepts and techniques developed during the Mercury and Gemini programs to be retained. Although these concepts and techniques were generally applicable, the recovery requirements resulting from flying a new spacecraft on a translunar trajectory necessitated the development of some new recovery force deployment concepts and also the development of specialized equipment, tools, and procedures. The aspects of recovery unique to the Apollo program are discussed.

7.4.1 Department of Defense Support

In consonance with the intent of the National Aeronautics and Space Act of 1958, existing Department of Defense resources were integrated into the Apollo program where possible to avoid unnecessary duplication of effort, facilities, and equipment. Department of Defense support responsibilities were assigned in the areas of launch and recovery operations, communications, medicine, meteorology, and public affairs. Personnel support ranged from approximately 4000 for the AS-201 mission to more than 9000 for the Apollo 8 mission. The greater portion of this support was for recovery operations. For a manned mission, the major recovery responsibilities entailed locating the command module; providing on-the-scene assistance to the crew if necessary; retrieving the crew and command module; and providing for the return of the crew, lunar samples, data, and equipment.

7.4.2 Recovery Posture

7.4.2.1 Earth orbital missions.- A four-zone recovery concept was used for the Apollo 7 and Apollo 9 manned earth orbital missions. Two zones were located in the Atlantic and two in the Pacific Ocean areas. The West Atlantic zone contained the primary landing area, which was supported by an aircraft carrier. Secondary landing areas, supported by destroyers and ships of similar capability, were located within or near all four zones.

7.4.2.2 Lunar missions.- The recovery posture for the lunar missions differed from that of the earth orbital missions in several ways. The concepts and support provided are perhaps best discussed as they relate to specific types of landing areas defined for different mission phases.

a. Launch phase. As in the previous manned space flight programs, recovery forces were deployed in the so-called launch site area to rescue the crew if it had been necessary to initiate an abort while the spacecraft was on the launch pad or during the first seconds of flight. The recovery area was defined by the range of launch azimuths, which were dependent on the launch window. For a given wind profile and launch azimuth, the loci of possible landing points lay in a narrow corridor within this area. The location of the corridor was identified and transmitted to the recovery forces before launch.

The next area of coverage required for the launch phase was the so-called launch abort area in which the command module would land if an abort were initiated between about 90 seconds after lift-off and the time of insertion into an earth-parking orbit. Figure 7-4 illustrates a typical launch abort area based on a range of launch azimuths from 72° to 106°. As in the launch site area, the loci of possible landing points lay within a relatively narrow corridor once the actual launch azimuth was established.

The probability of a landing in sector B of the launch abort area (from 100 to 3400 miles down range) was relatively low because the capability to insert the spacecraft into earth orbit using the S-IVB stage and the service propulsion system was present after reaching a downrange distance of less than 1000 miles. Therefore, a lower level of recovery support for sector B was justified. As the program progressed, the support for both sectors was reduced and dependence was placed on ships of opportunity for retrieval of the command module. The maximum time specified for providing pararescue assistance to the flight crew, however, was maintained at 4 hours for all flights. HC-130 search-and-rescue aircraft with pararescue personnel aboard were airborne in the launch abort area before launch. These aircraft were positioned so that the 4-hour access time requirement could be met. When a launch delay occurred, the aircraft moved south and maintained advantageous positions with respect to the updated launch azimuth.

The most significant change in the launch abort recovery force deployment was that, beginning with Apollo 16, the requirement for recovery ship support of sector A was deleted. The launch site HH-53C helicopter was used instead because, with inflight refueling, the aircraft had become capable of retrieving the flight crew to a distance of 1000 miles. Also, the insertion tracking ship U.S.N.S. *Vanguard* could have provided assistance if a contingency landing had occurred in its vicinity.

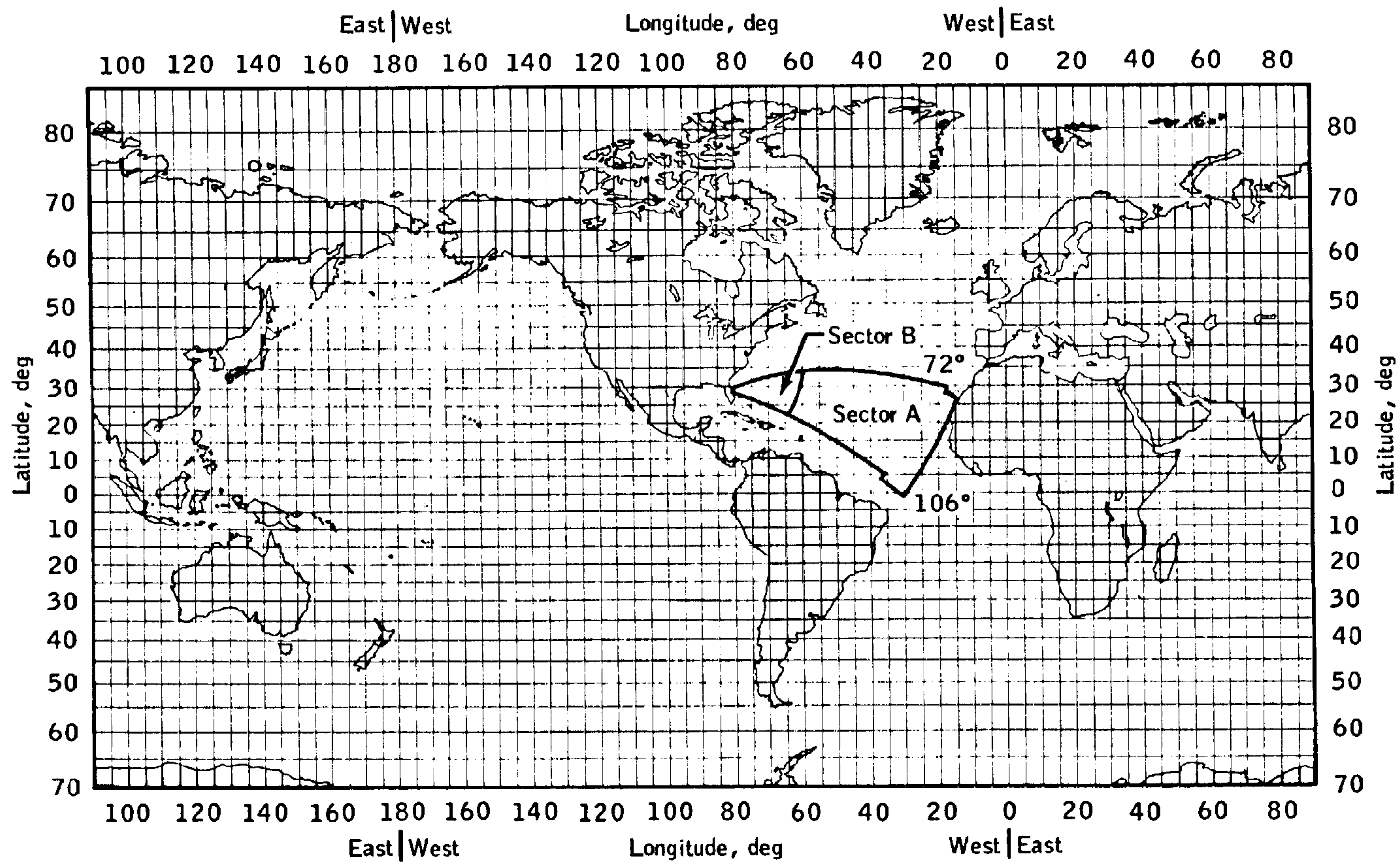

Figure 7-4.- Typical launch abort area.

b. Earth-parking-orbit phase. The second phase of lunar mission recovery support was implemented at insertion of the spacecraft/S-IVB stage into earth orbit. Two recovery zones were defined. One was located in the West Atlantic, and a larger zone was located in the mid-Pacific (fig. 7-5). Secondary landing areas, supported by ships and/or aircraft, were designated within or near these zones so that assistance could be provided to the crew within 6 hours if a landing became necessary before translunar injection.

A lower level of recovery support was provided for all the area (exclusive of the secondary landing areas) which was within the 40° latitude lines. This area was called the orbital contingency landing area. The recovery support consisted of specially equipped HC-130 aircraft (where possible, the same aircraft that supported the launch abort and secondary landing areas). These aircraft were deployed to staging bases from which they could have provided assistance to the crew within specified times, generally not to exceed 48 hours. Although some portions of the area were beyond the 48-hour capability of the aircraft, a degree of risk was accepted based on the low probability of a contingency landing in these locations weighed against the cost of maintaining higher support levels.

To provide for the possibility of an earth orbital alternate mission if the translunar injection maneuver could not have been performed, additional target points were selected to provide a landing opportunity on each revolution. Whenever possible, these points were chosen within the West Atlantic and mid-Pacific zones. On determination that an earth orbital alternate mission would be flown, the sizes of the zones would have been reduced and the recovery forces redeployed to provide optimum support. If a secondary recovery ship (destroyer or similar sized ship) had initially been supporting the mid-Pacific zone, the primary recovery ship (aircraft carrier) would have relieved the secondary ship.

c. Translunar injection to end of mission. After performance of a successful translunar injection maneuver, designated ships were deployed to support so-called deep-space secondary landing areas located on the north-south trending lines in the Pacific and Atlantic Oceans shown in figure 7-2. These lines were known as the mid-Pacific line and the Atlantic Ocean line. In addition, HC-130 aircraft were available to support these landing areas as well as the entire area within the 40° latitude lines where a landing could occur, shown by the shaded area in figure 7-2. As a mission progressed, the ships maintained positions that would allow them to retrieve the crew within specified times (ranging from 16 to 32 hours) in case of a deep-space abort. The spacecraft, preferably, was to be targeted for a landing area on the mid-Pacific line since the primary recovery ship was there. If this had not been possible, a landing would have been made where a secondary recovery ship was available. A ship was positioned on the Atlantic Ocean line for five of the nine lunar missions. The requirement was not levied for the later missions. If an Atlantic Ocean landing had been necessary for these missions, recovery of the command module would have been effected by a ship of opportunity.

When the Apollo 13 mission was aborted, the spacecraft was initially placed on a free-return circumlunar trajectory that would have resulted in a landing in the Indian Ocean. To shorten the return time and to provide primary recovery ship support, a transearth injection maneuver was performed approximately 2 hours after passing lunar pericynthion. This maneuver and two midcourse corrections placed the spacecraft on a trajectory that permitted a landing on the mid-Pacific line. Because of the emergency, additional support was provided by the Department of Defense and offers of assistance were made by many nations. Including voluntary support, 21 ships and 17 aircraft were available for an Indian Ocean landing, and 51 ships and 21 aircraft were available for an Atlantic Ocean landing. In the Pacific Ocean, 13 ships and 17 aircraft were known to be available in addition to the designated forces.

d. Normal end-of-mission landing. Before the command module entered the earth atmosphere, the primary recovery ship was positioned a few miles from the end-of-mission target point and aircraft were typically positioned as shown in figure 7-6. Shipborne aircraft were positioned in the immediate area, and land-based HC-130 aircraft were positioned up range and down range for tracking and for providing pararescue capability in case of an undershoot or overshoot.

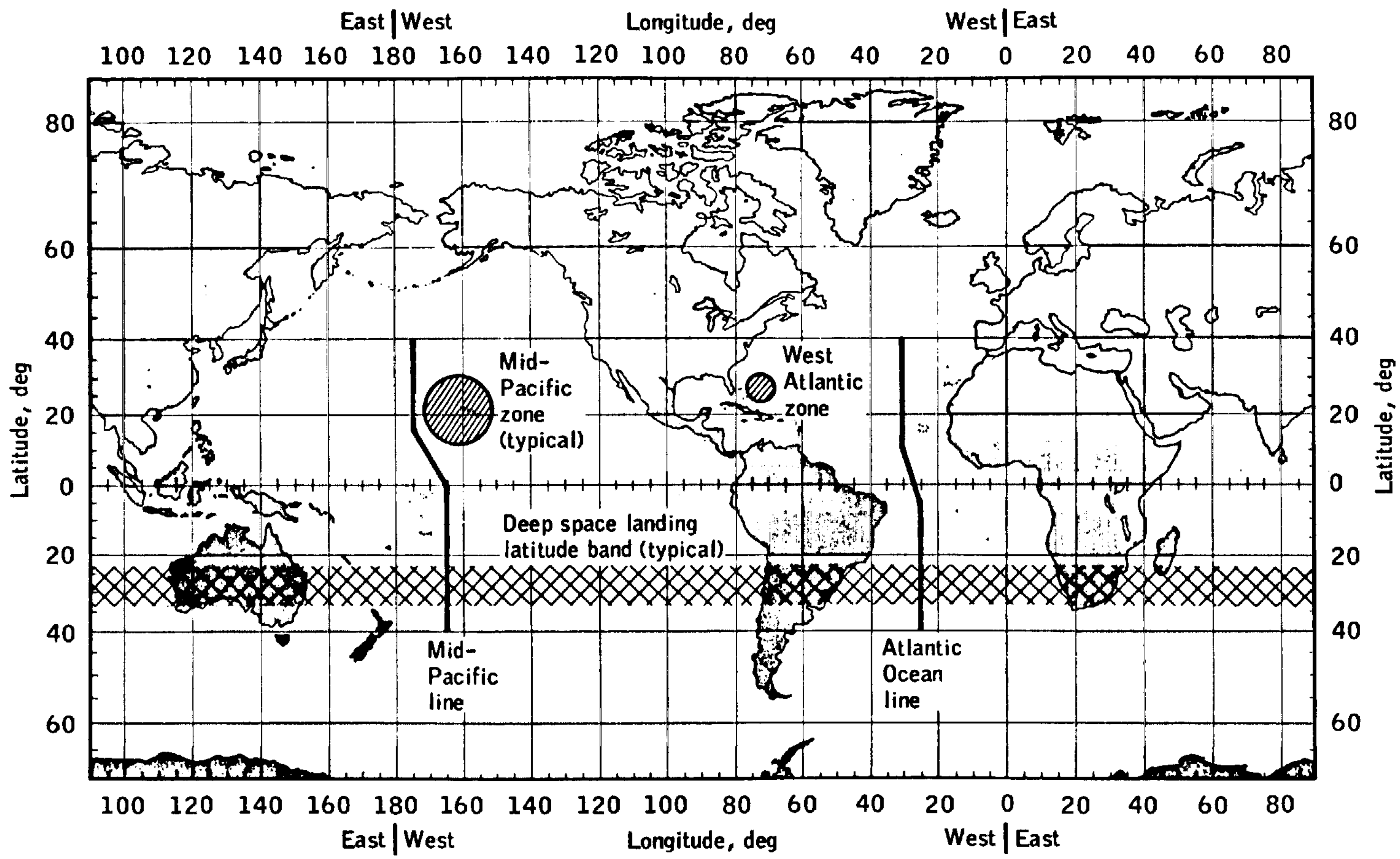

Figure 7-5.- Earth orbital recovery zones, deep space recovery lines and landing latitude band.

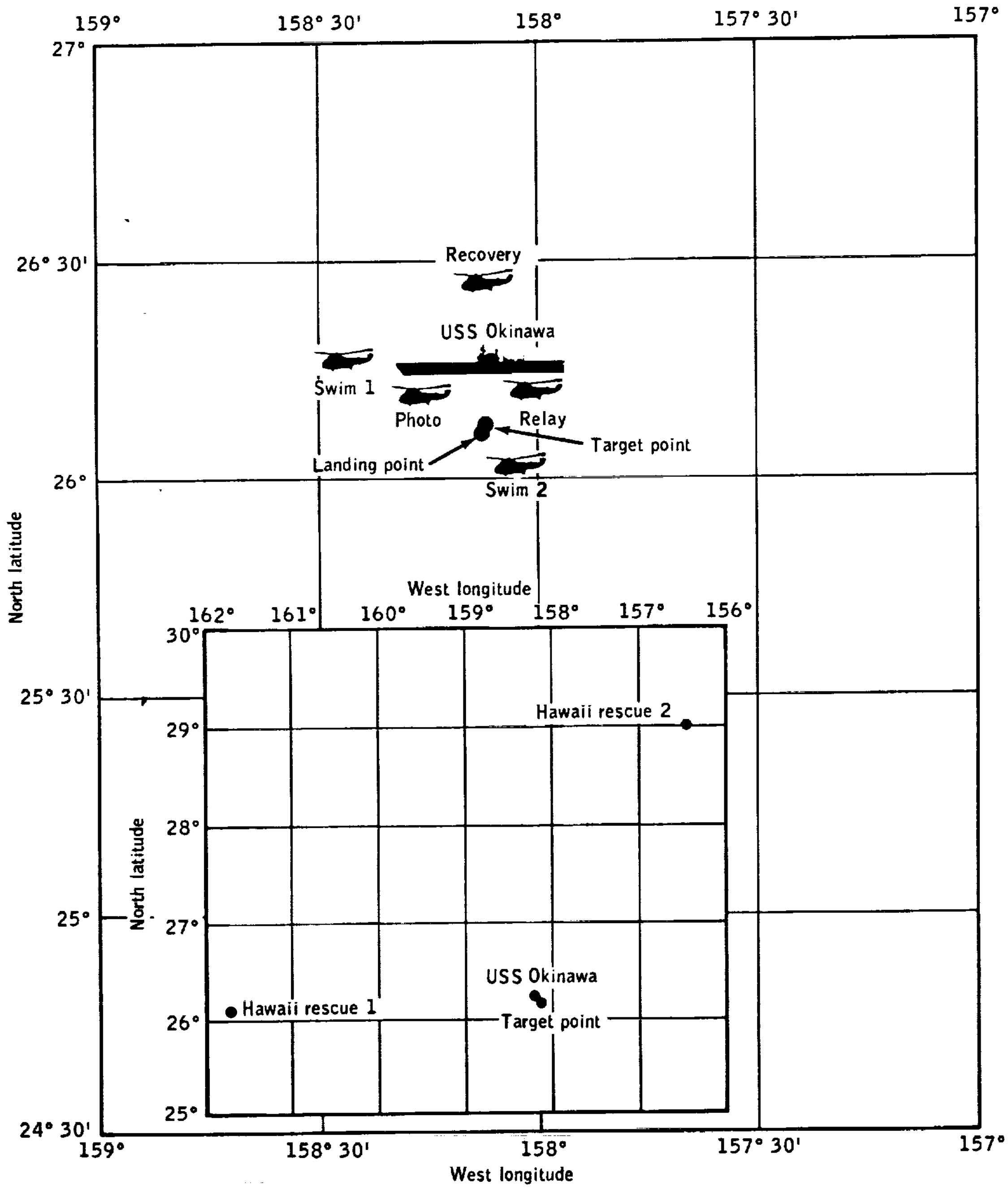

Figure 7-6.- Typical end-of-mission recovery support.

Elaborate precautions were taken for the first three lunar landing missions to prevent contamination from possible alien micro-organisms during retrieval and transportation of the crews and their spacecraft to the Lunar Receiving Laboratory at the Manned Spacecraft Center. At that time, the presence of lunar micro-organisms was thought possible, and the precautions taken were based on recommendations from an interagency committee on back contamination and the desire of NASA to be cautious. Because no micro-organism could be identified after three lunar sites had been explored, the precautions were eliminated for the final three missions.

Table 7-I gives the overall ship and aircraft support provided for the Apollo program. Additional landing and recovery data are given in appendix A.

7.4.3 Equipment and Procedures

Primary recovery ships and attendant swimmer/helicopter teams were used for recovery of all crews. In general, the normal crew retrieval procedures consisted of deploying swimmers, a flotation collar, and a sea anchor from helicopters; attaching the sea anchor and collar to the command module; deploying rafts from a helicopter; attaching a raft to the collar; opening the command module hatch; and assisting each crewmember, in turn, into a raft from which they were helped into a rescue net suspended from the pickup helicopter (fig. 7-7). These procedures were practiced by the Apollo crews before their missions and by the helicopter and swimmer teams both before the missions and while en route to recovery stations.

For the first three lunar landing missions, special equipment and procedures were used to isolate the Apollo crewmen and the recovery personnel required to enter the command module, to isolate the command module interior and its contents, and to decontaminate any areas that might have been exposed to contaminants. During the swimmer/helicopter operations, the crewmen donned biological isolation garments before egress and wore the garments until they were inside a mobile quarantine facility on the hangar deck of the recovery ship. The command module, when hoisted aboard, was positioned near the quarantine facility and connected to the facility by a tunnel which provided access to the cabin for removal of lunar samples and other items (fig. 7-8).

Airborne electronic location equipment consisted of NASA-furnished search-and-rescue-and-homing systems and AN/ARD-17 direction finder sets. The search-and-rescue-and-homing equipment was installed on primary recovery ship helicopters and on the helicopters used in the launch site recovery area and was compatible with the command module recovery beacon and survival beacon frequency of 243 megahertz. The AN/ARD-17 sets, developed especially for the Apollo program, were installed in HC-130 aircraft. Two aircraft were generally located approximately 200 miles up range and down range of the predicted landing point and offset from the command module groundtrack (fig. 7-6). The S-band tracking was used from the end of the communications blackout until approximately 1 minute before the predicted main parachute deployment. (The VHF recovery beacon was activated at that time.) The S-band tracking mode was used to help determine whether the landing would occur up range or down range of the particular aircraft. The set was then switched to the VHF mode to attempt recognition of the recovery beacon signal as soon as the beacon was turned on. Immediate recognition of the recovery beacon signal was desirable because the line-of-sight range was approximately 300 miles when the command module was at an altitude of 10 000 feet compared with a 195-mile range when the command module was on the water.

Small waterproof radios were issued to Air Force pararescue personnel and Navy swimmers to permit communications with aircraft, the recovery ships, and the Apollo crews during recovery operations. The radios had three operating modes: voice or beacon when operating on a frequency of 282.8 megahertz and voice only when operating on a frequency of 296.8 megahertz.

The special equipment carried aboard the HC-130 aircraft also included an aircraft-deployed drift reduction system. The system consisted of two parachute-delivered drag packages connected by a buoyant line. The drag packages were dropped in the path of the command module so that the line could be snagged as the command module drifted across the line. A grappling hook could have been deployed through the command module side hatch pressure equalization valve port (after removal of the valve) by a crewman to snag the line or, if the command module went underneath the line, the inflated uprighting bags would have snagged it. Tests of the system showed that the parachutes, acting as sea anchors, effectively slowed the drift rate of the command module, increasing the probability of reaching the command module quickly.

TABLE 7-I.- APOLLO RECOVERY SUPPORT

Mission	Overall recovery forces			
	Navy ships		Aircraft	
	Atlantic Ocean	Pacific Ocean	Navy	Air Force
AS-201	8	-	16	16
AS-202	4	3	43	4
Apollo 4	5	2	37	5
Apollo 5	1	-	-	-
Apollo 6	5	2	25	10
Apollo 7	4	5	8	23
Apollo 8	6	6	21	22
Apollo 9	3	3	7	22
Apollo 10	4	4	10	20
Apollo 11	3	2	13	18
Apollo 12	3	2	9	17
Apollo 13	2	2	8	14
Apollo 14	3	2	5	14
Apollo 15	2	2	5	12
Apollo 16	[a]1	3	6	11
Apollo 17	[a]1	2	5	10

[a]Small ships were used for sonic boom measurements in addition to the ship indicated.

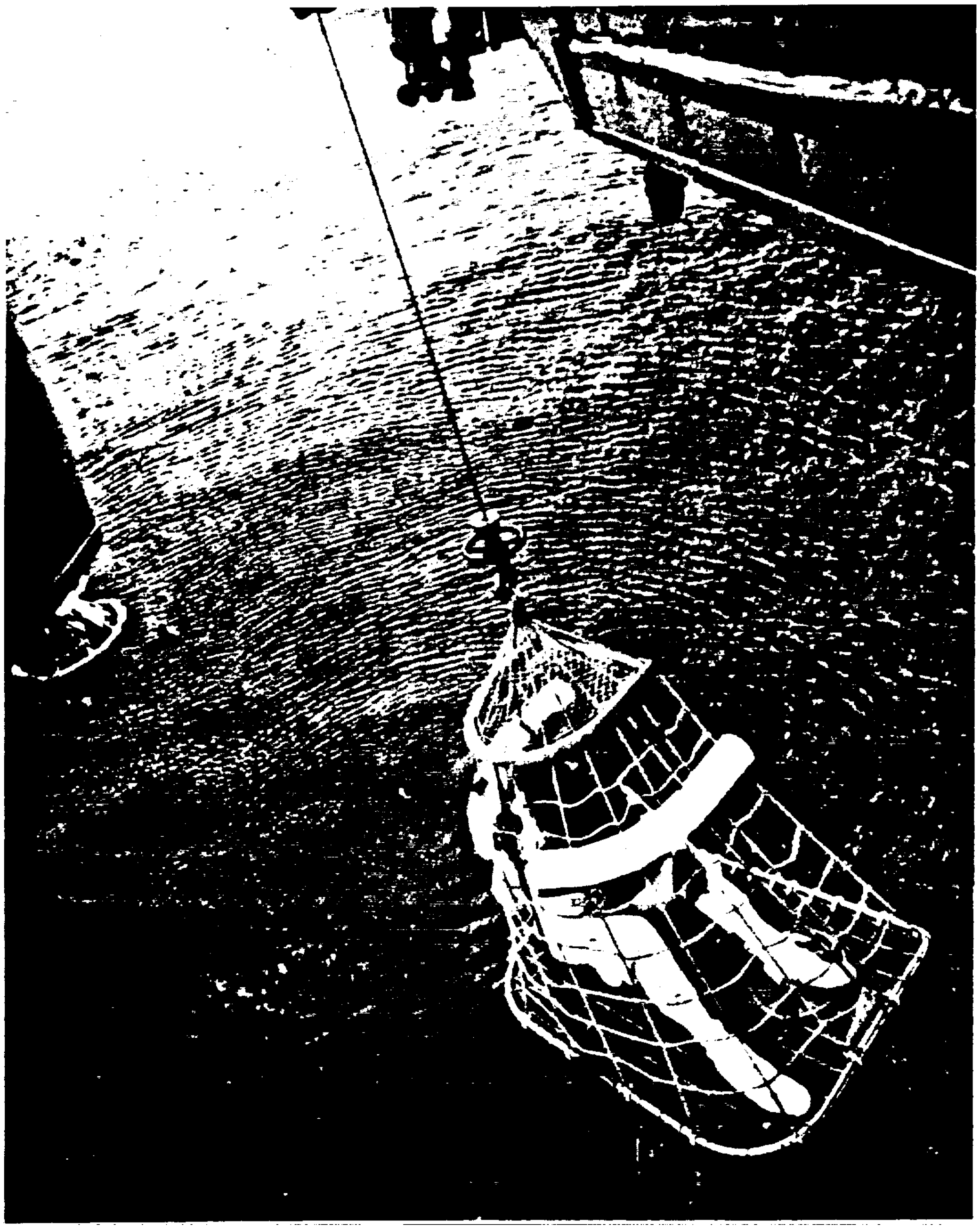

Figure 7-7.- Helicopter pickup of Apollo crewman.

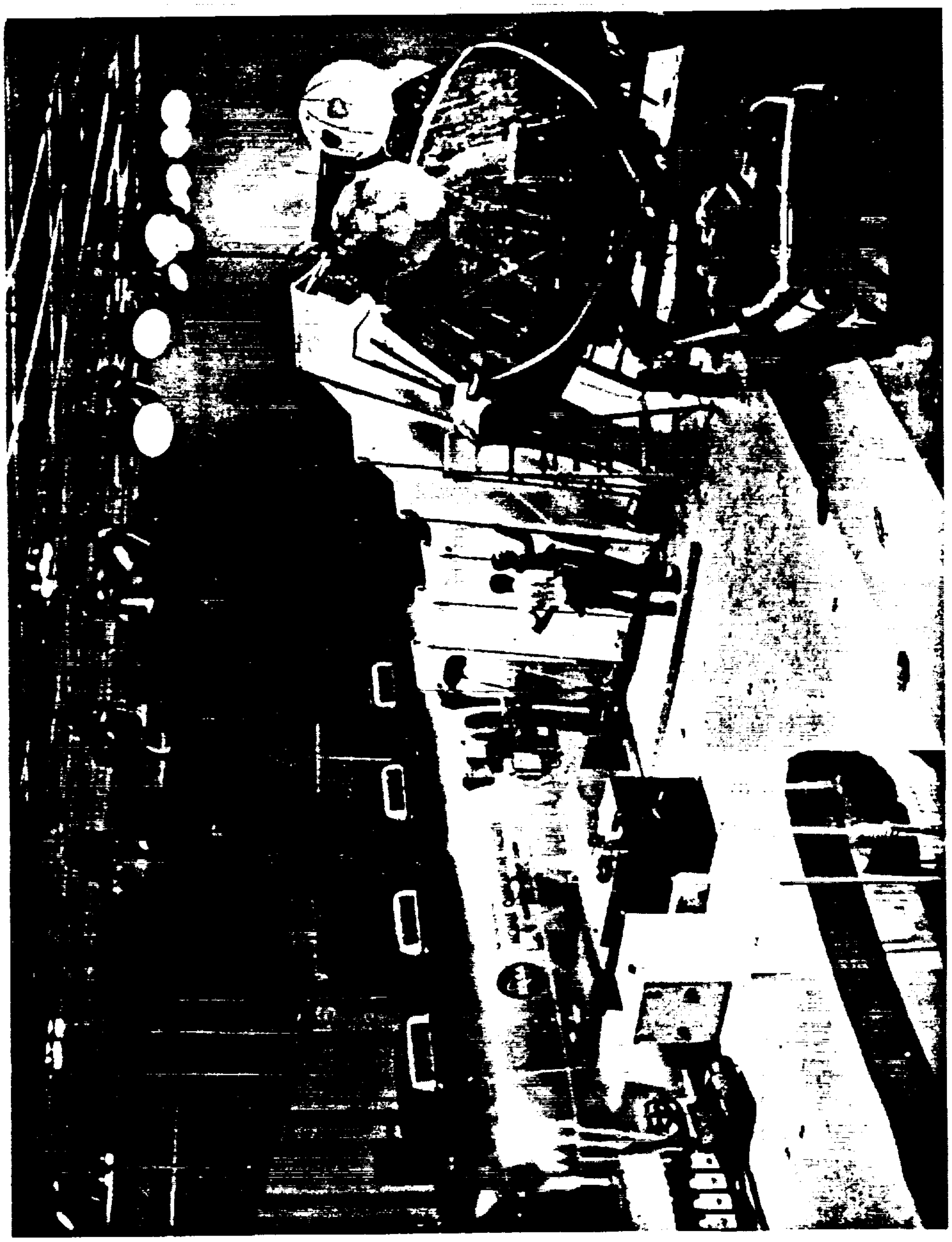

Figure 7-8.- Installation of the tunnel between command module and quarantine facility.

Much special equipment was carried aboard secondary recovery ships to facilitate command module retrieval and handling. The major item on destroyers was a NASA-developed davit crane that incorporated a holdoff ring to stabilize the command module during pickup. A boilerplate command module was furnished to all secondary recovery ships so that retrieval training could be conducted while the ships were en route to assigned areas. In addition, a kit containing auxiliary retrieval equipment was provided. Included in the kit were such items as line threaders, threaders, poles, hooks, fending pads, and a cradle to support the boilerplate command module during training or the actual command module, if recovered. No special facilities were furnished for the biological isolation of lunar landing mission crews; however, if a secondary recovery ship had performed a recovery, the Apollo crewmen would have been quarantined in whatever facilities were available.

The vehicles, equipment, and procedures used in the launch site recovery area were similar to those used for Gemini flights; however, several procedural changes were made and some new equipment was introduced. Starting with Apollo 7, the HH-53C heavy-lift helicopter was added to the complement of launch site recovery vehicles for uprighting the command module and for delivering pararescue personnel, firefighters, and equipment. For surf operations, the same type of amphibious vehicle used during Gemini was initially adapted for command module retrieval, but the use of this vehicle was discontinued after Apollo 11 when surf retrieval procedures using the HH-53C helicopter were developed. Examples of equipment developed or adapted for crew rescue from the command module include a "jammed hatch kit," containing special tools for gaining access to the command module crew compartment, and a helicopter-deployable fire suppression kit for extinguishing hypergolic fires. In addition, improved protective clothing was developed for firefighting personnel.

7.4.4 Command Module Postretrieval and Deactivation Procedures

Shipboard recovery activity after command module retrieval included photographing the command module; documenting observations and inspections; verifying electrical shutdown of the vehicle; and removing and expediting the return of lunar samples, data, and specified equipment.

On arrival at a designated deactivation site, the command module was inspected and its condition evaluated by a landing safing team. The pyrotechnic devices were safed, and the reaction control system propellants were removed according to prescribed procedures. Deactivation operations were carried out without incident except for the one performed on the Apollo 16 command module (sec. 4.4.7.2). While the oxidizer was being removed, the scrubber tank of the decontamination unit exploded, destroying the ground support equipment unit and damaging the building where the operation was being performed. The personnel in the area received only minor injuries, and the command module was not damaged. Tests showed that the explosion was caused by excessive gases produced because the quantity of neutralizer was insufficient for the quantity of oxidizer being removed. Corrective actions were implemented for the Apollo 17 command module and all subsequent vehicles, the primary action being to eliminate the requirement to neutralize residual propellants at the deactivation site.

7.4.5 Concluding Remarks

The effectiveness of the overall recovery support was maintained even with a trend toward the use of fewer ships and aircraft as the program progressed. The force reductions were based on several factors: a continually increasing confidence in the reliability of the spacecraft and launch vehicles, the availability of a tracking ship (the U.S.N.S. *Vanguard*) that could serve as a recovery ship during the launch abort phase, the deletion of the requirement for quarantine, and the availability of long-range heavy-lift helicopters late in the program.

7.5 EFFECTS OF WEATHER ON MISSION OPERATIONS

The weather had no significant effect on the major operations of the Apollo program. Some weather considerations are noteworthy, however, and are discussed briefly. The discussion is divided into three parts: operations during vehicle testing at the launch complex, the launch phase, and recovery operations.

7.5.1 Prelaunch Operations

Spanning a period of 7 years, approximately 106 instances in which weather had an impact on prelaunch operations were recorded. As the program progressed, work curtailments and interruptions decreased because of improved weather proofing, improved adverse weather warning systems, facility modifications, and less stringent ground rules governing work activity during adverse weather. Weather-related work interruptions during prelaunch operations caused no launch delays.

Several ground support units were damaged by the electromagnetic effects of lightning strikes during the prelaunch checkout of Apollo 15. Five incidents of lightning strikes on Launch Complex 39 were recorded during the prelaunch period. The first strike, one of 98 000 amperes, caused damage to eight units of ground support equipment. The second strike, one of 31 200 amperes, occurred the following day but damaged only one ground support unit. Ten days later, a strike of 22 000 amperes damaged two units of ground support equipment. The damage from the three strikes was attributed to improper grounding of cable shields and signal returns associated with the affected equipment. Modifications to the support equipment and facility grounding systems corrected these inadequacies and prevented equipment damage during two subsequent strikes of 23 000 and 6500 amperes.

7.5.2 Launch Phase

Only two Apollo missions experienced launch delays because of weather conditions. Mission AS-201 was delayed three times because of local cloudiness that was unsatisfactory for the required camera coverage. The Apollo 14 flight was delayed 40 minutes because of weather conditions that exceeded mission rule guidelines established after lightning struck the Apollo 12 space vehicle during launch (ref. 7-13).

Apollo 12 was the only mission affected by weather conditions during a launch. Before launch, launch officials were concerned about the approach of a cold front with its associated cloudiness and precipitation; however, these weather conditions did not exceed the then existing mission rule guidelines. At 36.5 seconds and again at 52 seconds after lift-off lightning caused major electrical disturbances. Many temporary effects were noted in both the launch vehicle and the spacecraft, and some permanent effects involving the loss of nine nonessential instrumentation sensors were noted in the spacecraft. After a thorough systems checkout in earth orbit, however, the spacecraft was found to be operating satisfactorily and the mission was continued.

Investigation of the Apollo 12 lightning incident showed that lightning can be triggered by a space vehicle and its exhaust plume in an electrical field that would not otherwise have produced natural lightning. Weather conditions such as the clouds associated with the cold front through which the Apollo 12 vehicle was launched can be expected to contain electrical fields and sufficient charge to trigger lightning. The possibility that the Apollo vehicle might trigger lightning had not been considered previously. Consequently, the launch rule guidelines were revised to restrict launch operations in weather conditions with potentially hazardous electric fields and charge centers. Additional instrumentation on the ground and in aircraft was used to monitor the launch mission rule parameters after the Apollo 12 incident.

7.5.3 Recovery Operations

The weather interrupted training operations of recovery teams in many instances but did not seriously affect the Apollo recovery operations. The weather affected recovery operations on only three occasions. Although the Apollo 7 command module landed in the Atlantic Ocean, the alternate landing area in the Western Pacific was moved to the Central Pacific because of high winds and seas caused by typhoon Gloria. The Apollo 9 deorbit maneuver was originally planned to occur on the 151st earth revolution with the landing to be made in the Western Pacific recovery zone. Because marginal wind and sea conditions were predicted for this area, the mission was extended an additional revolution and the landing area was moved 500 miles south. For Apollo 11, the nominal end-of-mission landing area in the Central Pacific was located near the northern boundary of the intertropical convergence zone — a region of significant shower and thunderstorm activity. Weather satellite information and aircraft reconnaissance reports indicated that a northward extension of the zone would affect the planned landing area. Consequently, the area was moved 200 miles northeastward where acceptable weather was assured.

7.6 APOLLO FLIGHT DATA

The three basic purposes for which flight data were used during the Apollo program were (1) operational monitoring and control of the spacecraft during various mission phases, (2) evaluation of spacecraft performance to resolve anomalous operation and to determine design changes required for future flights, and (3) collection of data from various mission experiments. Data from the Apollo spacecraft, lunar subsatellites, and lunar experiments were transmitted to the *Manned Space Flight Network*. Remote site telemetry data were retransmitted to Houston and also recorded on magnetic tape for possible later use. Figure 7-9 shows the telemetry portion of the command, communications, and telemetry system and illustrates the final system configuration after several changes were made during the program to increase the capacities of the data systems.

7.6.1 Operational Data

The data for operational control and preliminary anomaly identification and resolution were transmitted from the Manned Space Flight Network sites through high-speed data channels. Because of limited bandwidth, the available high-speed data channels would not accommodate all spacecraft telemetry data. Two methods were used to decrease the amount of retransmitted data. First, the data were thinned by reducing the sample rate. In most cases, selected measurements were transmitted to the Manned Spacecraft Center at one-tenth the normal sample rate. The second method was to transmit only those data that were of most interest during a particular mission phase. Thus, planned sets of measurement/sample-rate formats were used. Each of these formats was used for a particular mission activity or function. For example, a format containing mostly command and service module data was transmitted during the translunar coast mission phase, and a format containing both lunar module and command and service module data was transmitted during lunar orbit operations.

Data channels were also available to transmit selected full-rate data. Biomedical and limited amounts of critical-systems data were transmitted in this manner.

Once these data were received in Houston, several display methods were available to the analysts. Real-time data were available on television displays, strip charts, or high-speed printers.

7.6.2 Engineering Analysis Data

The prime sources for engineering analysis data were the magnetic tapes recorded at the remote sites. Data from these tapes were processedselectively. First, data retransmitted to Houston for operational control purposes were evaluated and specific times, where additional data were required, were identified; data from these time periods were then retrieved from the remote site magnetic tapes. Details of the engineering analysis data techniques are available in reference 7-14.

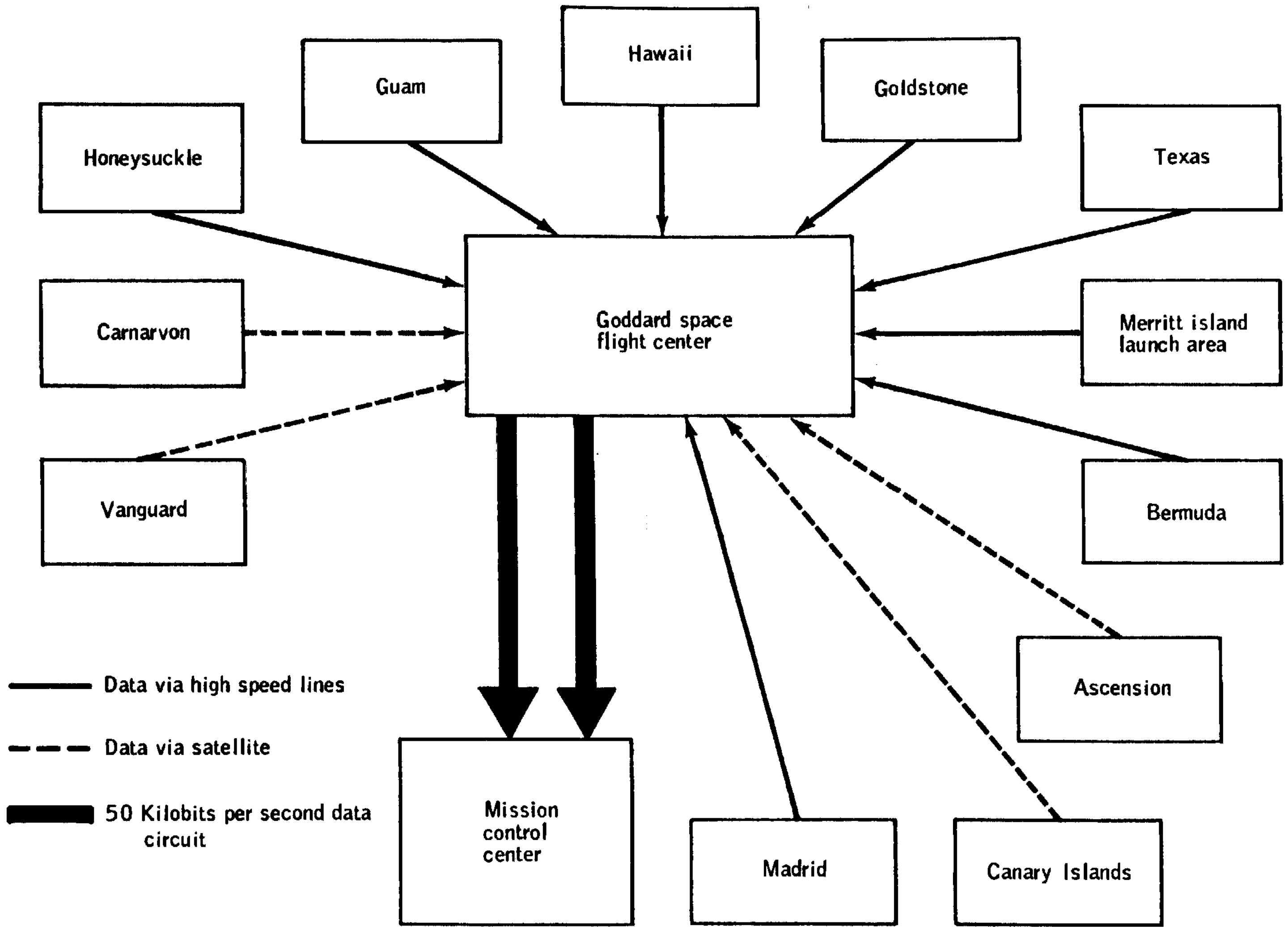

Figure 7-9.- Spacecraft tracking and data network data flow.

7.6.3 Experiment Data

Experiment data were reduced, primarily, from remote site magnetic tapes. Some of the data returned to Houston for operational control was also used for preliminary experiment analysis. This reduction was accomplished by using computer programs developed by principal investigators and processed on Manned Spacecraft Center computers.

The prime data for experiment evaluation were prepared from the remote site magnetic tapes and furnished to the principal investigators as merged computer-compatible tapes from which each principal investigator could perform additonal analyses on his own computers.

7.7 MISSION EVALUATION

An essential activity during the Apollo manned missions was the mission evaluation provided by an organized team of engineering specialists who resolved technical problems associated with the spacecraft systems. This team of engineers provided direct support to the Kennedy Space Center during prelaunch testing and to the flight control organization in the Mission Control Center during mission operations. Details concerning activities related to mission evaluation are given in references 7-15 through 7-18.

7.7.1 Prelaunch Support

The Apollo 13 Accident Review Board recommended that cognizant design personnel should be more closely associated with the prelaunch checkout activity. Based on the successful real-time mission evaluation team support, this concept was implemented during the prelaunch checkout. Starting with the Apollo 14 mission, prelaunch testing was monitored both at the Manned Spacecraft Center and at the contractor's mission support rooms. When the launch center requested support, the mission evaluation team was called on to evaluate the problem and provide a technical solution. As in the real-time mission support, government technical specialists and spacecraft contractor personnel were combined in a joint effort, under a NASA team leader, to provide the required answers.

The effort was typified by the retest requirements which were necessitated by the prelaunch lightning discharges that occurred first on the Apollo 15 vehicle and then on several subsequent spacecraft. The initial concept of retest, if a lightning discharge occurred in the vicinity of the spacecraft, was to retest all spacecraft systems. This concept proved to be impractical since all systems could not be checked because of safety considerations or time constraints. The retest philosophy that was developed was first to assess those vehicle measurements that would most likely be affected and then to verify visually whether any further retests were required, depending on the damage assessment. This technique permitted a rapid assessment of the initial damage and allowed the retest requirements to be limited to a reasonable minimal level.

7.7.2 Real-Time Evaluation

The analysis of spacecraft operations and performance was exercised at two levels of effort for separate reasons. During the conduct of a mission, the evaluation of spacecraft and/or crew status was required in real time to exercise proper mission control. When an abnormal condition occurred, alternate procedures, techniques, or activity plans were developed to ensure crew safety and to accomplish the mission objectives. After mission completion, a more detailed analysis was performed on equipment anomalies or failures. The postmission evaluation was intended to determine the solutions to experienced problems and the corrective actions to prevent recurrence on subsequent flights. Each type of evaluation was extremely important in the successful accomplishment of the Apollo program.

The real-time evaluation was conducted both by the mission control team in the Mission Control Center and by the mission evaluation team. The many systems specialists involved with mission preparation of the flight crew and/or equipment provided extensive support. The real-time evaluation of systems served two purposes. The first was to improve or optimize systems performance under normal operating conditions. Examples of work accomplished for this purpose were bias compensation for gyro/accelerometer values and attitude control configuration for the reaction control system propellant balance. The second purpose was, after a detection of a system anomaly or failure, to determine the remaining systems capability and required alternate operations. Perhaps the best example of effort of this type was the operational control exercised during the Apollo 13 mission after the oxygen tank failure described in section 4.4.5.

The real-time evaluation of a problem involved three actions: understanding the anomaly or failure, assessing its impact, and selecting an adequate solution to the problem. The symptoms of a problem were identified by means of spacecraft telemetry and by crew verbal descriptions. Often, special system configurations or operational modes were used to gain greater insight into the existing conditions and the extent of the problem. The data obtained were then used, in conjunction with reference documentation such as systems drawings and operations handbooks to isolate the source of the problem. This effort was conducted to identify the fault, but not necessarily to discover why the fault occurred.

Once a problem was detected and/or identified, its impact on the remaining mission activities had to be assessed. As with the problem itself, the resulting consequences were sometimes obvious but at other times were complicated and involved. Where possible, a component anomaly or failure would be duplicated in a simulator and the affected operations exercised. In this manner, the full implications of a problem could be determined under realistic conditions.

After the impact of a problem was determined, the next step was to develop alternate techniques or procedures to protect against or completely bypass the particular problem. This was the actual intent of real-time evaluation. The technical expertise of the mission control team and the mission evaluation team was used to find the best solution within the time frame allowed. Sometimes the solution was simple. For example, a problem wherein the Apollo 16 lunar module steerable antenna would not release was overcome by adjusting the spacecraft attitude to point the immovable antenna directly at the earth. Attitude was maintained until a 210-foot-diameter ground antenna acquired contact with the spacecraft on the landing revolution, as was originally planned. With the large ground antenna, high-bit-rate telemetry data could be received from other transmitting antennas on the lunar module. Other problems were more difficult to deal with, requiring new or additional crew checklist procedures. Perhaps the most difficult challenge of the Apollo program was encountered on the Apollo 13 mission as a result of the previously mentioned oxygen tank failure. New techniques had to be developed to operate the lunar module systems in a manner for which the systems had not been designed. The lunar module electrical and environmental resources had to be carefully managed for life support over a longer-than-normal timespan. Even as the mission neared completion, new procedures were necessary to separate the lunar module and then the crippled service module safely from the command module before entry. The techniques described, as well as those used to overcome problems on other missions, were thoroughly examined before they were actually applied. Where possible, all resolutions to problems were demonstrated on ground training or simulation facilities before actual use during the mission. The ground trainers and simulators proved to be valuable tools in the verification of new techniques. The verification process was used to ensure reasonable execution feasibility, time-line compatibility, crew safety, and a successful solution to the problem.

The real-time evaluation effort served to resolve the problems occurring during the mission that threatened crew safety or the accomplishment of mission objectives. The complexity and long duration of the Apollo missions provided ample opportunity to challenge the resources of the problem resolution teams. The successful achievements of the program were enhanced by the real-time evaluation capability.

7.7.3 Postflight Evaluation

Anomalies that involved flight safety or that would compromise the accomplishment of follow-on mission objectives required corrective action before the next flight. The frequency of the Apollo flights demanded that the anomalies be quickly identified and resolved so that prompt corrective action could be taken. Consequently, analysis of the pertinent data had to be compressed into a relatively short time frame. Also, within this time frame, the anomalies had to be analyzed to the extent that the mechanism for the cause was clearly understood.

The first problem was to identify the anomalies. Many anomalies were simple to recognize because a component failed to operate. The more difficult cases occured, however, when accrued data from the system operations were not sufficient to understand all the normal operating characteristics. A typical example of this condition occurred on the Apollo 7 mission when the battery recharging characteristics were below predicted levels throughout the flight. Preflight tests had been conducted at the component level; however, an integrated test of the entire system, as installed in the spacecraft, had not been conducted. Postflight testing of the flight hardware showed the same characteristics as those experienced in flight. A detailed analysis indicated that high line resistance between components of the system greatly limited the amount of electrical energy returned to the battery. The corrective action for this anomaly was to require integrated system testing to establish overall system characteristics of each spacecraft installation and thus to ensure adequate battery recharging capability. In this case, if the total system operating characteristics had been established in ground tests, no flight problem would have occurred.

At times, sufficient flight data were not available for an accurate analysis of the problem. This situation existed because of insufficient flight instrumentation or absence of recorded data. For these cases, the mission evaluation personnel relied on the information from previous missions, the experience gained from ground tests and checkouts, and the failure history of the system components.

After an anomaly was identified, the next steps were to determine the cause and implement the corrective action. Two basic techniques were used to determine the answer. The first was experimental, and testing of the actual or identical flight hardware was conducted under simulated static or dynamic conditions of temperature, pressure, load, or electrical environment. The second technique was analytical, and classical methods were generally used. One or both techniques were used, depending on the nature of the problem. In all cases, the most expedient approach in terms of time and cost was taken.

The depth and the extent of the analysis varied considerably, depending on the significance of the problem. For example, the failure of the Apollo 6 spacecraft/lunar module adapter (discussed in sec. 4.4.2) required the investigation of several possible failure modes and the implementation of a number of corrective measures. In other cases, because of the nature of the problem, no corrective action was taken. For example, an electroluminescent segment of the Apollo 11 entry monitor system velocity counter would not illuminate. A generic or design problem was highly unlikely because of the number of satisfactory activations before the recorded failure. A circuit analysis produced numerous mechanisms which could cause the failure; however, no previous failure had occurred in any of these areas. The spacecraft was designed with sufficient redundancy to accommodate this type of problem. Consequently, no corrective action was taken in such cases.

The causes of anomalies involved quality, design, and procedure considerations. The substandard quality items included broken wires, improper solder joints, incorrect tolerances and improper manufacturing procedures. The structural failure of the Apollo 6 adapter is an example of a quality problem. System anomalies caused by design deficiencies were generally traced to inadequate design criteria. Consequently, the deficiency passed development and qualification testing without being detected but appeared during flight under the actual operational environment. For example, a design deficiency became apparent during the Apollo 7 flight when the command module windows fogged between the inner surfaces of three windowpanes. A postflight examination showed that the fogging was produced by outgassing of room-temperature-cured material that had been used to seal the window. The design criteria had not required the sealing material to be heat cured or vacuum cured, a procedure that would have prevented outgassing when the material was exposed to the operating temperature and pressure environment of the spacecraft during flight. Correction of procedural problems in operating various systems and equipment was usually simple. An example of a procedural problem occurred when a camera struck an Apollo 12 crewman at landing. Had the flight plan or the crew checklist required stowage of this camera before landing, the incident would not have occurred.

An additional search for causes of anomalies was conducted when the command module was returned to the contractor's facility for a general inspection. Those systems or components that had been identified as having a problem or failure were either removed from the vehicle and tested or tests were performed with the affected equipment in position in the command module. In general, the postflight tests were limited to those components that were required to solve the inflight problem.

The concerted effort initiated to solve anomalies during the flight was continued after the mission until each problem was resolved and the required corrective action was established. This activity required close coordination and cooperation between the various government and contractor elements. Prompt and exact analysis for the understanding and timely solution of each problem was emphasized. To accomplish this task, a problem list was maintained during and after each flight. The list contained a discussion of each problem, the action being taken to resolve the problem, the name of the government engineer or contractor responsible for completing the action, and the anticipated closure date.

A discussion of the most significant problems was published after the flight in a 30-day failure and anomaly report. Discussed in this report were analyses of the anomalies and corrective actions that had been or would be taken. The Mission Report, which was published approximately 60 to 90 days after the mission, included a section which discussed the most significant flight anomalies and the corrective action for each anomaly that was closed out at the time of publication. Problems of lesser significance were discussed in the appropriate system or experiments section of the Mission Report. A separate report was published subsequently for each anomaly that had not been resolved in time for publication in the Mission Report.

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8.0 BIOMEDICAL SUMMARY

The initial medical consideration in the Apollo program was the preservation of the health and safety of the flight crews. However, many of the biomedical activities were based upon other considerations as well. The acquisition of new medical and biological data was made possible by astronauts traveling to another planetary body. Several biomedical experiments were conducted during the missions. Along with the opportunity to acquire new knowledge, however, was the fact that extraterrestrial exploration carried with it the possibility of introducing foreign material into the earth's biosphere that might be harmful to life. This possibility was minimized by the institution of a lunar quarantine program. The fear of biological back contamination proved to be unfounded after careful examination of the crews and lunar samples after each of the first three lunar landings. Therefore, the quarantine requirement was eliminated for the final missions.

Man's ability to tolerate the conditions of space flight for periods up to 2 weeks had been demonstrated in the Gemini program. Since all Apollo flights were planned to be of shorter duration, the effects of weightlessness on the body were not expected to be a serious threat to crew health or a detriment to the accomplishment of the Apollo program. This was indeed the case, although some cardiovascular deconditioning did occur.

A few new medical problems arose in the course of the program. Motion sickness occurred on several flights while the crewmembers were adapting to the zero-gravity environment and large departures from normal circadian periodicity on several flights resulted in crew fatigue. An initial concern was the degree of radiation to which the Apollo crewmen would be exposed. Fortunately, a major flare did not occur during a mission, and the radiation dose was below the threshold of detectable medical effects for all crewmen. Exposure of crewmembers to infectious diseases prior to flight was a problem for the first several flights but was adequately managed by the establishment of a preflight crew health stabilization program.

The crews of the eleven Apollo flights accumulated a total of approximately 7506 man-hours of space flight. Physiological measurements obtained during the flights remained within expected limits during all flights except the Apollo 15 mission. The life support systems of the command modules, lunar modules and extravehicular mobility units provided environments that allowed the program objectives to be achieved without compromising crew health or safety. Details of biomedical results are contained in references 8-1 through 8-11.

8.1 PREFLIGHT MEDICAL PROGRAM

8.1.1 Flight Crew Health Stabilization

Many conditions that are characteristic of the environment within a manned spacecraft are conducive to the development and transmission of disease. Since infectious disease represents a serious threat to the health of crewmembers and to the successful completion of missions, control and prevention are the most effective ways to deal with this potential problem. Control and prevention are most critical during the last few weeks before a manned mission.

Statistics recorded during the Apollo 7 through Apollo 11 missions show that 57.2 percent of the crewmembers were ill at some time during the preflight period. Based on observations of the first several flights and on the observation of crewmember activities during earlier manned Mercury and Gemini missions, the flight crew health stabilization program was developed and implemented for the Apollo 14 and subsequent missions. The elements of the program were designed to minimize exposure of crewmembers to infectious disease which might result in the subsequent development of symptoms during flight. Each program element is discussed.

8.1.1.1 Clinical medicine.- A clinical medicine program was provided for all crewmembers and their families. The program was continuous as long as the crewmembers were on flight status. Both routine and special physical examinations were provided. Rapid diagnosis of disease and effective treatment were ensured by the virology, bacteriology, immunology, serology, and biochemistry laboratories at the Manned Spacecraft Center.

8.1.1.2 Immunology.- All known immunizations were carefully reviewed by NASA medical personnel and by a special microbiology advisory committee. The immunizations listed in table 8-I were those used for crewmembers and their families. Other available immunizations were not included if:

a. Disease prevention was questionable.

b. A high percentage of traumatic side reactions occurred.

c. The probability of crew exposure to the disease agent was so remote that immunization was unwarranted.

Crewmembers and their families were immunized only after serological tests were performed to determine immunity levels.

8.1.1.3 Exposure prevention.- Prevention of crew exposure to disease was the most important aspect of the program. Regardless of the effectiveness of all the other phases of the program, if the exposure to infectious diseases had not been minimized or eliminated, the program as a whole would not have been successful.

Contaminated inanimate objects probably represent the least hazardous source of infectious diseases. However, certain spacecraft areas such as the communications equipment were controlled by providing individual headsets and microphones for each crewman.

To prevent air-borne transmission of an infectious disease, a closely controlled environment was provided in which crewmembers could reside during the prelaunch period. All areas which the crewmembers inhabited had to be modified by the installation of ultrahigh-efficiency bacterial filters in all air-supply ducts. Thus, an environment was provided in which crewmembers could reside and work without being exposed to microbial agents from other sources. In addition to providing filtered air, the air-handling systems were balanced in a manner that provided higher atmospheric pressure in those areas inhabited by the crew. In this situation, all air leakage was outward rather than inward.

The food consumed by the crew was also a potential source of infectious micro-organisms. No set pattern of food procurement was established to reduce accidental sources of infection. The procurement of food for the living quarters was handled by cooks under the direct supervision of the medical team. Portions of each lot of food purchased were subjected to microbiological evaluation to ensure the safety of the food. Also, all food preparation areas were inspected daily for cleanliness and maintenance of sanitary conditions.

Drinking water was another potential source of infectious disease agents. Sources of drinking water were limited to drinking fountains in the crew quarters and various working areas. To insure that the municipal water-treatment procedures were satisfactory and that safe water was provided, daily water samples were taken and subjected to microbiological evaluation.

Personal contacts represented the greatest source of infectious disease; consequently, minimizing possible exposure to disease from this source was required. First, the areas visited by crewmembers were very restricted, and the number of persons in contact with the crew during premission activities was limited to approximately 150. Second, a medical surveillance program of the primary contacts was instituted. The purpose of the program was to ensure that the probability of disease transmission from the persons who did have contact with the flight crewmembers was low.

The success of the flight crew health stabilization program, implemented in support of the Apollo 14, 15, 16, and 17 missions, was evidenced by the complete absence of illnesses during the preflight, inflight, or postflight periods.

TABLE 8-I.- APOLLO PROGRAM IMMUNIZATION REQUIREMENTS[a]

Disease	Required immunization for crewmen	Required immunization for members of crewmen's families
Diptheria	Yes	Yes
Pertussis	No	Yes
Tetanus	Yes	Yes
Typhoid	Yes	No
Influenza	Yes	No
Mumps	Yes[b]	Yes
Poliomyelitis	Yes	Yes
Rubella	Yes[b]	Yes
Rubeola	Yes[b]	Yes
Smallpox	Yes	Yes
Yellow Fever	Yes	No
Other	(c)	(c)

[a]Recommended by personnel of the United States Public Health Service and of the American Public Health association.

[b]Immunization if no serologic response was obtained.

[c]Only as indicated for travel to endemic areas.

8.1.2 Preflight Physical Examinations

Preflight physical examinations were performed to evaluate each flight crew's physical condition, and to detect and treat any minor physical problems which might compromise flight objectives, or the health and safety of the crew. For Apollo 7, the comprehensive preflight examination was performed 4 days prior to flight, while a preliminary examination was accomplished 14 days prior to launch and a cursory physical examination was performed on the morning of launch. For Apollo missions 8, 9, and 10, four preflight medical evaluations were accomplished, beginning approximately 30 days prior to the scheduled launch date. A 3-day postponement of the Apollo 9 launch resulted when all the crewmen developed common colds. Starting with Apollo 11 and continuing through Apollo 17, daily examinations were conducted for the 5 days immediately preceding launch.

The Command Module Pilot on Apollo 13 was exposed to rubella 8 days before the flight and since laboratory studies failed to demonstrate an immunity to rubella, a decision was made on the day prior to launch to replace the primary Command Module Pilot with the backup Command Module Pilot. A complete physical examination was conducted on the backup Command Module Pilot and he was found fit for flight.

8.2 MEDICAL OBSERVATIONS

8.2.1 Cabin Environment and Toxicology

Prior to the Apollo program, United States spacecraft were launched with a 100-percent oxygen cabin atmosphere. Following the disastrous Apollo I fire, one of the safety measures introduced was the use of a mixed oxygen and nitrogen cabin atmosphere during the prelaunch and launch periods. The cabin atmosphere was changed to pure oxygen during the early phase of flight. The flight crew denitrogenated prior to launch and remained isolated in the 100-percent oxygen environment of the suit loop until helmets and gloves were doffed.

The Apollo 7 spacecraft was the first to be launched with the mixed-gas cabin atmosphere. The oxygen enrichment curve followed the predicted curve fairly well, but it did not increase as fast as predicted because the cabin leak rate was lower than expected. The maximum cabin oxygen concentration measured during the flight was 97 percent (255 mm Hg) at 236 hours. The altitude equivalency was never above sea level (i.e., oxygen partial pressure was always greater than that at sea level). The cabin oxygen enrichment technique was thus verified by the Apollo 7 flight and used on all successive flights through Apollo 17.

During the Apollo 10 mission, the H-film insulation near the command module hatch vent detached when the docking tunnel was pressurized, and fiberglass insulation underneath this film was blown into the tunnel (ref. 8-4). When the hatch was opened, the fiberglass material permeated the atmosphere of the command module. Also, when the lunar module was pressurized through the command module hatch vent, a large amount of fiberglass was blown into the lunar module. Pieces of the material ranged from 2 inches in diameter to dust-size particles. Wet paper tissues and utility towels were used to collect part of the loose fiberglass. Most of the remaining material was collected in the filters of the environmental control system. However, small particles of fiberglass were still present in the command module cabin atmosphere at recovery. Fiberglass insulation is a skin and mucous membrane irritant and caused the crew to be uncomfortable in flight. The effects on the Apollo 10 crew consisted of scratchy throats, coughing, nasal stuffiness, mild eye irritation, and some skin rash.

After the Apollo 13 abort decision, one major medical concern was the possibility of carbon dioxide buildup in the lunar module atmosphere. Although the allowable limit of carbon dioxide buildup was increased the carbon dioxide level was above the nominal 7.6 mm Hg for only a 4-hour period, and no adverse physiological effects or degradation in crew performance resulted from this elevated concentration. Modified use of the lithium hydroxide cartridges (ref. 8-7) maintained the carbon dioxide partial pressure well below 1 mm Hg for the remainder of the flight.

8.2.2 Radiation

Various instruments were used during the Apollo program to monitor and record the degree of crew exposure to radiation. Each crewman carried a personal radiation dosimeter to measure the total absorbed dose received. In addition, the crewmen wore passive dosimeters to measure total radiation received at specific body locations such as the chest, thigh and ankle. Other instruments were installed in the spacecraft which provided data to the ground and permitted monitoring of the radiation environments. A moving emulsion particle detector apparatus was worn for short periods by crewmen of the final two missions to provide data for investigation of visual sensations of light flashes experienced by several crewmen on previous flights.

8.2.2.1 Radiation dose.- No data were reported for the Apollo 7 and Apollo 8 missions. For the remaining missions, the total radiation dose absorbed by any crewman was well below the threshold of detectable medical effects (ref. 8-12).

During the Apollo 12 mission, approximately half of the total dose recorded on the personal radiation dosimeters was received during the phase just prior to entry. This disparity was expected because of a different trajectory which resulted in a longer time going through the Van Allen belts.

The radiation doses received by the Apollo 14 crewmen were the largest observed on any Apollo mission; however, they were well below the threshold of detectable medical effects. The magnitudes of the radiation doses were apparently the result of two factors: (1) the translunar injection trajectory lay closer to the plane of the geomagnetic equator than that of previous flights and, therefore, the spacecraft traveled through the heart of the trapped radiation belts; (2) the space radiation background was greater than that previously experienced.

Three minor solar flares occurred on the Apollo 16 mission. Although the nuclear particle detection system registered a slight increase in proton and alpha particle fluxes, no measureable radiation dose increment was received by the crew from these flares.

8.2.2.2 Visual light flash phenomenon.- Astronauts of Apollo 11 and subsequent lunar missions reported seeing flashes of light while relaxing in the darkened command module or while wearing light-tight eye shades. These events were generally described as colorless star-like flashes, narrow streaks of light, or diffuse light flashes. The flashes were observed during translunar coast, in lunar orbit, on the lunar surface, and during transearth coast. The frequency of occurrence of the light flashes typically averaged about one flash every 1 to 2 minutes.

Evaluation of reports obtained from Apollo crewmen has established the reality of the phenomenon. The hypothesis generally accepted to explain the origin of the light flashes involves exposure to high-energy cosmic ray particles. One or both of the following mechanisms are suggested: (1) relativistic cosmic ray particles passing through the eye emit Cerenkov radiation that produces the light flash sensations; (2) direct interactions of high-energy cosmic ray particles or their secondaries with the retinal cells or associated optic nerve tissues produce the light flash sensations. Results of laboratory experiments during which human subjects were exposed to X-ray and several types of particulate radiation have shown that such radiation does produce similar light flash sensations, and further suggests that most of the light flashes observed by the Apollo astronauts are due to direct interactions of ionizing radiation with cells of the visual nervous system.

8.2.3 Adaptation to Weightlessness

With only two exceptions, the crewmen for all eleven flights experienced a fullness-of-the-head feeling upon orbital insertion. The persistence of the feeling was variable, lasting from 4 hours to 3 days.

All three Apollo 8 crewmembers experienced nausea soon after leaving their couches. The Apollo 9 Command Module Pilot and Lunar Module Pilot, the Apollo 10 Lunar Module Pilot, the Apollo 13 Lunar Module Pilot, and the Apollo 15 Lunar Module Pilot also experienced nausea. In addition, the Apollo 9 Command Module Pilot and Lunar Module Pilot reported momentary episodes of spatial disorientation. All three members of the Apollo 17 crew had "stomach awareness" but did not experience any pronounced nausea. In some of these cases, the nausea appears to have been the result of rapid body movement before adaptation to weightlessness. Symptoms subsided or were absent when the crewmen performed all movements slowly during the period of adaptation. There was no recurrence of the problem after adaptation to the weightless state. Specific head movement exercises also helped to accelerate adaptation to weightlessness.

The crews of the Apollo 7, 12, 14, and 15 missions reported soreness of the back muscles. This condition was relieved by exercise and hyperextension of the back. Although a calibrated inflight exercise program was not planned for any of the flights, an exercise device was provided. The crewmen typically used the exerciser several times a day for periods of 15 to 30 minutes when in the command module.

Another condition resulting from the lack of gravitational pull was puffiness of the face. This symptom was specifically reported by the crews of the Apollo 11, 12, 13 and 15 missions; however, it probably occurred on all the flights.

8.2.4 Work/Rest Cycles

Based on previous flight experience, simultaneous crew rest periods were instituted, and were referenced to a crew's normal launch site sleep cycle. The Apollo 9 crew was the first to utilize the simultaneous rest periods. Departures from the crew's normal circadian periodicity caused problems during most of the flights. Since the problems impacting the scheduled sleep programs differed, unique occurrences for each flight are discussed individually.

a. Apollo 7: At least one crewman remained on watch while the others slept during the Apollo 7 mission. Simultaneous sleep was precluded because it was the first manned flight of a new spacecraft. Large departures from the crew's normal circadian periodicity caused problems during the mission. The crew slept poorly for about the first 3 days of the flight and experienced both restful and poor sleep after that period of time. The amount of sleep each crewman obtained was indeterminable.

b. Apollo 8: A very busy flight schedule for Apollo 8 precluded simultaneous sleep and resulted in large departures from normal circadian periodicity and consequent fatigue. Changes to the flight plan were required because of the crew fatigue, particularly during the last few orbits before the transearth injection maneuver.

c. Apollo 9: Apollo 9, the first mission in which all three crewmen slept simultaneously, was a definite improvement over the previous two missions in observed estimated quantity and quality of sleep. The lack of postflight fatigue was correspondingly evident during the physical examination on recovery day. However, the crew workload during the last 5 days of flight was significantly lighter than on previous missions, which undoubtedly contributed to the absence of fatigue.

The flight plan activities for the first half of the mission resulted in excessively long work periods for the crew, and the time allocated for eating and sleeping was inadequate. Crew performance, nonetheless, was outstanding. Departures from the crew's normal circadian periodicity also contributed to some loss of sleep during this time. The crew experienced a shift in their sleep periods which varied from 3 to 6 hours from their prelaunch sleep periods.

d. Apollo 10: The three Apollo 10 crewmen were scheduled to sleep simultaneously and, in general, slept very well during the nine periods.

e. Apollo 11: The crewmen slept well in the command module. The simultaneous sleep periods during the translunar coast were carefully monitored, and the crew arrived on the lunar surface well rested. A 4-hour sleep period prior to the extravehicular activity was provided in the flight plan but the sleep period was not required. The crewmen slept very little in the lunar module following the lunar surface activity; however, they slept well during all three transearth sleep periods.

f. Apollo 12: Sleep periods during the translunar coast phase of the Apollo 12 mission began approximately 7 to 9 hours after the crew's normal bedtime of 11 p.m. The crew had no particular trouble in adapting to the shifted sleep periods; however, the first flight day was extremely long, and the crew was thoroughly fatigued by the time the first sleep period began 17 hours after lift-off.

The crewmen slept well in the command module during the translunar and transearth coast phases. Even though the Lunar Module Pilot took at least two unscheduled naps during transearth coast, sleep periods were considered by the crew to be longer than necessary, since they would invariably awaken about 1 hour ahead of time and would usually remain in their sleep stations until time for radio contact.

The crew slept approximately 3 hours in the lunar module on the lunar surface prior to the second extravehicular activity period. In the next sleep period, following rendezvous and docking, all three crewmen in the command module slept only 3 or 4 hours, which was less than desirable.

g. Apollo 13: The Apollo 13 crew slept well the first 2 days of the mission. All crewmen slept about 5-1/2 hours during the first sleep period. During the second period, the Commander, Command Module Pilot and Lunar Module Pilot slept 5, 6, and 9 hours, respectively. The third sleep period was scheduled to begin 61 hours after lift-off, but failure of the oxygen tank at 56 hours precluded sleep by any of the crew until approximately 80 hours of flight time had elapsed.

After the incident, the command module was used as sleeping quarters until the cabin temperature became too cold (approximately 43° F). The crew then attempted to sleep in the lunar module or the docking tunnel, but the temperature in these areas also dropped too low for prolonged, sound sleep. In addition, coolant pump noise from the lunar module and frequent communications with the ground further hindered sleep. The total sleep obtained by each crewman during the remainder of the mission is estimated to have been 11, 12, and 19 hours for the Commander, Command Module Pilot, and Lunar Module Pilot, respectively.

h. Apollo 14: The shift of the Apollo 14 crew's normal terrestrial sleep cycle during the first 4 days of flight was the largest experienced in the Apollo series. The displacement ranged from 7 hours on the first mission day to 11-1/2 hours on the fourth. The crew experienced some difficulty sleeping in the zero-gravity environment, particularly during the first two sleep periods. They attributed the problem principally to a lack of kinesthetic sensations and to muscle soreness in the legs and lower back. Throughout the mission, sleep was intermittent; deep and continuous sleep never lasted more than 2 to 3 hours.

The lunar module crewmen received little, if any, sleep between their two extravehicular activity periods. The lack of an adequate place to rest the head, discomfort of the pressure suit, and a 7-degree starboard list of the lunar module on the lunar terrain were believed responsible for the lack of sleep. The crewmen looked out the window several times during the sleep period for reassurance that the lunar module was not starting to tip over.

Following transearth injection, the crew slept better than they had previously. The lunar module crewmen required one additional sleep period to make up the sleep deficit that was incurred while on the lunar surface.

The crewmen reported during postflight discussions that they were definitely operating on their physiological reserves because of inadequate sleep. This lack of sleep caused them some concern; however, all tasks were performed satisfactorily.

i. Apollo 15: Very little shift of the Apollo 15 crew's normal terrestrial sleep cycle occurred during the translunar and transearth coast phases of this mission. As a result, all crewmen received an adequate amount of sleep during these periods.

Displacement of the terrestrial sleep cycle during the three lunar surface sleep periods ranged from 2 hours for the first sleep period to 7 hours for the third sleep period. This shift in the sleep cycle, in addition to the difference between the command module and lunar module sleep facilities, no doubt contributed to the lunar module crewmen receiving less sleep on the lunar surface than was scheduled in the flight plan. However, the most significant factors causing loss of crew sleep were operational problems. These included hardware malfunctions as well as insufficient time in the flight plan to accomplish assigned tasks. Lengthening the work days and reducing the planned sleep periods on the lunar surface, coupled with a significant alteration of circadian rhythm, produced a sufficient fatigue level to cause the lunar module crewmen to operate on their physiological reserves until they returned to the command module.

j. Apollo 16: In comparison to his Apollo 10 experience, the Commander slept better during all the scheduled Apollo 16 sleep periods. The Lunar Module Pilot slept well during all sleep periods except the first. However, the Command Module Pilot had uninterrupted sleep only two nights of the mission and, characteristically, would awaken about once every hour. He reported that he never felt physically tired nor had a desire for sleep.

On this mission, displacement of the terrestrial sleep cycle ranged from 30 minutes to 5 hours during translunar coast, and from 3-1/2 hours to 7 hours during the three lunar surface sleep periods. This shift in the sleep cycle on the lunar surface contributed to some loss of sleep; however, this was the first mission in which the lunar module crewmen obtained an adequate amount of good sleep while on the lunar surface. This assessment of the amount of sleep is based on a correlation of heart rate during the mission sleep periods with preflight sleep electroencephalograms and heart rates. The estimates of sleep duration made by ground personnel were in general agreement with the crew's subjective evaluations.

k. Apollo 17: As on previous missions, displacement of the terrestrial sleep cycle contributed to some loss of sleep for the Apollo 17 crew. In addition, changes to the flight plan occasionally impacted previously planned crew sleep periods. In general, however, an adequate amount of good sleep was obtained by all crewmembers during both translunar and transearth coast, as well as during lunar surface operations. All three crewmen averaged approximately 6 hours of sleep per day throughout the mission. Only during the first inflight sleep period was the amount of sleep obtained (approximately 3 hours) inadequate from a medical point of view.

8.2.5 Crew Illness and Medications

The only medical problem commonly shared by all of the flight crewmen was skin irritation caused by the biosensors. Skin cream was used to relieve this condition. Since each flight crew experienced a different set of problems requiring the use of medications, each mission is discussed separately.

a. Apollo 7: Three days prior to launch, the Commander and Lunar Module Pilot experienced slight nasal stuffiness and were successfully treated.

Approximately 15 hours after lift-off, the crew reported that the Commander had developed a bad head cold. Aspirin and decongestant tablets (Actifed) were taken for relief. The Command Module Pilot and Lunar Module Pilot experienced cold symptoms 24 hours later and used the same treatment.

Middle ear blockage was of concern because it was considered necessary for the crew to wear pressure suits during entry. Equalization of pressure within the middle ear cavities is difficult in the pressure suit with the helmet on. Consequently, 48 hours prior to entry, the decision was made that the crew would not wear helmets or gloves.

In the postflight physical examinations, the two crewmen who had experienced the most distressing inflight symptoms showed no obvious evidence of their colds. The other crewman did exhibit a slight amount of fluid in the middle ear.

b. Apollo 8: After the Commander's symptoms of motion sickness dissipated, he experienced symptoms of an inflight illness believed to be unrelated to motion sickness. When the Commander was unable to fall asleep 2 hours into his initial rest period, he took a sleeping tablet (Seconal) which induced approximately 5 hours of sleep, described as "fitful." Upon awakening, the Commander felt nauseated and had a moderate occipital headache. He took two aspirin tablets and then went from the sleep station to his couch to rest. The nausea, however, became progressively worse and he vomited twice. After termination of the first sleep period, the Commander also became aware of some increased gastrointestinal distress and was concerned that diarrhea might occur. No medication was taken for this illness, which was described as a "24-hour intestinal flu." (Just prior to launch, an epidemic of acute viral gastroenteritis lasting 24 hours was present in the Cape Kennedy area.)

c. Apollo 9: Three days before the scheduled launch, the Commander reported symptoms of general malaise, nasal discharge, and stuffiness. These common cold symptoms were not present on the physical examination performed the previous day. The Commander was treated symptomatically and his temperature remained normal throughout the course of his illness. Two days before the scheduled launch, the Command Module Pilot and the Lunar Module Pilot also became ill with common colds and were treated symptomatically. However, because the symptoms persisted, the launch was postponed for 3 days.

During the flight, the Lunar Module Pilot experienced motion sickness and vomited twice, once while preparing for transfer to the lunar module, and again after transfer. After about 50 hours of flight, the Lunar Module Pilot was still not feeling well but had experienced no further vomiting. He reported that his motion sickness symptoms subsided when he remained still. The Lunar Module Pilot took Seconal several times during the mission to induce sleep.

d. Apollo 10: The crewmen experienced abdominal rumblings caused by the ingestion of hydrogen gas present in the potable water, and were concerned that diarrhea might develop. Aspirin was taken occasionally by all crewmen.

e. Apollo 11: The Commander and Lunar Module Pilot each took one Lomotil tablet to prevent bowel movements when on the lunar surface. Four hours before entry, and again after splashdown, the three crewmen each took scopolamine/dextroamphetamine anti-motion-sickness tablets. Aspirin tablets were also taken by the crewmen.

f. Apollo 12: All crewmen took Actifed decongestant tablets to relieve nasal congestion at various times throughout the flight. The Lunar Module Pilot also took Seconal throughout most of the mission to aid sleep. Aspirin was taken occasionally by all the crewmen.

g. Apollo 13: Upon awakening on the second day of the mission, the Lunar Module Pilot took two aspirin to relieve a severe headache. After eating breakfast and engaging in physical activity, the Lunar Module Pilot became nauseated and vomited. One Lomotil tablet was taken by the Command Module Pilot after 98 hours of flight. All crewmen took scopolamine/dextroamphetamine anti-motion-sickness tablets prior to entry.

h. Apollo 14: No medications were used other than nose drops to relieve nasal stuffiness caused by the spacecraft atmosphere.

i. Apollo 15: Aspirin and nose drops were the only medications used. The Commander took 14 aspirin tablets during the last 4 days of the mission to relieve pain in his right shoulder that had developed after difficult deep core tube drilling on the lunar surface. The Command Module Pilot used nose drops just prior to earth entry to prevent possible middle ear blockage.

j. Apollo 16: The Lunar Module Pilot used three Seconal capsules for sleep. One capsule was taken on the night prior to lunar descent and the other two capsules were used for the first and second lunar surface sleep periods. In the postflight medical debriefing, the Lunar Module Pilot reported that the Seconal was effective in producing a rapid onset of good sleep.

k. Apollo 17: More medications were taken on Apollo 17 than on any of the previous missions. Seconal was used intermittently for sleep by all three crewmen and simethicone was used daily for symptomatic relief of flatulence. The Commander took a scopolomine/dextroamphetamine tablet on the second day of flight as a substitute for the simethicone tablets, which he could not initially locate.

The Command Module Pilot and the Lunar Module Pilot experienced one loose bowel movement each on the 11th and 12th days of flight, respectively. In each case, Lomotil was taken and was effective.

8.2.6 Cardiac Arrhythmias

Both of the Apollo 15 lunar surface crewmen demonstrated cardiac arrhythmias at various times during the mission. The Lunar Module Pilot experienced these irregularities during translunar and transearth coast, and during the lunar stay. The Commander experienced them only during transearth coast. A loss of body potassium during flight was considered to be an important factor in the genesis of the Apollo 15 arrhythmias. As a result, several changes were instituted on Apollo 16 to reduce the likelihood of inflight arrhythmias and to further investigate the causes of body potassium loss during space flight. These changes included provision of a high-potassium diet, commencing 72 hours prior to launch and continuing until 72 hours after the flight, and provision of cardiac medications (procaine amide, atropine, and Lidocaine) in the onboard medical kits. In addition, a daily high-resolution electrocardiogram was obtained from each crewman, and an accurate metabolic input/output report was transmitted daily during flight.

No medically significant arrhythmias occurred during the Apollo 16 and 17 flights, but isolated premature heart beats were observed in two of the three crewmen on each flight. The fact that the frequency (less than one per day) and character of these prematurities remained consistent with electrocardiographic data obtained on these same crewmen during ground-based tests clearly indicates that they were not related to or resultant from space flight. Apollo 16 post-flight exchangeable body potassium intake apparently was effective in maintaining normal potassium balance.

Even though significant cardiac arrhythmias were not experienced on the Apollo 16 and 17 missions, their absence cannot be attributed to the high potassium diet because fatigue, stress, and excitement can also produce arrhythmias. The absence of arrhythmias on Apollo 16 and 17 can best be attributed to a combination of factors such as high dietary intake of potassium, better fluid and electrolyte balance, more adequate sleep, and less fatigue.

8.2.7 Postflight Medical Evaluation

Comprehensive medical evaluations were conducted immediately after recovery to determine any physical effects of the flight upon the crew and to detect and treat any medical problems. The medical evaluations included microbiology and blood studies, physical examination, orthostatic tolerance tests, exercise response tests, and chest X-rays. Although all of the crewmen were shown to be in good health, they exhibited varying degrees of fatigue and weight loss, and suffered varying degrees of skin irritation caused by the biosensors. The skin irritation subsided within 48 hours without medical treatment.

All crewmen tested demonstrated some degree of cardiovascular deconditioning during the lower body negative pressure measurements and bicycle ergometry tests, as compared to preflight tests. Individual variations in the time required to return to preflight baseline levels were observed, taking from 2 days to 1 week. Both the Apollo 15 Commander and Lunar Module Pilot had a cardiovascular response to the bicycle ergometry tests not observed after previous flights. This response was characterized by an almost normal response at low heart rate levels and progressively degraded response at the higher heart rate levels. The lack of a significant decrement in the Apollo 16 Command Module Pilot's exercise performance was a surprising postflight finding. Because of the high degree of preflight aerobic capacity demonstrated by this crewman, a significant postflight decrement had been anticipated. One Apollo 17 crewman was within his preflight bicycle ergometry baseline when tested postflight; the other two crewmen returned to their preflight baseline by the second postflight day.

As already noted, the Apollo 10 cabin atmosphere became contaminated with fiberglass particles. Postflight examinations of the Apollo 10 crewmen showed no significant changes attributable to their exposure to the fiberglass. Four days after recovery, the Lunar Module Pilot developed a mild infection in his left nostril which may have been caused by a small piece of fiberglass; he responded rapidly to treatment.

Other significant immediate postflight findings were as follows.

a. A definite residual of an inflight upper respiratory infection was noted in one of the Apollo 7 crewmembers.

b. The Apollo 9 Commander suffered from bilateral aerotitis media. This condition responded rapidly to decongestant therapy and cleared after 2 days.

c. The Apollo 11 Commander had a mild serous otitis media of the right ear but no treatment was necessary when he found that he could clear his ears satisfactorily.

d. The Apollo 12 Lunar Module Pilot had a small amount of clear fluid with air bubbles in the middle ear cavity which disappeared after 24 hours of decongestant therapy.

e. The Apollo 13 Lunar Module Pilot had a urinary tract infection.

f. The Apollo 14 Commander and Command Module Pilot each exhibited a small amount of clear, bubbly fluid in the left middle ear cavity with slight reddening of the ear drums. These findings disappeared in 24 hours without treatment. The Lunar Module Pilot had moderate eyelid irritation in addition to slight redness of the eardrums.

g. The Apollo 15 Commander had hemorrhages under some of his fingernails of both hands and a painful right shoulder. These hemorrhages were attributed to an insufficient arm-length size of his pressure suit which caused the fingertips to be forced too far into the gloves during hardsuit operations. The painful right shoulder was due to a muscular/ligament strain which responded rapidly to heat therapy.

h. The Apollo 16 Commander had some sinus congestion which responded to medication, and also a slight reddening and retraction of the right eardrum.

i. The Apollo 17 Commander and Lunar Module Pilot both exhibited subunguinal hematomas from the pressure suit gloves; these were more extensive and vivid on the Lunar Module Pilot.

j. The Apollo 17 Commander had a herpetic lesion on the right side of the upper lip, which was approximately 72 hours old at the time of recovery.

During the landing of the Apollo 12 command module, a camera came off its window bracket and struck the Lunar Module Pilot on the forehead, causing him to lose consciousness for about 5 seconds. He sustained a 2-centimeter laceration over the right eyebrow. The cut was sutured soon after the crew was recovered and it healed normally.

Delayed postflight minor illnesses occurred as follows:

a. Six days after recovery of Apollo 8, the Lunar Module Pilot developed a mild pharyngitis which evolved into a common cold and nonproductive cough. He recovered completely after 6 days of treatment. The Commander developed a common cold 12 days after the flight, and treatment resulted in complete recovery 7 days later.

b. Four days after recovery, the Apollo 9 Lunar Module Pilot developed an upper respiratory infection with a secondary bacterial bronchitis. He was treated with penicillin and was well 7 days later. The Commander developed a mild upper respiratory syndrome 8 days after recovery. He was treated and recovered 4 days later. Both of these cases were determined to be type-B influenza virus.

c. On the day after recovery, the Apollo 12 Commander developed a left maxillary sinusitis which was treated successfully with decongestants and antibiotics.

8.3 BIOMEDICAL EQUIPMENT PERFORMANCE

8.3.1 Instrumentation

In general, the biomedical instrumentation system worked well, although some minor losses of data were experienced throughout the program. Problems with lead breakage and pin connector disconnection encountered on the Apollo 7 mission were corrected for subsequent flights. Some degradation of physiological data was caused by loose biosensors, but restoration of good data was usually obtained by reapplication of the sensors. Sponge/pellet electrodes were used in the bioharness for the first time on the Apollo 15 mission. This type of biosensor was developed to reduce skin irritation produced by the continuous-wear electrodes used previously. The quality of the data obtained with the new electrodes was good and less skin irritation was seen at the biosensor sites than had been seen after previous missions. Physiological data losses resulting from trapped air under the electrodes were not experienced after the Apollo 15 mission because small vents were added to the electrodes.

8.3.2 Medication Packaging

All the medications in tablet and capsule form were packaged in individually sealed plastic or foil containers. On the Apollo 11 mission when the medical kit in the command module was unstowed, the packages had expanded because insufficient air had been evacuated during packaging. This ballooning prevented restowage of the items in the kit until a flap was cut away from the kit. Venting of each of the plastic or foil containers prevented this problem from recurring on subsequent flights. The nasal spray bottles in the inflight medical kits were replaced by dropper bottles for Apollo 14 and subsequent missions because previous crews had reported difficulties in obtaining medication from spray bottles in zero-gravity.

8.4 FOOD

The Apollo program food was primarily of the freeze-dried variety which could be reconstituted with water. This type is low in weight and volume, is stable without refrigeration, can be readily packaged, and can withstand the stresses and environmental conditions of space flight. Preparation of these meals requires cutting of the package, measuring and adding water, kneading the mixture, and waiting for the rehydration process to be completed. Although the rehydrated foods were generally the most satisfactory, the texture and flavor of this type of food was affected by the command module potable water (fuel cell product water). Complete rehydration was prevented because excessive hydrogen gas dissolved in the water expanded the packages, reducing the transfer of water to the food. Offensive tasting food resulted from ionic contaminants in the water and difficulties in the chlorination procedures. These problems were alleviated on the later flights because of improvements in the potable water system and methods of treatment.

Bite-size compressed or freeze-dried products with special coatings to inhibit crumbling were also used. These foods, designed to have an average moisture content of only 2 to 3 percent, were intended to be rehydrated in the mouth with saliva or with small quantities of water when saliva was inadequate. In general, the crews found the bite-size foods to be too dry and, therefore, undesirable.

Special thermostabilized wet-pack foods were added to the flight menus to provide variety, improved taste, and a closer similarity to conventional food. Both bite-size and wet-pack foods required minimum preparation time and, therefore, were more convenient than the rehydrated meals. The main disadvantages of the wet-pack foods were that some of the foods which are normally eaten hot (such as potatoes and gravy) were not as palatable when eaten cold.

In an attempt to make the food pleasant to the crew, menus were designed to meet the psychological as well as the physiological needs of each crewmember. Prior to flight, each crewman was provided with a 4-day supply of flight food for menu evaluation and selection. Flight menus were them established to provide each crewman with adequate nutrients to meet basic physiological requirements. No foods were included in the final flight menus which had been rejected during the preflight evaluations.

A control diet was used for the first time on Apollo 16 to insure that each crewman was in an optimum nutritional condition prior to launch, and to facilitate postflight interpretation of medical data. The diet was initiated 3 days prior to launch and was terminated 2 days after recovery. In addition, food and fluid intake were closely monitored during the flight.

In-suit food bars were used by the Apollo 15 and Apollo 17 lunar module crewmen, and in-suit beverage assemblies were used by the Apollo 16 and Apollo 17 lunar module crewmen. The beverage assembly consisted of a drinking device and a 32-ounce bag containing water or potassium-fortified orange drink. Several minor problems were experienced in using the assembly during the Apollo 16 mission. Inadvertent activation of the tilt valve by the communications cable or the microphone caused some release of fluid into the Lunar Module Pilot's helmet prior to lunar landing. Prior to the first extravehicular period, the Commander installed the in-suit beverage assembly after donning his pressure suit and could not properly position it. Thus, he was unable to consume any fluid during the first extravehicular activity.

Four different types of Skylab food packages were evaluated on Apollo 16 for function under zero-gravity conditions by each crewman. These included a rehydratable soup package, a beverage package, a peanut wafer package, and a liquid table-salt package.

The menus for the Apollo 17 mission were designed to meet physiological requirements of each crewmember as well as requirements of a food compatibility assessment study. This study was implemented (1) to determine metabolic requirements of space flight, (2) to assess compatibility of menus with respect to gastrointestinal function, and (3) to acquire data on the underlying endocrinological control of metabolism.

Negative nitrogen and potassium balances occurred during the Apollo 17 flight and confirmed a loss in total body protein. In addition, a loss of body calcium and phosphorus was demonstrated. This is consistent with previous flights. Although some of the observed weight loss can be attributed to changes in total body water, the hypocaloric regimen in conjunction with the well-known tendency to lose body tissue under hypogravic conditions indicates that a considerable portion of weight loss is from fatty and muscle tissues.

Water intake and output data were generally consistent throughout the Apollo 17 flight. However, when insensible water loss is considered, the crew on this mission were in a state of mild negative water balance. These data are consistent with water-balance data from Apollo 16. During the immediate postflight period, only the Lunar Module Pilot's urine volume was significantly decreased; the other two remained normal. This postflight finding, along with the slight decreases in total body water, confirms the normal-to-decreased level of antidiuretic hormone. This observation differs from that of Apollo 15 where high urine volumes and increased levels of antidiuretic hormone were observed. The more complete data from the Apollo 17 mission suggests that the major weight loss resulted from loss of tissue mass rather than loss of total body water. The lack of weight gains during the first 24 hours postflight provides additional evidence that fatty and muscle tissues were the predominant components of the observed weight loss.

8.5 APOLLO LUNAR QUARANTINE PROGRAM

The Apollo lunar quarantine program was instituted to deal with the remote possibility that micro-organisms hazardous to life on earth could be introduced into the biosphere by the crewmembers of lunar landing missions and the material brought back by them. Representatives of the National Academy of Sciences, the U.S. Public Health Service, the U.S. Department of Agriculture, and the U.S. Department of the Interior reviewed and approved plans proposed by NASA; the details of implementation of the program were the responsibility of NASA. Much of the following discussion has been excerpted from reference 8-13.

8.5.1 *Quarantine Program Guidelines*

The coordination of the multidisciplinary and often contradictory requirements of the lunar quarantine programs presented a unique series of problems. Many of these problems were associated with the hypothetical nature of an unknown lunar hazard. Therefore, if precise scientific and technical decisions were to be made, basic assumptions and guidelines had to be followed. The basic guidelines that were established for development of the program were as follows.

a. Hazardous, replicating micro-organisms exist on the moon.

b. The preservation of human life should take precedence over the maintenance of quarantine.

c. Biological containment requirements should be based on the most stringent means used for containment of infectious terrestrial agents.

d. The sterilization requirements should be based on the methods required for the destruction of the most resistant terrestrial forms.

e. Hazard detection procedures should be based on an alteration of the ecology and classical pathogenicity.

f. The extent of the biological test protocol would be limited to facilities approved by the Congress of the United States, to well-defined systems, and to biological systems of known ecological importance.

8.5.2 Program Elements

8.5.2.1 Lunar-surface contamination.- Nations involved in the exploration of extraterrestrial bodies have agreed to take all steps that are technically feasible to prevent the contamination of these bodies during exploration. The primary reasons for preventing contamination of extraterrestrial bodies are (1) to ensure that scientific analyses for the detection of viable life originating from an extraterrestrial body can be conducted without the complications associated with terrestrial contamination of such a body, and (2) to ensure that, if life does exist on an extraterrestrial body, the ecological balance existing on that body is not disturbed by the introduction of terrestrial microbial life-forms.

Several problems complicate the implementation of this agreement. First, if unmanned landers are used, the problems associated with minimizing or eliminating contamination sources are principally those technological problems involved with the design and fabrication of hardware that will withstand decontamination or sterilization or both. The problems associated with this technology development should not be minimized, as evidenced by the amount of engineering and design effort already expended in planning for unmanned vehicle exploration of other planets. However, these decontamination problems are simple when compared to those associated with manned exploration of other planets, because man is a virtual factory for the production and dissemination of viable microbial contaminants. The other main problem associated with preventing contamination of extraterrestrial bodies is the probability that a terrestrial life-form can establish itself and survive in the alien environment.

The physical evidence concerning the environment of the moon indicated that the probability was extremely small that a terrestrial life-form could establish itself. This, in addition to the low probability that a viable ecological system could exist on the moon, resulted in the relaxation (but not elimination) of the requirements for the prevention of lunar surface contamination. The Apollo crewmembers represented the prime source of contamination of the lunar surface. Three other sources were determined to be (1) waste products such as feces, urine, and residual food; (2) viable terrestrial micro-organisms released during lunar module depressurization; and (3) micro-organisms present in the lunar module waste-water system. Procedures were defined to eliminate massive contamination of the lunar surface from these three sources.

8.5.2.2 Lunar sample collection.- Because one of the primary objectives of the Apollo program was the collection and return of lunar material, advisory groups were established to determine the requirements for sample collection. One requirement was that lunar samples should be collected by using only sterile tools and should be returned to the Lunar Receiving Laboratory in a sterile environment. The collection of lunar samples with hardware that contained minimum organic and inorganic contamination was also established as a physical science requirement. The types of materials that could be used for fabricating tools and other items that would come in contact with lunar material were severely limited by the scientific requirements and weight restrictions. A high-temperature bakeout under vacuum conditions was the best method for removing volatile terrestrial contaminants from the hardware. This treatment, at a sufficient temperature for a sufficient period of time, also satisfied the sterilization requirements for the hardware.

The procedures and hardware necessary for the stowage of the collected lunar samples were considered next. The physical scientists decided that the lunar samples should be transported to earth under environmental conditions as nearly like those on the moon as was technically feasible. This decision necessitated the design and fabrication of a pressure vessel that could be filled with lunar samples and sealed on the lunar surface, and in which the internal environment could be maintained throughout the sample transfer from the lunar surface to the Lunar Receiving

Laboratory. Because the pressure vessel had to be an ultraclean, gastight container, no additional requirements were necessary in terms of quarantine control. The Apollo lunar sample return containers (fig. 3-14) were designed to contain approximately 1 cubic foot of lunar material and to be sealed on the lunar surface.

8.5.2.3 Inflight contamination control.- It was anticipated that during lunar surface extravehicular operations the exterior of the crewmen's suits and the equipment used on the lunar surface would become contaminated with lunar material. As a result, specific hardware and procedures were developed to minimize the transfer of contamination from these sources to the biosphere. The procedures were initiated before the crewmen entered the lunar module after each extravehicular activity. Each crewman brushed the other crewman's suit to remove as much loose lunar material as possible. A footpad was provided on the steps of the lunar module so that lunar material could be scraped from the boots. Also, the sample return containers and other items were brushed off before being returned to the lunar module. Once inside the lunar module, all items to be transferred to the command module were placed in sealed Beta-cloth bags to minimize the leakage of lunar dust into the lunar module or command module environment. Items that were not transferred to the command module, such as the gloves and overboots, were discarded onto the lunar surface. After the last hatch closure on the lunar surface, the crewmembers cleaned the interior surfaces of the lunar module using a vacuum cleaner in conjunction with the environmental control system.

After the lunar module ascent from the lunar surface and rendezvous with the command module, the lunar module crewmen transferred hardware and lunar materials to the command module. Because the command module entered the biosphere, procedures were developed to minimize the possible transfer of lunar contaminants from the lunar module to the command module. These procedures included wiping and vacuuming all items being transferred from the lunar module to the command module, establishing a positive air flow from the command module to the lunar module to prevent atmospheric contaminants in the lunar module from entering the command module, and bagging and storing items after transfer to the command module. When the transfer of the crewmembers and all hardware to the command module was completed and the lunar module had been separated from the command module, the command module interior was vacuumed and cleaned.

Other potential quarantine considerations involved the exterior of the command module. Although the command module exterior was considered to be an unlikely source of potential contamination, a concern was that lunar-surface contaminants would be transferred from the lunar module to the command module exterior during docking. However, this possibility was remote because the docking area of the lunar module was never in direct contact with the lunar surface and was subjected to solar radiation during the lunar surface operations.

8.5.2.4 Return to the terrestrial biosphere.- Once the command module containing the crewmen and lunar samples entered the terrestrial environment, careful control of potential lunar contamination was required. Because the exterior of the command module was not considered to be a source of extraterrestrial contamination, it was determined that landing in the ocean could occur without any special precautions against contamination. After landing, the command module environmental control system was to be deactivated and a postlanding ventilation system was to be activated. The system consisted of a fan that circulated fresh air from the outside through the command module and forced the air to the outside through a vent valve. The system, which had been incorporated in the command module before the lunar quarantine requirements had been formulated, presented a problem in that potentially contaminated air would be exhausted from the command module. The postlanding ventilation system was not modified, however, primarily because the measures taken to minimize possible contamination of the command module atmosphere, and the use of protective garments and biorespirators by the crew were judged to be adequate protective measures.

Next, in terms of contamination control, the procedures for removing the crewmembers, lunar samples, and hardware items from the command module and transporting them to quarantine isolation in the Lunar Receiving Laboratory were developed. The crewmembers left the command module before it was lifted to the deck of the recovery vessel. Swimmers assisted the crewmembers in egressing the command module. The swimmers were protected from potential lunar contamination by using their breathing apparatus during installation of the flotation collar on the command module. Furthermore, the swimmers sprayed areas of potential contamination, such as the hatch and docking areas, with a germicidal solution to decontaminate these areas before the hatch was opened. The crewmembers emerged from the command module wearing biological isolation garments which effectively prevented the transfer of microbial contaminants from the respiratory tract and body surface to the exterior environment. After pickup by helicopter, the crewmen, still wearing the biological isolation garments and physically isolated from the helicopter crewmen, were transported to the recovery vessel. The flight surgeon, who was quarantined with the crewmembers, was also on board the helicopter. Upon arrival at the primary recovery vessel, the helicopter was towed close to a mobile quarantine facility and the crewmembers and flight surgeon walked to the facility. The deck area traversed by the crewmembers during the transfer was decontaminated.

The command module hatch was sealed after egress of the crewmen, and the area surrounding the hatch was decontaminated with a germicide. All decontamination equipment and the life rafts used by the Apollo crewmen were then sunk at sea. Later, the command module was hoisted aboard the primary recovery vessel and placed near the mobile quarantine facility. A flexible plastic tunnel was then installed between the command module and the mobile quarantine facility to allow removal of lunar samples and other data by a recovery technician. The command module hatch was then sealed, the surrounding area was decontaminated, and the tunnel was drawn inside the mobile quarantine facility.

Because some experiments planned for the lunar materials were time-critical, the samples removed from the command module were packaged in vacuum-sealed plastic bags, sterilized, and air-locked out of the mobile quarantine facility. The packages were placed in shipping containers and transported immediately by aircraft to the Lunar Receiving Laboratory. The crewmembers, the flight surgeon, and the recovery technician remained in the mobile quarantine facility until the primary recovery vessel reached the nearest port. There, the mobile quarantine facility and the occupants were transferred to a transport plane and flown to Houston, Texas. Upon arrival, the mobile quarantine facility was transported to the Lunar Receiving Laboratory. The operations performed in the Lunar Receiving Laboratory are described in section 11.

8.6 SPECIAL MEDICAL STUDIES

Special medical studies conducted in support of the Apollo program included a crew microbiology program and a virology program.

8.6.1 Microbiology

The microbiology program was instituted in response to a requirement by the Interagency Committee on Back Contamination that identified a need to produce a catalog of micro-organisms carried to the moon by Apollo crewmen. The primary use of the catalog was to provide a means of recognizing whether a micro-organism, if found in lunar material, was of terrestrial or extraterrestrial origin. The catalog was also used for operational medical purposes.

The return of sterile lunar soil indicated that the preventive measures and handling methods developed to prevent contamination of lunar soil were successful. If a terrestrial micro-organism had been found in lunar soil, the catalog would have been extremely useful as supportive evidence to the laboratory analysis of the contaminant. The micro-organism could possibly have been shown to possess the same morphological and biochemical characteristics as one identified prior to a particular mission.

The operational medical objectives were the same for each flight. The primary objective was always to detect the presence of potentially pathogenic micro-organisms on the crewmen so that possible medical problems could be recognized and preventive measures established. A second objective was to identify medically important micro-organisms from crew specimens collected as a result of illness events so that the flight surgeon could use these data to aid in diagnosis and treatment of inflight illnesses. A third objective was to collect microbial data which could aid in explaining the responses of the crew microbial autoflora to the space flight environment and the resultant effects on crewmembers. In order to accomplish the three stated objectives, a variety of specimens were collected. In general, eight body surface swabs as well as fecal, urine, and gargle samples were collected from each of the crewmembers. Although the exact sampling schedule varied from flight to flight, specimens were usually obtained approximately 1 month prior to launch, 2 weeks prior to launch, the morning of launch day, and immediately upon recovery. In addition to the specimens obtained from the crewmen, swab samples were obtained from selected sites in the command module cabin immediately prior to launch and after recovery. Following identification of all micro-organisms, the laboratory data on each isolate were stored in a computer. A computer program was developed to provide a "match test" of the stored data with data that might be collected from an unknown micro-organism. The program was designed to search the catalog until an identification was made of those micro-organisms that had the greatest number of similar characteristics. Although no micro-organisms were found in the lunar material, significant medical data were produced. Specific observations are summarized for Apollo missions 7 through 12, and 13 through 17.

8.6.1.1 Apollo 7 through 12.- Considerable variation in the microfloral response was observed. *Staphylococcus aureus* was shown to increase in number, and transfers were effected between crewmen during two of the six missions. Although the micro-organism was present on two of the remaining four missions, an increase was not detected postflight. The variables of host susceptibility, external environmental factors, and ecological relationships between competing species of micro-organisms are undoubtedly responsible for the observed response of the microflora. Increase in numbers and spread of *Aspergillus fumigatus* and beta-hemolytic streptococci were also shown on Apollo 7. The increase was not detected on any of the remaining five missions.

Preflight and postflight microbial analysis of samples obtained from the command module showed that a loss of the preflight micro-organisms occurs during the mission. The preflight microflora at the sampling sites were replaced by micro-organisms from the crew microflora.

8.6.1.2 Apollo 13 through 17.- Immediately upon return from a space flight, species of micro-organisms were recovered from a particular crewmember that had not previously demonstrated the presence of this species. This phenomenon occurred on all flights with several different species, implying that intercrew transfer of microbes is a regular occurrence during space flight. Transfer of micro-organisms between crewmembers and the command module or extravehicular clothing is even more obvious because the preflight microbial loads of these inanimate objects are quite different from the microbial loads of the crewmembers. Occupation of the command module during the space flight does not generally effect a significant change in the numbers of different contaminating species. However, there is an obvious loss of the original contaminants on each site with a concurrent invasion of microbes belonging to different species. In addition, there is a buildup of medically important species during the space flight. In particular, the buildup of *Proteus mirabilis* on the urine collection device has been a recurrent problem throughout most of the Apollo missions. Close contact of susceptable parts of the body with these contaminated urine collection devices presents a significant medical hazard.

8.6.2 Virology

The virology program conducted in support of the Apollo missions consisted of characterization of the viral and mycoplasma flora of the crewmembers; viral serology on crewmembers, crew contacts and key mission personnel; and an analysis of specimens obtained as a result of crew illnesses, the mission personnel surveillance program, and the flight crew health stabilization program. Serology studies were initiated with Apollo 14; the mission personnel surveillance program was in effect during Apollo missions 11 through 14; and the flight crew health stabilization program was in effect during Apollo missions 14 through 17.

The characterization of the viral and mycoplasma flora was accomplished by utilizing state-of-the-art procedures and consisted of challenging tissue cultures, embryonated eggs, suckling mice, and mycoplasma media with specimens obtained at various preflight and postflight times.

8.7 BIOCHARACTERIZATION OF LUNAR MATERIAL

Immediately after lunar samples were unpacked, small, yet representative, samples were distributed to biological test laboratories within the Lunar Receiving Laboratory where the samples were assessed to insure that they were not biologically hazardous, and to otherwise study the effects of lunar material on various plant and animal species. As mentioned previously, the containment aspects of the quarantine program were discontinued after the Apollo 14 postflight evaluation. As a result, the number of tests was substantially reduced for the Apollo 15 studies, and the scope of the testing was further reduced for the final two missions.

8.7.1 Microbiology

Microbiological tests for viruses, bacteria, and other agents were performed on specimens from the crew, on lunar samples, and on various test species that had been exposed to lunar material. The host systems used for the isolation of viruses from crewmembers and contacts within the crew reception area helped the biologists isolate and identify member viruses representing essentially all known groups capable of producing acute illnesses in human populations. In addition to the host systems used for crew virology, supernatant fluids from lunar soil suspensions were tested in tissue cultures of mammals, birds, and cold-blooded species.

8.7.1.1 Virological investigations.- The virological studies conducted on the lunar material obtained during the Apollo missions consisted primarily of analyses for replicating agents. The materials tested and the systems challenged are presented in table 8-II. The supernatant fluid obtained from centrifuging 50 percent weight/volume suspensions of lunar material in sterile media was used as the inoculum. There was no evidence of replicating agents in any of the systems utilized.

Additional studies were performed on the Apollo 15 lunar material to assess alterations in host susceptibility. No significant differences were observed between terrestrial basalt (simulated lunar material) and actual lunar material suspensions. Colonies grown on agar containing lunar material were similar to those grown on agar medium alone or agar containing simulated lunar material. Another study was conducted to determine the effect of lunar materials on the stability of poliovirus. No significant differences were detected between the simulated lunar material and the actual lunar material suspensions.

8.7.1.2 Bacteriological and mycological investigations.- Samples from all six lunar exploration missions were examined for the presence of biologically formed elements or viable organisms. No evidence of viable organisms was obtained from any of these analyses.

Following incubation of the lunar material in the culture media complexes, microbial growth dynamics studies were conducted with known test species to evaluate the possible presence of toxic factors. Only extracts of culture media which had been in contact with a mixture of lunar material from both Apollo 11 core tubes proved to be toxic to all species tested (refs. 8-14 and 8-15). Attempts to reproduce this toxic effect with individual Apollo 11 core samples obtained at other parts of the core stem and analyzed under somewhat different conditions were unsuccessful. In all, 48 different lunar samples, collected to a depth of 297 centimeters from six different landing sites, were examined.

8.7.2 Zoology

Various types of animals and invertebrates were exposed to lunar material to test for possible harmful effects. Maintenance of germ-free animals under positive pressure conditions was forbidden, and a special procedure using a double biological barrier was developed. The germ-free mouse was chosen as the prime test subject to represent the mammalian portion of the zoological program. A second category of the program was the exposure of various aquatic species to lunar material. These test subjects included marine and freshwater species and ranged from protozoa to the oyster, the shrimp, and various types of fish. A third category was the terrestrial invertebrate, represented by the insects. It was impossible to cover all the taxa in this enormous group, but the three major orders were represented by the German cockroach, the fly, and the greater wax moth. The animals were exposed orally and by inhalation, injection, and direct contact.

Following the Apollo 11, 12 14, and 15 missions, fifteen species of animals representing five phyla were exposed to untreated lunar material. These tests were complementary to the other protocols and were designed to detect any viable or replicating agents capable of infecting and multiplying in animals. Results of exposure of the various animal species were uniformly negative (refs. 8-16 and 8-17). No viable or replicating agents, other than identifiable terrestrial micro-organisms, were ever recovered or observed in the test animals. In addition, only minimal and transitory inhibition or toxicity followed exposure of some of the animals to the lunar material.

TABLE 8-II.- SYSTEMS CHALLENGED IN THE VIROLOGICAL ANALYSES OF LUNAR MATERIAL OBTAINED DURING THE APOLLO MISSIONS

Mission	Number of samples tested	Tissue cultures	Systems challenged		
			Embryonated eggs	Suckling mice	Mycoplasma media
11	3	African green monkey kidney, primary human embryonic kidney, diploid human embryonic lung, primary bovine embryonic kidney, primary duck embryonic fibroblast, rainbow trout gonadal tissue, *Pimepholes promelas*, grunt fin, *Haemulon sciuras*	X		X
12	2	African green monkey kidney, primary human embryonic kidney, diploid human embryonic lung, heteroploid bovine kidney, heteroploid porcine kidney, primary duck embryonic fibroblast, rainbow trout gonadal tissue, *Salmo gairdneri*, fathead minnow, *Pimepholes promelas*, grunt fin, *Haemulon sciuras*	X		X
14	6	African green monkey kidney, primary human embryonic kidney, diploid human embryonic lung, heteroploid bovine kidney, heteroploid porcine kidney, primary duck embryonic fibroblast, rainbow trout gonadal tissue, *Salmo gairdneri*, fathead minnow, *Pimepholes promelas*, grunt fin, *Haemulon sciuras*	X	X	X
15	1	African green monkey kidney, primary human embryonic kidney, diploid human embryonic lung	X	X	X
16	1	African green monkey kidney, primary human embryonic kidney, diploid human embryonic lung	X	X	X
17	1	African green monkey kidney, primary human embryonic kidney, diploid human embryonic lung	X	X	X

Following relaxation of the containment requirements after the Apollo 14 mission, life-span studies were initiated with germ-free mice inoculated with lunar material. Classical inflammatory reactions were noted and lunar fine material was observed to persist for the life of the animal (20 months). The observations suggest the lunar fine material is relatively insoluble in tissue and that, while acting as a low-grade irritant, it has little tendency to evoke reactive fibrosis. The significance of such a chronic low-level stimulus and the various factors governing the retention, elimination, and turnover of lunar fine material in mammalian tissue are not clear at this time.

8.7.3 Botany

The botany program emphasized exposure of 33 plant species to lunar samples for the detection of possible plant pathogens. Sterile cabinets were maintained to grow pure cultures of algae and diatoms, to germinate surface-sterilized seeds, to grow pathogen-free seedlings, and to develop tissue cultures, all of which were exposed to lunar material in various forms.

The same materials and methods were used in botanical investigations following all of the lunar exploration missions, except that fewer species were employed in the studies for the last three missions. Emphasis in these latter investigations was placed upon collection of more definitive data on changes of pigmentation and cytoplasm density of lunar or terrestrially treated cells, tissues, and whole plants. Methods unique to these studies are described in references 8-18 through 8-22. Of potential interest was the application of many principles of germ-free animal research to the culture of the large number of plant seedlings required for the biocharacterization program. Lunar samples used in these studies were either composites of representative rock fragments and surface fines (Apollo 11, 12 and 14), or composites of surface fines (Apollo 15, 16 and 17). Descriptions of the terrestrial controls may be found in references 8-23.

Treatment of algal cultures with lunar material caused growth inhibition in dense cellular suspensions and growth stimulation in cultures grown on semisolid mineral media. Growth promotion was evident by marked increase in cell density in areas adjacent to lunar particles. Treatment of algal cells by exposing them to lunar material suspended via gently agitation resulted in cultures having higher respiration rates than untreated controls. Microscopical examination of treated cultures revealed no significant differences between cells treated with lunar material or terrestrial material.

The fern, *Onoclea sensibililis L.*, which was tested with each composite lunar sample, appeared to be the most sensitive plant for demonstrating that lunar material can act as a source of nutrients for plants. Clumps of spores germinating on lunar material placed within a well cut into mineral agar showed a several-fold increase in mass. The resulting gametophytes were also greener than those treated with terrestrial basalts. Other lower plants such as *Lycopodium cernuum L.* and *Marchantia polymorpha L.* (liverwort) exhibited similar stimulation. Within the treated plants, measurements of chlorophyll-a showed significantly higher concentrations of the pigment, but not chlorophyll-b or carotenoids.

Seeds germinated in the presence of lunar materials grew vigorously and absorbed significant quantities of aluminum, chromium, iron and titanium (ref. 8-21) and a variety of others including rare earth elements. In addition, cabbage and brussels sprouts absorbed large amounts of manganese. Lettuce seedlings generally did much better in the presence of lunar material.

Germ-free plants of bean, citrus, corn, sorghum, soybean, tobacco and tomato showed no deleterious effect when their leaves or roots were treated with 0.2 gram of lunar material per specimen. Plants of citrus, corn and soybean appeared to grow consistently better if treated in the sand-water culture system originally described by Hoagland and Arnon (discussed in ref. 8-18). Histological specimens taken from lunar treated plants revealed no deleterious effects of prolonged contact between lunar particles and leaf, meristematic, or root cells.

Twelve plant tissue culture systems employed in the biocharacterization program (ref. 8-20) appeared to be the most useful for studying cell-lunar particle interactions. Tobacco cells treated with lunar material accumulated approximately 30 percent more chlorophyll-a than untreated ones (ref. 8-23). Relative and absolute concentrations of fatty acids and sterols were changed by lunar-material treatment (ref. 8-24). Many cellular differences were noted. Both stationary and suspension-cultures of lunar-material-treated tobacco tissue cultures exhibited an increased maturation of chloroplasts, and apparent secretory activity (ref. 8-25). Pine cells, on the other hand, exhibited a remarkable increase in tannin accumulation but not fatty acids or sterols.

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9.0 SPACECRAFT MANUFACTURING AND TESTING

Complete systems, subsystems, and individual components for the Apollo spacecraft were furnished by numerous subcontractors. Subcontracts were generally managed by the prime contractors, although in a number of cases the government furnished hardware directly to the prime contractor. During the manufacturing process, subcontractors were required to observe the same rigor that was imposed by NASA upon the prime contractors with regard to the selection of materials, maintenance of dimensional tolerances, environmental control, and the demonstration of proper performance. The majority of subcontractors manufactured and assembled the contracted hardware in their own facilities; however, numerous organizations that specialized only in design and construction required the services of independent testing and certification organizations to perform the required test and checkout functions. In all cases, the subcontractors were responsible for the checkout of the hardware to be delivered to the prime contractors and the prime contractors were responsible for the end-to-end checkout of the spacecraft.

This section presents the sequences of operations that began with the assembly of spacecraft components to form the primary vehicle structures and terminated with final inspection before shipment. No attempt is made to establish the schedules or to describe the processes by which each separate component or assembly was produced. Each component or assembly was inspected and/or tested according to a rigorous set of quality and reliability requirements and determined to be flightworthy before installation. The described sequence is representative of operations for a typical flight spacecraft rather than for a specific vehicle. Modifications, mission requirements, schedule commitments, hardware availability, personnel, experience, facility loading, and other factors influenced the sequence of operations to an extent that required constant management. The individual vehicle time lines used to achieve the basic objectives of the manufacturing program are reflected in appendix E.

9.1 COMMAND AND SERVICE MODULE, LAUNCH ESCAPE SYSTEM AND SPACECRAFT/LUNAR MODULE ADAPTER

9.1.1 Command Module Assembly and Checkout

The command module was comprised of two major structural elements - the heat shield structure (outer) and the crew compartment structure (inner). The sequence of assembly of these two structures and systems installation and checkout operations are described in the following paragraphs.

9.1.1.1 Heat shield structure.- The heat shield structure consisted of brazed stainless steel honeycomb sandwich panels which were welded into three separate major assemblies: the forward compartment heat shield, the crew compartment heat shield and the aft heat shield. Figure 9-1 shows the assembly flow of the crew compartment heat shield. This is typical of all three heat shield assemblies.

The completed heat shield structural assemblies were delivered to a subcontractor for application of the ablative thermal protection material. The heat shields were returned from the subcontractor and installed on the command module during final assembly.

9.1.1.2 Crew compartment structure.- The crew compartment structure consisted of bonded aluminum honeycomb sandwich construction with the inner shell (facesheet) of the sandwich being a welded assembly to minimize cabin leakage. Figure 9-2 shows the assembly flow of the two major subassemblies of the inner shell. These subassemblies were welded together to complete the crew compartment pressure vessel assembly. The honeycomb core, the outer facesheets and splice plates were then fitted to this assembly and bonded in place. This completed the fabrication and assembly of the crew compartment primary structure and pressure vessel.

A second major bonding operation was performed to install the various ties and angles required on both the inside and outside for attachment of the secondary structural assemblies. The main display console, equipment support structures, cold plates, guidance and control system support structure, and interior equipment bays were installed. The crew compartment structure was then proof pressurized to demonstrate structural integrity. Throughout the assembly of the crew compartment structure, component locating, machining operations, fitting and trimming were controlled by master tools which assured proper assembly and fit of all components.

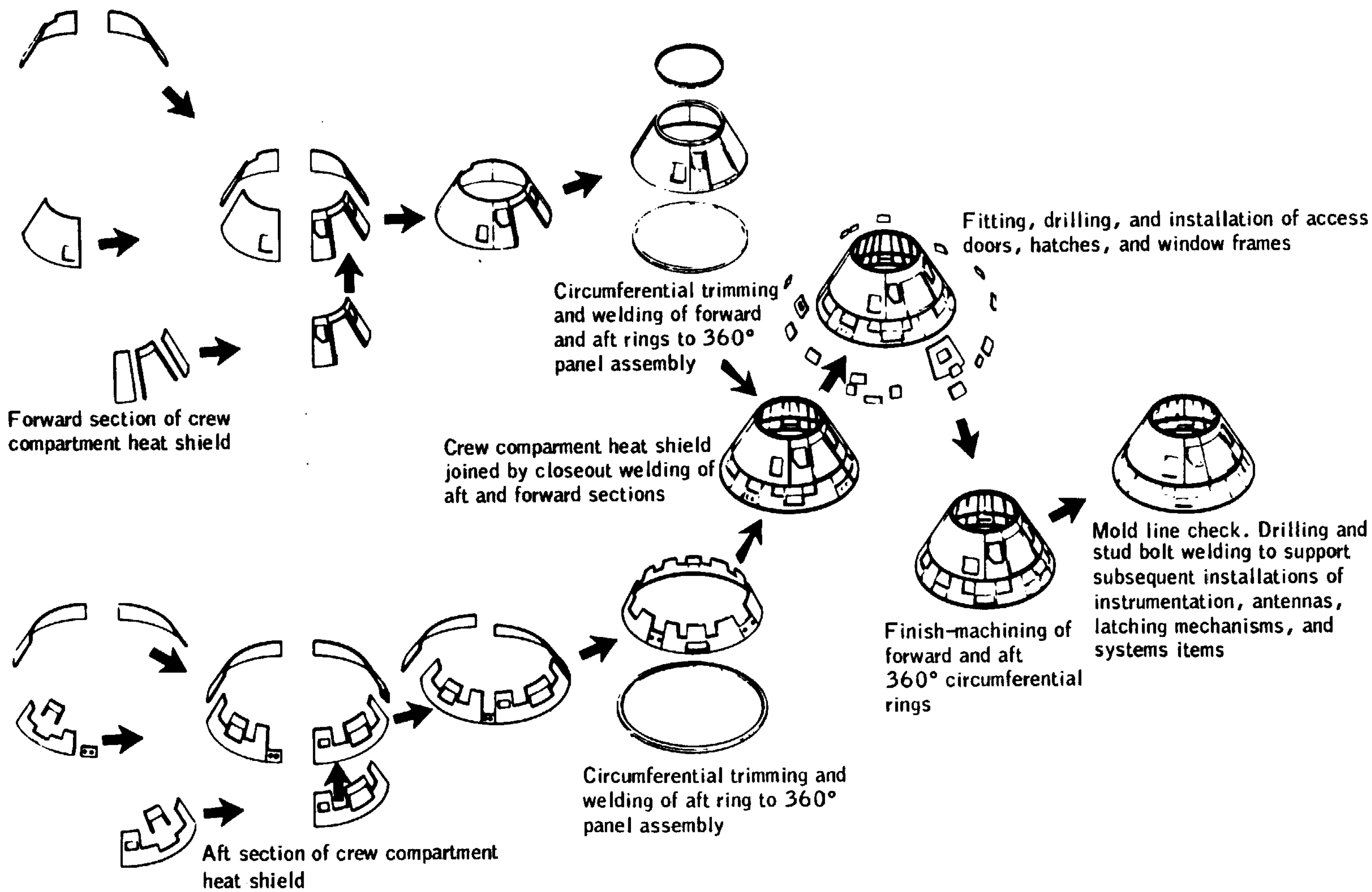

Figure 9-1.- Command module crew compartment heat shield assembly flow.

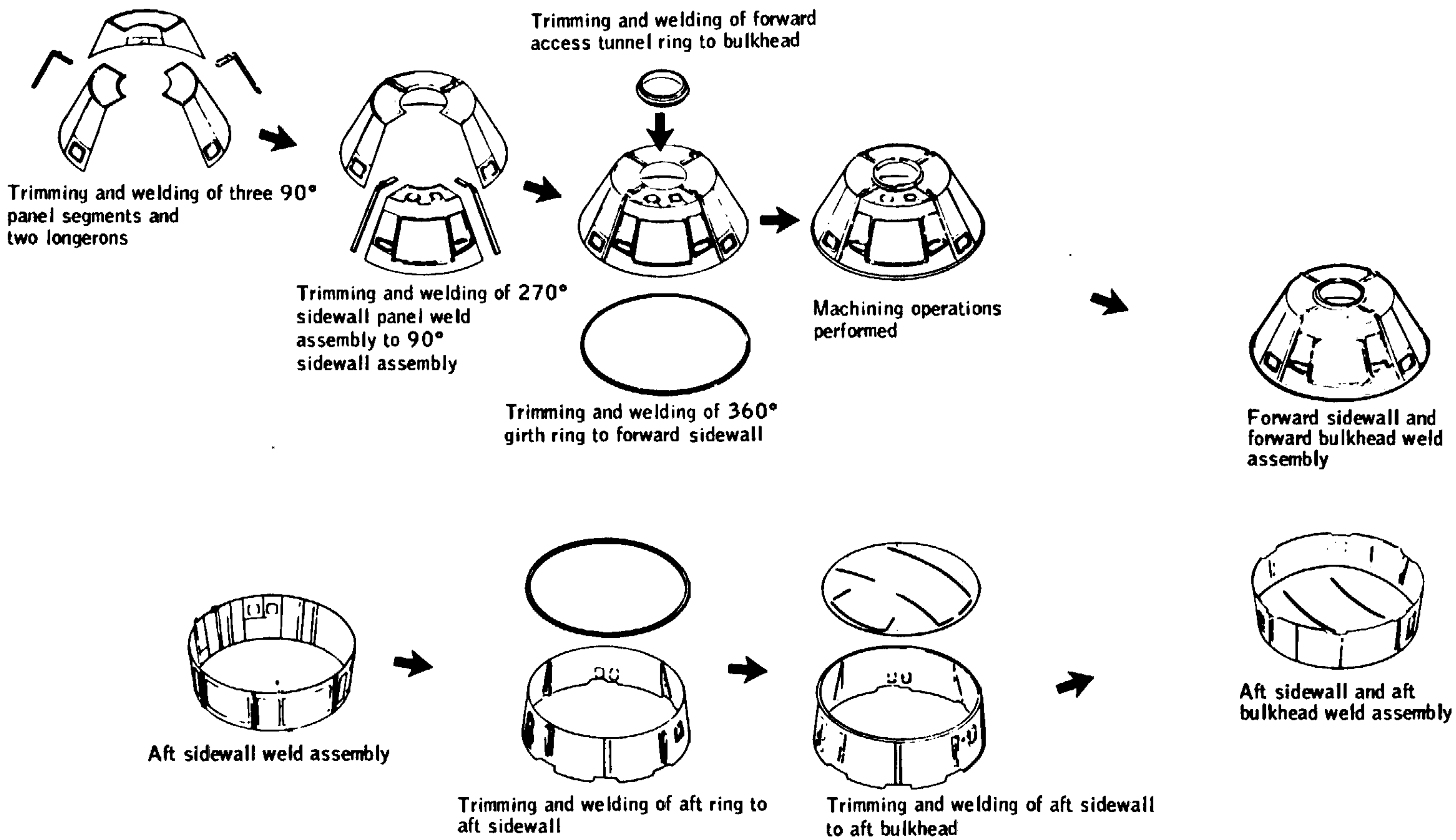

Figure 9-2.- Command module crew compartment structure inner shell assembly flow.

On completion of the structural assembly, the crew compartment was cleaned in a tumble-and-clean positioner and prepared for systems installation at an installation workstand. Systems were tested before installation in the spacecraft. All electrical systems, wire harnesses, and related wiring were then installed, and a high-potential test, a continuity test, and circuit analyzer tests were performed. Plumbing was installed, and flushed, purged and dried. The assembly was moved to pressure test cells where each fluids system was subjected to a complete performance and functional test series and verified if operational and within specified limits. This test series contained such operations as flow checks, leak tests, contingency and backup mode checks, regulator operation checks, proof checks, and instrumentation output checks. The assembly was then transferred back to the installation workstand for completion of systems installation.

When the electrical and fluids systems installations were complete, the crew compartment was connected to the service module and launch escape tower by cables (soft mate) for individual and combined systems tests. Throughout this period, each system was subjected to a series of carefully controlled functional tests that demonstrated proper operations. These tests established the performance data baseline to support all downstream test activities. The crew compartment was then placed in a workstand for installation of the heat shield, a fit check of the boost protective cover, installation of parachutes, a fit check of the crew couches, and final modifications, if necessary. This operation virtually completed the command module assembly.

9.1.1.3 Final operations.- In the final phase of command module manufacturing, the vehicle was cycled through another tumble-and-clean operation in which the vehicle was rotated through 360° in each axis to dislodge and remove debris. The weight and center of gravity were then determined, and the vehicle was subjected to an integrated test (sec. 9.1.5). The command module was subsequently moved to the shipping area and prepared for shipment. Such items as crew couches and crew equipment were removed, packed, and shipped separately.

9.1.2 Service Module Assembly and Checkout

In the service module manufacturing cycle, maximum use was made of jigs and fixtures to assure proper fit and clearance of all components and subassemblies and to provide good accessibility for removing, replacing, and interchanging components. A generalized flow through the manufacturing and assembly process is shown in figure 9-3.

Three major stands were used in the assembly flow. The primary structural assembly stand was used to assemble six radial beams to fore and aft bulkheads. To this structure were attached bonded-aluminum-honeycomb-structure equipment support shelves and other secondary structural attachment provisions for mounting of wire harnesses and tubing assemblies. In the next series of operations, the bonded-aluminum-honeycomb outer shell panels and reaction control system panels were prefitted and located, and the attaching holes drilled. Holes were then drilled for installation of tanks and other equipment.

The service module was then mounted to a support stand where command-to-service-module fairing panels and the aft heat shield were installed, and provisions were made for service propulsion engine installation. The weight and center of gravity were determined and axis markings were completed. The module was then cycled through the tumble-and-clean facility during which rotation through 360° in each axis was used to separate or dislodge any debris from manufacturing operations.

After being cleaned, the module was installed in a large workstand for systems installation. Components and systems installed included tubing, propellant storage and distribution systems, the cryogenic storage system, the service propulsion drain and vent system, the environmental control system, the helium pressurant system, the electrical power system, the main service module electrical harness, terminal boards, coaxial cables, and the lower engine bay structure. Low-pressure gross leak tests, flushing and cleaning of fluid lines, and automatic circuit analyzer checks were performed after installation but before electrical hookup.