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APOLLO EXPERIENCE REPORT - SYSTEMS AND FLIGHT PROCEDURES DEVELOPMENT

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16. Abstract

This report describes the process of crew procedures development used in the Apollo Program. The two major categories, Systems Procedures and Flight Procedures, are defined, as are the forms of documentation required. A description is provided of the operation of the procedures change control process, which includes the roles of man-in-the-loop simulations and the Crew Procedures Change Board. Brief discussions of significant aspects of the attitude control, computer, electrical power, environmental control, and propulsion subsystems procedures development are presented.

Flight procedures are subdivided by mission phase: launch and translunar injection, rendezvous, lunar descent and ascent, and entry. Procedures used for each mission phase are summarized.

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APOLLO EXPERIENCE REPORT

SYSTEMS AND FLIGHT PROCEDURES DEVELOPMENT

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SUMMARY

The participation of many engineering specialists was required to determine effective crew procedures because of the complex nature of the Apollo spacecraft systems and missions. Two distinct lines of procedural development were required. The first of these, systems procedures, encompassed all of the various systems operating modes and was generally independent of the mission plan. The second category, flight procedures, produced an optimum crew time line for each mission phase by incorporating mission constraints and requirements into appropriate system operating modes.

Verification of flight crew procedures was often accomplished simultaneously with crew training in man-in-the-loop simulators. Procedures in the final flight plans were further verified during simulations that involved the NASA Manned Space Flight Network and the Mission Control Center as well as the flight crews. Changes in procedures could be made during the mission definition phase, during the procedures verification phases, or within the final flight plans.

During the Apollo Program, it was found that a procedures control board was necessary to maintain correct crew procedures when changes were made in the mission and systems. The operation of this board ensured that every organization concerned with mission operations was provided with current and complete information on crew operation of the spacecraft, that all proposed procedural changes received a thorough review, and that management was provided with sufficient information concerning the number and nature of procedural changes.

During procedures development for the Apollo Program it was learned that the crew, given certain basic flight displays, could monitor and assess the performance of automated systems during normal operation; accomplish the primary mission objectives despite a variety of possible subsystem failures or degraded situations; and make real-time decisions during emergencies to abort the primary mission and return safely to earth, to accomplish alternate missions, or to continue the primary mission using manual backup techniques, thereby enhancing crew safety and mission success.

INTRODUCTION

The major contributors to this report and their respective areas of responsibility were: Charles C. Thomas, guidance and control systems; John F. Whitely, electrical power systems; David R. Brooks, communications systems; James L. Baker, environmental control systems; William A. Chanis, propulsion systems; Michael R. Wash, launch and translunar injection (TLI); Clark M. Neily, rendezvous; Charles O. Lewis, lunar descent/ascent; and James O. Rippey, entry.

Scope

The development of systems and flight procedures is described in this report, and the information gained through the period ending with the Apollo 11 mission is summarized. Detailed development, formats of flight plans, and procedures for photographic and extravehicular activity are beyond the scope of this report.

Definition of Systems Procedures

The operational modes of each spacecraft system were defined by NASA and prime contractor personnel during system design, development, and testing. Systems procedures were defined as the sequence of crew actions necessary to operate a spacecraft system. The systems procedures were compiled into a spacecraft operations handbook before mission plans were defined in detail. This handbook was a baseline or control document for Apollo missions, and it included modifications to systems procedures that were based on previous mission experience. Alternate modes of operation were described from which particular modes could be selected for specific mission requirements. Malfunction procedures also were developed, verified, and documented. These systems procedures were the building blocks for mission-dependent flight procedures and flight plans.

Definition of Flight Procedures

Flight procedures were defined as the timed sequence of all crew actions necessary to accomplish a particular mission task. Flight procedures prepared for time-critical or extremely involved crew activities were developed by combining systems procedures and specific mission requirements. Several iterations of the basic mission task were necessary to establish the detailed steps required of the crewmen and to ensure compatibility with available flight consumables. The flight procedures were highly dependent on the mission definition and were constrained by such factors as elapsed time, mission rules, and interactions of the different spacecraft systems. Separate flight procedures documents were published, and these documents formed the basis for the procedures included in the flight plan or in the onboard data for each Apollo mission. Appropriate systems procedures were combined for the normal mission profile and for contingency situations.

Definition of Flight Plans

Flight plans integrated the relevant systems procedures and flight procedures into an overall time line and schedule for the effective accomplishment of a specific manned space mission. Essentially, the flight plan provided the sequences by which separate tasks were performed and the schedule by which critical mission maneuvers were controlled.

PROCEDURES DEVELOPMENT TECHNIQUES

Because of its complexity and scope, the Apollo Program allowed more autonomy for the flight crew than had existed for the crews of previous space flight programs. Communications between ground control and the spacecraft would not be possible when the vehicles were behind the moon. Rapid flight crew decisions would be necessary in some situations in which neither adequate time nor complete information was available for ground-based decisions. As a result, the development of complete, accurate, and accessible flight crew procedures was vital for mission success.

The technique used to develop flight crew procedures was basically a progressive process. Systems operating procedures were provided by the equipment contractors. Flight procedures were developed from the systems procedures when all the goals, requirements, and trajectories of a specific mission had been established. Portions of the flight plan and the onboard data were developed from the flight procedures. The procedures were subjected to verification tests and simulations, were documented, and were rigidly controlled with respect to additions or changes. The flight crews were trained to follow the established procedures in the use of all systems and in the various mission phases.

Developmental Processes

Systems procedures. - A comprehensive knowledge of the specifications to which the equipment was designed and fabricated, of the limits on equipment applications, and of the operating configurations and sequences of the system was necessary to the establishment of operating procedures. Details on such activities as activating a system, performing the tasks necessary to operate a system in the correct sequence, and interpreting system-monitoring indicators were included in the operating procedures. Procedures for operating each spacecraft system were first written by the manufacturer of that system.

Systems procedures included normal/backup operational conditions of spacecraft systems together with abort, malfunction, and emergency operations. Frequently, backup procedures consisted only of activating secondary systems or backup equipment. Malfunction procedures, in particular, required detailed knowledge of the structure and operation of the system. Systems-failure modes for as many malfunctions as possible were grouped under the symptoms they could be expected to cause. Symptoms and failures were then grouped to facilitate location and correction of problems. Malfunction procedures were subjected to repeated reviews, tests, and simulations.

As systems operating procedures were developed for each Apollo spacecraft, they were reviewed by systems engineers and subjected to tests and systems-oriented simulations. Errors, equipment malfunctions, constraints, and gaps in the procedures were identified and either corrected or noted. The cycle of review, test, and amendment of systems procedures continued through the flight procedures development phase.

Flight procedures.- Flight procedures were, essentially, systems procedures applied to mission-oriented tasks, maneuvers, and trajectories. The development of flight procedures can begin only after the requirements, rules, and trajectories for a specific mission have been established. The flight procedures were developed on a step-by-step basis from the systems procedures and were timed and sequenced appropriately for each activity or phase of the mission. The preparation of flight procedures involved the generation of onboard charts, definition of propellant requirements, and performance of digital computer checkruns to confirm the feasibility and accuracy. The development process demanded attention to a wide spectrum of factors, such as mission goals and rules, constraints to the operation of individual systems and to the simultaneous operation of interacting multiple systems, time requirements for specific tasks, consumables budgets, most efficient maneuvering rates, and crew rest periods. Some of these factors imposed constraints on certain activities or conflicted with other factors. Such factors were subjected to additional analysis, testing, and reformulation of flight procedures.

Because of the variety of systems, crew activities, and mission factors to be considered, a broad span of skills was required for flight procedures development. Specialized knowledge and contributions were provided by systems engineers, systems analysts, mission planners, flight controllers, test and simulation specialists, and flight crews. Preliminary flight procedures were reviewed and tested repeatedly in man-in-the-loop simulations.

The activities for specific mission phases were checked out in mission-phase simulations and in integrated spacecraft systems simulators to establish flight procedure compatibility with the time to be available during the mission, variations in the mission (such as dispersed trajectories), and contingency situations resulting from degraded system performance or from failed components. Eventually, the Mission Control Center or other ground-support systems, such as the Manned Space Flight Network, were also included in the simulations.

As flight procedures became firmly established, they became the basis for flight crew training. The training activity, in turn, resulted in significant improvements and modifications to the procedures. The schedule for development of systems and flight procedures and the organizational relationships involved in the development are detailed in table I and in figures 1 and 2.

TABLE I. - MILESTONES FOR CREW PROCEDURES AND TRAINING

[Based on 4-month launch schedules]

Months before launch	Premission events	Systems procedures	Flight procedures	Flight plan	Crew training	Change control
12	Mission requirements defined	Apollo Operations Handbook (AOH) prepared	Reference trajectory analyzed			No change control during definition phase
11	Procedures documents listed					
10	Crew assigned				Part-task training and subsystem checkout performed	
9	Training plan issued	Basic AOH issued	Reference draft completed			Change control at branch level during validation phase
8	Stowage compartment review performed			First draft completed		
7	Integrated test and crew compartment fit and function validated	First revision of AOH completed	Preliminary draft completed	Reference flight plan issued		
6			Crew simulations performed	First draft verified		
5		Second revision of AOH completed	Preliminary procedures validated			
4	Spacecraft shipped to John F. Kennedy Space Center	Review and update of AOH continued as required	Crew simulations performed	Preliminary flight plan issued	Full-mission training and integrated checkout performed	Change control by Crew Procedures Control Board after validation of flight procedures
3	Altitude-chamber test completed		Final procedures issued			
2				Final flight plan issued		
1	Flight readiness review performed	Final issue of AOH issued				

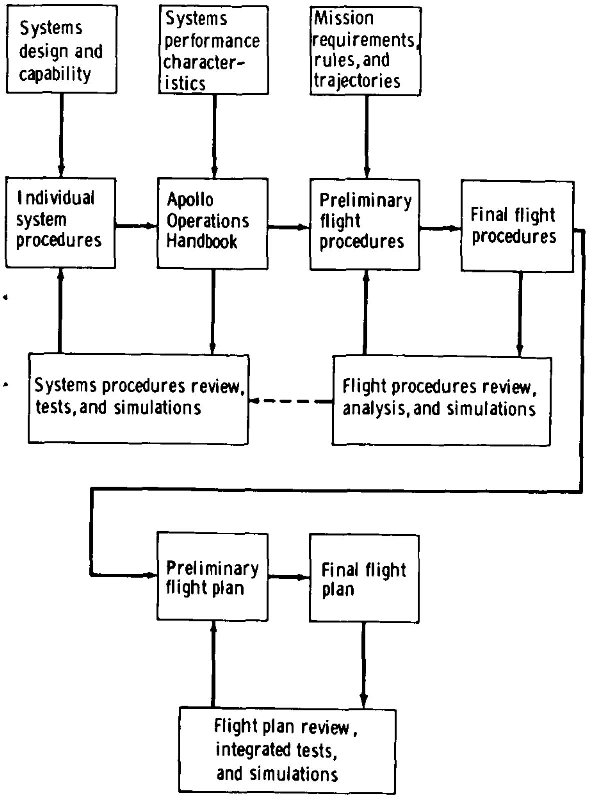

Figure 1. - Procedures development cycles.

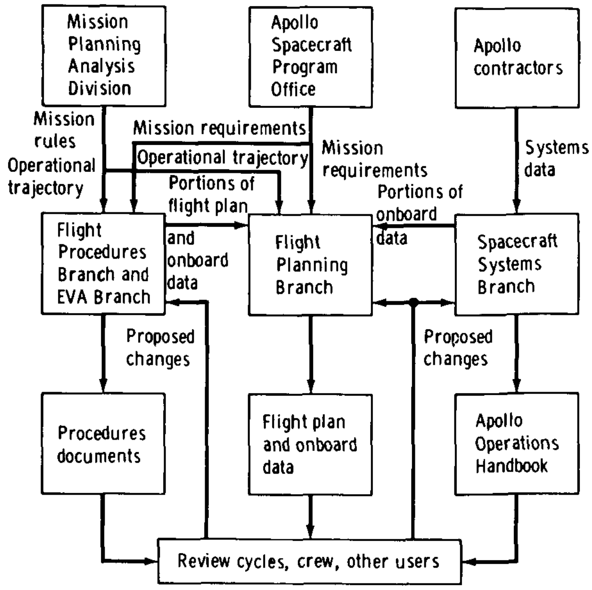

Figure 2. - Organization chart for development of Apollo flight plans.

Verification Processes

Verification of procedures continued throughout the procedures development process. During the design, fabrication, and testing of the spacecraft components and systems, test and simulation facilities were developed to establish systems procedures and operating characteristics.

The contractor suppliers of spacecraft systems developed important test and simulation facilities. A high-fidelity, digital simulation facility for flight computer programs was built in Cambridge, Massachusetts, to check out various digital routines, verify program modifications, and define operations for the use of the onboard Apollo computer. Major contractor simulation facilities also included the Mission Evaluator at Downey, California, and the Full-Mission Engineering Simulator at Bethpage, New York.

After individual spacecraft systems procedures were verified, simulations that combined two or more individual systems were conducted to verify the compatibility of the operational procedures of the combined systems. The facilities used to verify flight procedures are listed in table II.

Mission simulations with the Mission Control Center and the Manned Space Flight Network in the simulation loop verified flight procedures for critical mission phases and maneuvers. For example, air-to-ground communications were tested in a highly elaborate simulation that included ground-tracking coverage and network functions,

TABLE II. - FLIGHT PROCEDURES VERIFICATION FACILITIES

Procedure	Facility
Launch and translunar injection	Command module simulator (mission simulation) Dynamic crew procedures simulator
Rendezvous	Command module simulator Lunar module simulator (mission simulation) Command module procedures simulator Lunar module procedures simulator Docking trainer
Entry	Command module simulator Dynamic crew procedures simulator Command module procedures simulator
Lunar ascent	Lunar module simulator Lunar module procedures simulator Docking trainer
Lunar descent	Lunar module simulator Lunar module procedures simulator Lunar landing training vehicle

spacecraft trajectories, telemetry, up-link and voice communications, and all major spacecraft systems operations. The simulation was accomplished by coupling the Apollo mission simulator (the spacecraft simulator of the highest fidelity available) to a simulation of the Manned Space Flight Network. The Mission Control Center was used to verify the procedures and to provide training for flight crews and ground-support personnel. Additional verification of flight crew procedures was developed with the completion of each Apollo mission. Flight crew debriefings included the recording of crew procedures information that served as either a validation of the existing procedures or a basis for improvement of the procedures for the next mission.

Documentation

Systems procedures were developed, tested, and verified for each Apollo spacecraft and documented in the respective Apollo Operations Handbook (AOH). The operational procedures were organized within the handbook under normal/backup procedures and under contingency procedures. Abort, malfunction, and emergency procedures were subclassified under contingency procedures. The AOH was issued 9 months before a scheduled mission and was updated 7 months before launch.

Flight procedures were produced by integrating specific mission rules and requirements with the procedures from the AOH. Final flight procedures were developed for each mission phase, and the flight procedures for a specific mission were combined and integrated into the flight plan.

The number of mission phases covered by flight procedures increased as rendezvous and lunar activities were added to the mission goals. The flight procedures documents included launch-abort, rendezvous, lunar descent and ascent, and earth-entry procedures. To ensure the acquisition of useful documentation, it was essential that procedures be developed on a timely schedule. Preliminary drafts of the procedures were prepared for test and review cycles. Final procedures were prepared for crew training and for inputs to the data packages and checklists used on board the spacecraft. Flight procedures were validated 5 months before launch, and final documents were issued 3 months before launch. The preliminary flight plan was issued 4 months before launch, and the final flight plan was issued 2 months before launch. Onboard data packages used by each mission crew were prepared from the AOH, the flight procedures, and the final flight plans.

Change Controls

Crew procedures for operating spacecraft systems were closely interrelated and interdependent. Often, the changing of a certain procedure would affect other procedures, crew training, or activity schedules. As a result of this interdependence, overall control of procedural changes was critical. Three levels of procedures control were established: first, the branch chief of the organization responsible for a particular procedures document; second, the Crew Procedures Control Board; and, third, the Apollo Configuration Control Board.

For each proposed change, the branch chief responsible for the specific procedure provided relevant information from earlier manned space flights: the relationship between the proposed change and the existing procedure; definitions of any conflicts involving spacecraft capabilities, propellant budgets, mission rules, trajectories, or abort criteria or limits; and a plan for resolving any conflicts.

The Crew Procedures Control Board was authorized to approve changes that affected crew training schedules, onboard data packages, or mission simulators. The board, chaired by the Director of Flight Crew Operations, was composed of representatives from the Apollo Spacecraft Program Office and from each directorate of the NASA Lyndon B. Johnson Space Center (JSC), formerly the Manned Spacecraft Center (MSC). For the Apollo 11 mission, this board met weekly to consider proposed changes in crew procedures. The Apollo Configuration Control Board was responsible for authorizing any change that altered mission objectives; necessitated changes in spacecraft hardware or software; resulted in a change to a mission rule, trajectory, or limit line; increased a propellant requirement or spacecraft weight; or affected the launch schedule.

The normal Crew Procedures Control Board process proved adequate for review, approval, and implementation of proposed changes until approximately 1 month before launch. From then on there was insufficient time for the entire review process to be accomplished. The few changes proposed within the last month were transmitted directly to the Director of Flight Crew Operations, who was frequently in contact with the flight crew and key personnel from the other organizations affected. This method provided adequate consideration for all proposed procedural changes with minimal delay.

APOLLO OPERATIONS HANDBOOK

Detailed descriptive material on the spacecraft systems and equipment was published in volume 1 of the AOH. Volume 2, bound separately, contained basic flight crew procedures for operating all spacecraft systems. The prime contractors for the command and service module (CSM) and the lunar module (LM) prepared the initial operational procedures. Two issues of the handbook were produced and updated for each mission: one for the CSM and one for the LM. Each issue contained the two volumes described previously. The systems procedures in the handbook consisted of normal/backup procedures and contingency procedures. Normal procedures were used when all systems were operating properly. Backup procedures were applicable if a system failure or some other anomaly prevented the use of normal procedures. Contingency procedures consisted of actions to be taken for abnormal situations that might occur during the missions. These procedures enabled the crew to abort the mission, implement an alternate mission, or continue the planned mission under degraded conditions. The contingency procedures, consisting of necessary immediate actions and the limitations that might be imposed on subsequent activities from such actions, were divided into three classes: abort procedures (considered a specialized form of backup procedures involving early mission termination); malfunction procedures (encompassing recognition and diagnosis of system malfunctions and appropriate corrective action); and emergency procedures (procedures other than abort procedures that would require instant implementation if the crew were in immediate danger).

The AOH was written to accommodate differences in specific spacecraft. Changes and updates were made by changing pages or reissuing the entire handbook. The CSM handbook contained certain pages applicable only to specific vehicles or selected series of vehicles. Therefore, some pages were repeated in modified form to reflect material unique to specific vehicles. A manual for use on a specific vehicle could thus be prepared by supplementing a complete set of common pages with pages marked specifically for that vehicle. The LM handbook was similarly written.

Normal/Backup Procedures

Systems procedures for normal/backup operations were presented in the AOH in tabular form and in numerical sequence. An example of a page from the normal/backup procedures section of the CSM handbook is shown in figure 3(a). The column headings were STA/T (station/time), STEP, PROCEDURE, PANEL, and REMARKS. An example of the LM handbook format, which was slightly different from that of the CSM handbook, is shown in figure 3(b). The column headings were CREWMAN, PNL (panel), PROCEDURES, and REMARKS.

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APOLLO OPERATIONS HANDBOOK

STA/T STEP	PROCEDURE	PANEL	REMARKS
	4.20 POSTLANDING		
	4.20.1 POSTLANDING STABILIZATION		
LMP	cb MN REL (2) - close	229	
CMP	MN REL - on (up)	2	Guarded. On position is momentary. Releases main parachutes.
	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx		
	If no main chute release		
CDR	ELS AUTO - AUTO (verify)	1	Switch should have been on at least 14 seconds to allow timer to time out and enable MN REL switch.
	ELS LOGIC - on (up) (verify)		
CMP	MN REL - on (up)	2	
	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx		
	WARNING		
	• (Deleted)		
	• If fire or smoke after impact, refer to Fire/Smoke in CM During Postlanding, para 5.3.3.1.		
	(Deleted)		
CDR	DIRECT O2 vlv - close (CW)	7	Conserve remaining O2 and enable use of water gun.
	(Deleted)		
	SECS PYRO ARM (2) - SAFE	8	Lever lock.
	SECS LOGIC (both) - OFF		Lever lock.
	(Deleted)		

4.20.1 POSTLANDING

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(a) Command and service module.

Figure 3.- Example of normal/backup procedures in the AOH.

CREW-MAN	PNL	PROCEDURES	REMARKS
		4.2.12.5 Suit Fan Activation, Checkout, and Water Separator Check (cont)	
	2	4. ECS: PART PRESS CO2 ind - zero mm Hg	CO2 level is function of time that crew is on ARS. At initial ARS activation or following LiOH cartridge replacement, reading should be zero mm Hg.
	16	5. CB ECS: SUIT FAN 2 - open	
	1,2 1 2 1/2	6. MASTER ALARM - on SUIT/FAN warn lt - on SUIT FAN comp caut lt - on ECS caut lt - on H2O SEP comp caut lt - on MASTER ALARM pb/lt - reset	When suit fans are deactivated, water separator will slow down, causing delayed activation of ECS caut lt and H2O SEP comp caut lt. Time for water separator to slow down is approximately 15 seconds when wet; 2.5 to 3 minutes when dry. ECS caut lt and H2O SEP comp caut lt go off when selected water separator comes up to speed, approximately 1 minute when dry; 15 minutes when wet.
	ECS	7. WATER SEP SEL vlv - PUSH SEP 1	
	11	8. CB ECS: SUIT FAN 1 - close	
	2	9. SUIT FAN sel - 1	
	1 2	10. SUIT/FAN warn lt - off SUIT FAN comp caut lt - off ECS caut lt - off H2O SEP comp caut lt - off	
	16	11. CB ECS: SUIT FAN 2 - close	
		4.2.12.6 O2 Demand Regulator Checkout WARNING This procedure requires 2.2 to 2.5 pounds of oxygen to be dumped overboard. This checkout must not be performed when staged. It may be performed (using descent oxygen) when unstaged only if dumping 2.2 to 2.5 pounds of oxygen overboard does not compromise the mission.	Assumption: ARS/PGA Pressure Integrity Check (para 4.2.19) has been performed. If CB ECS: CABIN FAN - open, references to cabin fan do not apply.

(b) Lunar module.

Figure 3. - Concluded.

Explanations of the column headings are as follows.

1. The term STA (or CREWMAN) designated the crewmember assigned to the spacecraft location where the procedure or step was performed. Station CDR, CMP, and LMP represented the commander, the command module pilot, and the lunar module pilot, respectively, and corresponded to the left, middle, and right positions of the crewmen in the vehicle. The designation CMP also pertained to the activities performed in the lower equipment bays, which were inaccessible to the other crewmembers. The time column (T) contained mission time, event time, or altitudes.

2. The term STEP designated the numerical position of elements within a sequence of events forming a complete procedure. The LM handbook did not show step numbers in a separate column.

3. The term PROCEDURE was used to designate the group of steps or the overall task involved in performing a complete function or operation. The CSM backup procedures relative to a preceding step were indicated with a perimeter of X's around the backup procedure. The LM backup procedures consisted of alternatives listed in the same procedure.

4. The term PANEL was used to designate the particular control or display involved in a given procedure by number. For example, in the CSM, the main display console panels were numbered from 1 to 12. The panels in the lower, right-hand, and left-hand lower equipment bays were numbered from 100 to 164, 225 to 278, and 325 to 382, respectively. Charts of all panel control locations were included as an appendix to the handbook.

5. The term REMARKS was used to provide the rationale and explanations for the particular procedure. Remarks considered important to the performance of procedures were generally included in the PROCEDURE column as WARNING or CAUTION notes, depending on the severity of the situation. In some cases, a remark was labeled NOTE.

Volume 2, containing overall coverage of the procedures with supporting rationale, became the repository of comprehensive systems procedures and was used as a reference base line for the abbreviated checklists and for the use of support personnel recently assigned to the program. The CSM systems procedures were written concerning the subjects listed in table III.

TABLE III. - HANDBOOK CONTENTS FOR CSM SYSTEMS PROCEDURES

Subject	Typical no. of pages
Backup crew prelaunch checks	34
Prime crew prelaunch checks	17
Boost and insertion	17
Lunar module interfaces	59
Rendezvous	73
Systems management	101
Guidance and control reference data	53
Guidance and control reference modes	25
Guidance and control general procedures	53
Alinements	39
Coasting	23
Orbit change vehicle preparation	2
Guidance and navigation orbit change	33
Stabilization and control system orbit change	17
Deorbit and entry of lunar-return-entry vehicle preparation	15
Guidance and navigation deorbit and entry	57
Stabilization and control system deorbit and entry	25
Earth-landing phase (less than 50 000 ft)	7
Postlanding	13
Mission test requirements	1
Abort procedures	50
Malfunction procedures	83
Emergency procedures	21
Total	818

Malfunction Procedures

Malfunction procedures were used by the crew to correct or isolate off-nominal conditions, which were indicated by displays, caution and warning lights, or the absence of a scheduled function or event. Where the procedures for multiple or complex symptoms would become too numerous and unmanageable, malfunction procedures were usually designed to cover significant single symptoms.

Malfunction procedures were presented in logic-flow diagram format and were arranged by symptoms, as shown in figure 4. The primary malfunction procedures (symptom routines) were supplemented by special subroutines and system-reconfiguration subroutines where necessary. A three-column format was used for symptom-routine, logic-flow diagrams.

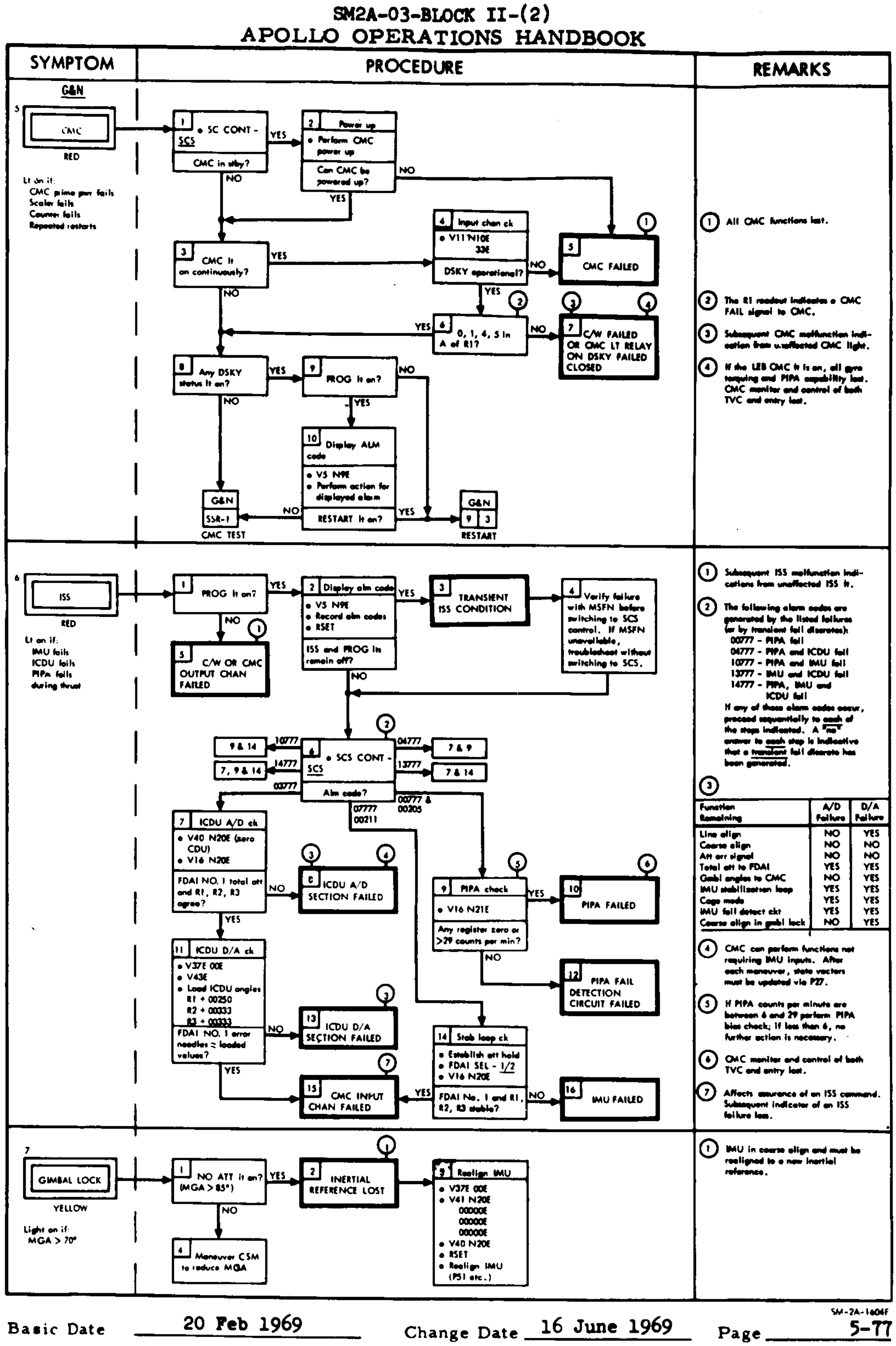

Figure 4. - Example of malfunction procedures in the AOH.

Emergency Procedures

Emergency procedures were provided for quick alleviation of flight-hazardous or time-critical situations. Ordinarily, an emergency condition would be physically sensed by the crew, rather than being brought to their attention by warning signals or by voice communications from the mission controllers. Emergency procedures were prepared for the following possible problem areas.

1. Prelaunch emergencies that required rapid hatch opening

2. Flight emergencies including fire or smoke in the command module (CM) during boost, orbit, or entry phases; contamination in the CM; contamination in the suit while being worn by the crewman; failure of the launch escape tower to jettison; reinstallation of the forward hatch impeded; premature emergency safing of apex-cover jettison; one couch Y-strut not fully extended or locked; and failure of the CM reaction control system (RCS) to pressurize or to provide propellant

3. Postlanding (earth) emergencies involving fire or smoke in the CM

Lunar Module Malfunction Procedures

The original LM malfunction procedures prepared by the contractor were arranged in a four-column format (SYMPTOM, FAILURE, PROCEDURES, and REMARKS) similar to that used on Gemini missions. In a review of Apollo procedures, it was found that the direct location of failures was not always possible after an indication of a failure was received. The crewman had to perform several procedural steps before the possible causes of a failure could be separated. Therefore, a new format was devised by rewriting a sample malfunction procedure. The columns of the format were rearranged to read SYMPTOM, PROCEDURE, NEXT STEP, REMARKS, and FAILURE. Later, the format was further changed from a line-by-line to a block format.

After the format was changed, an extensive effort to write a complete set of malfunction procedures for the LM was begun. The contractor made a parallel effort. It was decided that, to cover every situation completely, all symptoms that could be detected should be listed. In addition, every possible failure and the resulting symptom should be listed for each component. The two lists should then be combined to group each possible failure under the appropriate symptom.

Because of redundancy, however, some component failures would not result in failure symptoms; likewise, a certain symptom was possible, although no failure existed that could produce the symptom. For example, a cold soak in a pressurized ascent propulsion system would not cause a low ullage-pressure reading (because the regulators would make up the pressure), but a low-pressure reading would occur if the ascent propulsion system were unpressurized.

Another area in which procedures were documented was that of the LM checklists or, more correctly, the LM onboard data. The onboard data were prepared from procedures in the handbook and were tailored for each specific mission. It was most important that the onboard data be available for review by systems engineers for technical accuracy and consistency, which constituted the greatest problems in procedures preparation. Availability of the onboard data and coordination between the systems engineer, the crewman, the hardware engineers, and the flight controllers greatly reduced these problems.

SYSTEMS PROCEDURES

The procedures for the use of the spacecraft systems were, by definition, independent of the type of mission and were developed through an evolutionary process of design, analysis, and use. Unforeseen problems and unique situations that occurred during testing and operations resulted in corrections or changes in the systems procedures and, in some cases, improvements or changes in the hardware configuration.

Procedures were written to describe flight crew operations for each of the major systems of each spacecraft. The spacecraft systems procedures and the major problems encountered in their development are described in the following sections.

Attitude Control

Orbital operations. - Orbital operations included rendezvous and optics tracking. Rendezvous required both coasting flight and RCS thrusting. Automatic attitude control was normally used for main-engine burns in rendezvous operations; however, manual override was made possible by moving the attitude controller out of detent. For RCS thrusting, automatic pointing was available only for rotation to the initial ignition attitude. The digital autopilot attitude-hold mode controlled the spacecraft attitude during RCS maneuvers. Pulse-mode control of coasting flight during rendezvous was used to conserve propellant and because rapid, precise maneuver changes were rarely required.

Lunar descent. - The lunar landing presented several unique problems that required special consideration in the development of attitude control.

1. During descent, freedom to rotate the LM around the thrust axis (X axis) was necessary to provide downward and upward visibility and to adjust the attitude of the antenna for optimum communications with earth. To satisfy this requirement, the yaw channel of the rotational controller was made active while the remaining channels remained under automatic attitude control. Because the attitude was constrained at lower altitudes to ensure landing radar lock, automatic attitude control was available only at altitudes above 30 000 feet.

2. The capability to redesignate the location of the computer-stored landing site was incorporated into the attitude control system to provide terrain avoidance without switching out of the automatic mode. Redesignation was accomplished by moving the controller out of detent in the pitch axis for up-range or down-range movements, and out of detent in the roll axis for lateral movements. The computer interpreted each detent signal as a target position increment and initiated the proper attitude commands.

3. During final descent, the sink rate could be controlled by a rate-of-descent mode, which maintained a fixed vertical component of velocity. The components were in 1-ft/sec intervals and were controlled by means of the rate-of-descent switch. The manual attitude control (using the attitude-hold mode) was used to control forward and lateral velocity during the final descent.

4. The normal attitude-hold mode, in which the throttle controls the percentage of thrust, was also available during descent.

An undesirable design characteristic of the LM digital autopilot was that, at lunar touchdown and thrust termination, the attitude jets fired automatically in an attempt to return the LM to the pretouchdown attitude. Workaround procedures and software fixes were implemented to correct this firing problem. On the Apollo 11 mission, the flight crew moved the hand controller momentarily out of detent immediately after the LM had settled on the surface, thus sending a discrete signal to the computer, which established a new attitude reference and terminated thruster activity. For subsequent missions, a software change that accomplished the same purpose by means of a keyboard entry was implemented to simplify the procedure.

Entry. - Development of attitude control for earth entry presented a unique problem because of vehicle dynamics introduced by aerodynamic forces. Although the configuration of the CM was stable and tended to trim in two axes, the damping ratio was low. Therefore, the main control-system requirement in pitch and yaw was to damp oscillatory motion. Cross-range and down-range locations of the landing point were controlled by rotating the aerodynamic lift vector out of the entry plane; thus, an attitude-hold mode was required in the roll axis. The normal attitude-control mode for entry was fully automatic. The preferred backup to the automatic mode was manual damping of pitch and yaw oscillations by means of rate-command and manual control of roll attitude with the attitude-hold mode.

Platform alinement. - Optics-tracking modes were designed to include accurately controlled rotations for pointing the optics at selected stars, closing on a drifting rendezvous target, or locating landmarks. Automatic maneuvering to point the optics at preselected stars was desirable to conserve propellant and to minimize the time required to locate stars for platform alinement. Because landmarks passed from horizon to horizon at a nonlinear rate, a special automatic pointing capability was added to the CM for tracking landmarks from low orbits. Typical tracking rates varied from near 0 to 5 deg/sec during a single pass. The automatic capability was achieved by use of the knowledge in the spacecraft computer concerning the location of the landmark relative to the inertial guidance frame. The attitude of the CM was changed automatically to point the optics along the computed line of sight. The only task remaining for the crewmen was removing any error encountered in pointing with the optics controller. A list of the preferred attitude-control modes for each major function of orbital flight is shown in table IV.

A technique for orienting the spacecraft to a known inertial attitude and alining the reference system to the spacecraft was developed for use in the event that the CM onboard computer failed. The procedure for orienting the spacecraft was to set the optics to a fixed position and then to maneuver the spacecraft so as to center two known stars in the crosshairs of the scanning telescope.

TABLE IV. - ORBITAL-ATTITUDE-CONTROL MODES

Requirement	Preferred control mode (a)			
	Automatic	Attitude hold	Pulse	Direct (manual)
Rotation to thrust attitude	1	4	2	3
Translation using main engine	1	2	(b)	3
Translation using reaction control system	(c)	1	(b)	2
Braking and line-of-sight control	(c)	1	(b)	2
Boresight on target vehicle	3	2	1	4
Track landmarks	1	3	2	4
Rotation to track stars	(c)	2	1	3

[a]Numbers indicate order of preference.

[b]Not used.

[c]Not available.

The normal procedures for the alinement of the inertial measurement unit on the lunar surface required a high degree of crew participation. The procedures involved the use of a pair of telescopic sightings of each of two stars, and, to minimize operator error, repetitive sightings on each star. A faster technique for alinement was needed to expedite emergency lift-off procedures in a time-critical situation. The following methods were investigated: use of a star and gravity, use of previously stored attitude and gravity, and use of a ground-calculated alinement matrix and gravity. The star-and-gravity method was rejected because a telescopic star sighting was required. The stored-attitude-and-gravity method, although requiring little crew participation, was rejected because the stored attitude would not be retained by the computer during power-off operations. The ground-calculated-matrix-and-gravity method was adopted because it required only a minimum of crew participation and also offered flexibility: any number of usable matrices could be calculated and transmitted from the earth to the LM computer. Use of a ground-calculated alinement matrix and gravity permitted the crew to devote more time to activating ascent consumables such as electrical power, water, oxygen, and propellants. After the data up link was completed, the crew selected the alinement programs and completed the alinement with minimum effort.

Computers

The methods by which various parameters were put into the guidance computer and displayed to Apollo crewmen were as follows.

1. Inputs could be made through such cockpit controls as switches and hand controllers, either as discrete signals or as analog inputs to a digital-conversion device.

2. Inputs could be made directly, in alphanumeric form, through the computer keyboard.

Examples of unique input devices are the MARK and MARK REJECT buttons for star or landmark navigation sightings; the rate-of-descent switch for incrementing or decrementing the descent-rate counter; and the landing-point-designator function of the hand controller, which caused the computer to redesignate the location of the lunar landing site. The flexibility provided by the facility for making direct inputs through the keyboard was a valuable feature in Apollo guidance procedures. Problems were solved, and changing requirements were met with procedural changes or with inexpensive software changes, rather than with costly hardware changes.

Information from the Apollo guidance system was presented to the flight crews by one of the following methods.

1. A display in numerical form on the computer keyboard

2. Lights illuminated by computer-generated discrete signals

3. Analog displays driven by computer information

Alarm codes. - The computer program for the LM contained almost 100 different alarm codes that could be displayed by the keyboard to indicate a procedural or system deviation to the crew. The alarms were divided into routine and priority groupings. A routine alarm was indicative of a non-time-critical situation and illuminated a PROGRAM light, rather than removing the displayed information from the keyboard. The crewman would later call the alarm for display and diagnosis. A priority alarm flashed the PROGRAM light immediately, removed any previously displayed data from the keyboard, and notified the crew whether the alarm condition caused a software restart, termination of the current program, or neither.

Fault detection. - The possibility of error existed for any onboard computer function. The principal causes of these errors were computer hardware failures, input data error, and algorithmic error (from such functions as roundoff and quantization). The first category of error, hardware failure, was detectable by means of several methods, including the caution and warning system, computer status lights, and a computer self-test. Input data errors and algorithmic errors were not so easily detected, and one or more methods of cross-checking were necessary to verify computed results. In the case of the LM backup guidance computer, computed results were compared with predetermined threshold values. This comparison had the disadvantage of requiring that the crew procedures be lengthened to include reading out and verifying computed quantities. For example, the procedure for calibrating gyroscopes and accelerometers required read-out of 12 quantities for verification purposes. This activity was not essential to performing the calibration function but was necessary only to guard against error. Furthermore, the time required for this method precluded its use in time-critical situations.

The primary guidance computers used a more complex implementation of cross-checking. The threshold values were internally stored, and the computer performed the comparison automatically. Although requiring more computer memory, this implementation was much faster than read-out verification, which allowed its use in time-critical situations, and relieved the crew of performing tasks not essential to a mission function. However, even these more complex techniques were incomplete. The error information displayed to the crew was in cryptic form, so that once the system detected an error, the crew was still faced with the task of interpreting the error information. It was necessary during Apollo flights to spend considerable time and effort in generating and maintaining error-interpretive aids, including malfunction procedures and alarm-code decals. More importantly, a considerable portion of crew training time had to be devoted to exercising and refining these aids. Most, if not all, of these aids could have been programed into the computer. This procedure, which would have relieved the crew of the task of interpreting error information, would have shortened training time and would have been valuable in time-critical situations.

Electrical Power

Displays. - Onboard displays of current and voltage statuses were needed to monitor the performance and condition of spacecraft batteries and fuel cells. The displays in the Apollo spacecraft are summarized in table V. Fuel cells required other onboard displays in addition to current and voltage. The flight crews monitored the quantities and pressures of the cryogenic reactants to assess the integrity and performance of the reactants supply system. Internal fuel cell reactant pressures, pressure differentials and temperatures were used by the flight crews in determining fuel cell condition.

Voltage and current read-outs for the main power-distribution buses were most desirable; however, monitoring of these displays by the flight crews had to be time-shared and was often relegated to system-management periods. Thus, an alarm or warning signal was needed to inform the flight crew of an out-of-tolerance main-bus voltage. Power-source characteristics made an alarm necessary only for undervoltages. The requirement for immediate corrective actions resulted primarily from the sensitivity of most guidance-system components to low voltages. The onboard assessment of the Apollo main-bus load-sharing and possible malfunction analysis of shorting on main buses was hampered because main-bus currents were not displayed.

TABLE V.- ELECTRICAL POWER SYSTEM DISPLAYS

Parameter	CSM	LM
Power distribution		
Direct-current amperage	No	No
Direct-current voltage	Yes	Yes
Direct-current low-voltage light	Yes	Yes
Alternating-current amperage	No	No
Alternating-current voltage	Yes	Yes
Alternating-current low-voltage light	Yes	Yes
Alternating-current high-voltage light	Yes	No
Alternating-current overload light	Yes	No
Alternating-current frequency	No	No
Battery to main-bus light	No	No
Power conversion		
Inverter current	No	No
Inverter voltage	No	No
Inverter temperature	Light only	No
Battery-charger current	Yes	(a)
Battery-charger voltage	Yes	(a)
Power supply		
Battery current	Yes	Yes
Battery voltage	Yes	Yes

[a]Not applicable.

Procedures.- Apollo spacecraft displays were most useful when the power for the displays and the power for the functions came from separate sources. Power for the fuel cell radiator bypass valve and for the display indicating the position of the valve was supplied from the fuel cell radiator circuit breaker as shown in the upper portion of figure 5. To protect against closure of the fuel cell radiator bypass valve by inadvertent bumping or vibration of the fuel cell radiator bypass switch, a crewman opened the fuel cell radiator circuit breaker. With this circuit breaker open, however,

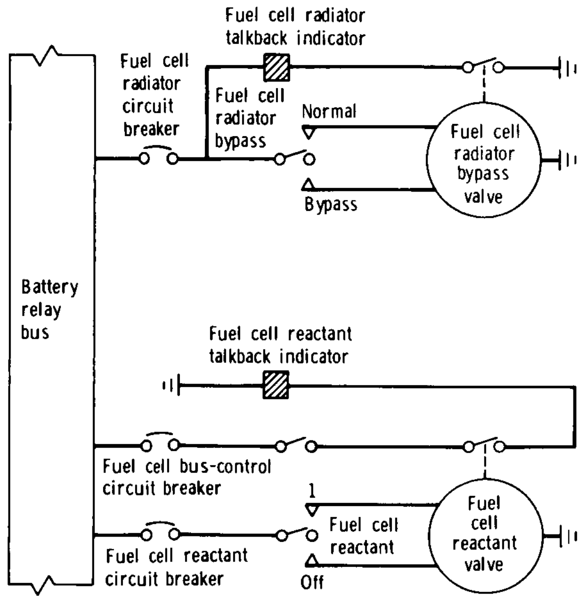

Figure 5. - Example of Apollo electrical power displays.

power was also removed from the display that indicated a successful power transfer. Inverters had caution and warning sensing circuits that initiated alarms if the inverter transfers were not correct. However, when the spacecraft batteries were connected to the main buses with motor switches, no indications of the transfer were available. During critical phases of the mission (such as the entry), voltage or current readings were monitored by the crewmen to ensure that appropriate power transfers were accomplished.

Environmental Control

Operation. - Environmental control for the CSM consisted of regulating the pressure and temperature of the cabin and suit gases; maintaining the desired humidity by removing excess water from cabin and suit gases; controlling the level of contamination of the gases by removing carbon dioxide, odors, and particulate matter; and ventilating the cabin after landing. During the boost phase, the cabin was vented to a total pressure of less than 5.6 psia. An inflight oxygen purge through an overboard vent resulted in an oxygen enrichment of the cabin.

The flight crew was fully suited during launch and critical mission phases; however, the shirt sleeve suit configuration was used for other phases, including entry. Though it was originally planned to disconnect the suit oxygen umbilicals at the environmental control unit (ECU) hose-connector assembly during suit-doffing operations, tests revealed that the hose disconnect and reconnect forces were of sufficient magnitude that the crew's ability to perform this task at zero g was questionable. The oxygen-supply ports of the ECU hose-connector assembly (suit hoses disconnected and the control lever in the cabin flow position) were so noisy that intercrew communications during the unsuited mode were difficult or impossible. It was found that leaving all suit hoses intact at the ECU connector assemblies and disconnecting at the pressure suit lowered the noise level by 6 to 8 decibels in the speech-interference range. Procedures were prepared to keep the suit hoses connected to the panel assemblies at all times except during doffing (when suit oxygen hoses were disconnected). Suit-donning time in the event of emergency was minimized, and the integrity of the suit hose and panel-connector-assembly interlocks was maintained, as verified by prelaunch ground tests. Inflight use of cabin fans for forced convection was not required because cabin air was drawn into the suit circuit, thereby controlling the cabin humidity, temperature, and level of carbon dioxide. The suit fans were active during all mission modes.

Water management consisted of collecting, sterilizing, and storing potable water produced by the fuel cells. The water was delivered chilled or heated for crew consumption. The excess potable water was either transferred to the waste water system for boiling or dumped overboard. The water was chlorinated periodically during flight to control bacterial growth.

The CM was designed to provide a comfortable environment for a 48-hour period after splashdown. Two electrically actuated gate valves located in the tunnel area were opened after splashdown. A fan on the intake valve provided forced cabin ventilation, and air was vented overboard through the exhaust valve. A distribution duct was affixed to the main-display-console outlets to provide individual cooling ports for each crewman. The inlet and outlet gate valves were automatically closed if the spacecraft attitude allowed sea water to enter the cabin.

Problem areas. - Relatively few problems were encountered in environmental control system procedures with the Apollo spacecraft. The following are examples of some problems and solutions.

1. Buildup of hydrogen gas (generated by the fuel cells) within the CM environmental control system presented two potential problems during early Apollo flights: diffusion of hydrogen collected in the water tank through the bladder into the oxygen pressurization gas, and hydrogen gas in the drinking water during closed-loop suit operation. The first problem was corrected by providing a very low continuous purge (0.032 lb/hr) of the bladder pressurization gas. The second problem was solved by introducing operational procedures to purge the suit circuit with 100-percent oxygen, thereby reducing the hydrogen concentration level by venting any hydrogen buildup into the larger cabin volume. In addition, a hydrogen separator was added to the water subsystem.

2. The CM cabin fans are not required for forced air convection at zero g. Because of excessive acoustic noise, the fans have not been operated on lunar missions. The exhaust oxygen hose (shirt-sleeve mode) provides adequate mixing of cabin gases and may be used to eliminate local areas of condensate buildup.

3. The CM cabin heat exchanger is ineffectual in controlling the cabin temperature. The thermal lag is of such a duration that the cabin temperature control exercised by the heat exchanger is masked by other thermal effects. It was determined that cabin temperature is a function of the spacecraft power load and vehicle attitude.

4. Inspiration of toxic fumes during CM RCS propellant burnoff and dump (after main-parachute deployment) was considered a hazard to the flight crew. It was planned that the crew remain fully suited with a suit pressure slightly higher than cabin pressure to preclude inspiration of these fumes. In-flow valves were cycled to prevent fume entry into the cabin. It was determined that the contaminant level is slight; normal entry without the pressure garments has been demonstrated.

Propulsion

Operating procedures were essentially completed before the first manned flight; however, hardware development and testing necessitated procedural changes. The following is a summary of some of the procedural changes.

1. The service propulsion system (SPS) (fig. 6) had redundant propellant supply paths (bores). Before the first manned flight, the decision was made to operate the systems in the dual-bore mode for critical burns such as deorbit. Because the engine had been tested using only the single-bore mode for starts, additional tests were necessary. The data from these tests uncovered a potential problem: considerable overshoot (overpressure) in the thrust level at ignition was experienced when the dual-bore mode was used for starts, and the increased thrust levels could induce loads into the spacecraft-tunnel interface that would exceed design limits for docked burns. The operating procedures were then changed to start the engine by using the single-bore mode and to open the redundant bore several seconds later.

2. The propellant utilization and gaging system in the SPS provided the crew with read-outs of oxidizer and fuel quantities and with an indication of propellant unbalance. By use of an oxidizer flow-control valve, the crew could correct propellant unbalance once it occurred. To check this system adequately, a long-duration burn of the service propulsion engine was required. No long-duration burns were planned during the Apollo 7 flight, and the system was deactivated on the Apollo 8 flight because of a sensor failure. The system was not checked until the Apollo 9 and 10 flights. During these flights, two problem areas were discovered: a time delay, incorporated in the system to allow the propellants time to settle before the quantity was displayed, was insufficient; and a bias input to the system, to correct for an inherent problem and unexpected fluid-flow characteristics, resulted in erroneous propellant quantity and unbalance read-outs for the flight crew. The operating procedures were changed; and, by the time of the Apollo 11 flight, the procedures were well defined.

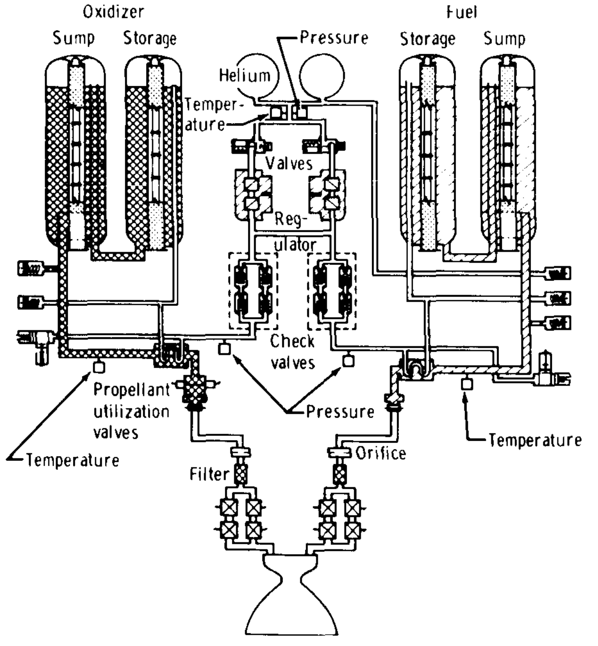

Figure 6.- Apollo SPS.

3. The flight combustion-stability monitor was incorporated into the original design to protect the SPS against rough or unstable ignition. The monitor would cause automatic engine shutdown should ignition problems develop. Before the Apollo 7 flight, the engine injector was redesigned, and the problem of unstable ignition was virtually eliminated. The procedures for using the monitor were changed, and the automatic shutdown mechanism was disabled for the first three manned flights. The entire monitor was removed from later spacecraft.

In several instances, hardware was developed and tested with incomplete knowledge of how it would be operated, resulting in restrictions and limitations on the operation of the propulsion systems. For future programs, every effort should be made to have all systems totally operational during the early system-evaluation flights. Full fuel loads and burns of adequate length should be planned to verify both hardware and procedures.

FLIGHT PROCEDURES

The developmental techniques used to prepare flight procedures documents have been discussed in a preceding section of this report. The preliminary and final editions of each type of flight procedure for the manned Apollo missions are listed in table VI.

TABLE VI. - FLIGHT PROCEDURES PUBLICATION SCHEDULE

Document	Edition of document	Publication dates by mission (a)				
		Apollo 7 (Oct. 11, 1968)	Apollo 8 (Dec. 21, 1968)	Apollo 9 (Mar. 3, 1969)	Apollo 10 (Apr. 18, 1969)	Apollo 11 (July 16, 1969)
Abort summary	Preliminary	Nov. 15, 1967	Oct. 11, 1968	Nov. 25, 1968	Feb. 3, 1969	Mar. 17, 1969
	Final	Apr. 15, 1968	Oct. 29, 1968	Jan. 17, 1969	Mar. 17, 1969	May 22, 1969
LM rendezvous procedures	Preliminary	(b)	(b)	June 13, 1968	Feb. 1, 1969	Mar. 17, 1969
	Final			Dec. 3, 1968	Mar. 17, 1969	May 16, 1969
CSM rendezvous procedures	Preliminary	Apr. 29, 1968	(b)	July 19, 1968	Jan. 23, 1969	Mar. 17, 1969
	Final	June 21, 1968		Feb. 1, 1969	Mar. 17, 1969	May 15, 1969
Lunar descent and ascent procedures	Preliminary	(b)	(b)	(b)	Feb. 12, 1969	Mar. 17, 1969
	Final				Mar. 17, 1969	May 22, 1969
Entry summary	Preliminary	Mar. 6, 1968	(b)	Aug. 19, 1968	Jan. 20, 1969	Mar. 17, 1969
	Final	June 24, 1968	Oct. 29, 1968	Dec. 23, 1968	Mar. 17, 1969	May 15, 1969

[a]Numbers in parentheses are mission launch dates.
[b]Not applicable.

Launch and Translunar Injection

Launch into earth orbit. - The Saturn launch vehicles were designed specifically for manned space flight, and system redundancy was designed into all parts of the vehicle. The primary crew task during the launch phase was to monitor the space vehicle for failures that might affect crew safety or mission success. A decision to abort the mission manually would have to be based on reliable data; therefore, detailed analyses of failure mode effects on all vehicle systems were formulated and evaluated by an inter-Center crew-safety panel. Limits were defined for spacecraft attitude, rate of change in attitude, and error of attitude readings. Limits were set for the angle of attack of the spacecraft to give the crew an adequate warning of possible structural breakup. In case of breakup, the crew would initiate abort procedures manually.

The important system parameters were monitored by ground-support personnel by telemetry. The time required for ground response was at least 15 seconds. This delay and the lack of some telemetry were acceptable for measuring and responding to slow deviations in attitude such as inertial platform drift; but, for rapid failures, the crew was provided with onboard displays for rapid response. The crew would abort if the onboard data for two separate parameters indicated that a failure had occurred and that an abort limit had been exceeded. The requirement for two separate indications of failure was necessary to guard against an instrumentation failure and the unnecessary initiation of a manual abort. However, preliminary studies indicated that the Saturn V vehicle could not withstand two S-IC engine failures from either a structural or a control standpoint; therefore, an automatic abort system was incorporated into the basic design. The automatic abort limit for the triply redundant (voted two of three) sensors was identical to the manual abort limit. The automatic abort system was deactivated just before the S-IC/S-II staging.

Malfunction procedures: Certain malfunctions of the launch vehicle or of the spacecraft were considered insufficient cause for abort and, because of systems redundancy, did not affect crew safety or the success of the mission. An example of such a malfunction is the loss of a single engine on the first or second stage of the Saturn launch vehicle. Failure of a single engine would not be cause for mission termination except for a brief period during the first-stage burn when launch-vehicle control problems could occur. The mission ground rules were written to cover all known situations and to allow the crew to assess the severity of a malfunction and to decide whether abort was required. Many simulations of known malfunctions were performed to decide the point of no return. The results of these simulations were distributed to the appropriate NASA panels, which established additional abort limits that were incorporated into the flight procedures and were verified by further simulations and training.

Abort procedures: For the launch phase, the abort procedures (fig. 7) were divided into four primary modes, using the launch escape tower or the SPS. The launch-escape-tower abort mode (mode I) was subdivided into three parts (A, B, and C), each of which was designed to be fully automatic in the postabort sequence. Mode IA was primarily a launch-complex abort and was in effect from 30 minutes before lift-off until 42 seconds after lift-off. The transition to mode IB was accomplished by activation of a timer to change the postabort computer logic. The RCS propellants were dumped rapidly through the aft heat shield for the mode IA abort because at that point the spacecraft would be too low to expel the propellants by conventional methods. In a mode IB abort, a canard system located on the launch escape tower would be used for spacecraft orientation. The transition to mode IC was dependent only on attaining

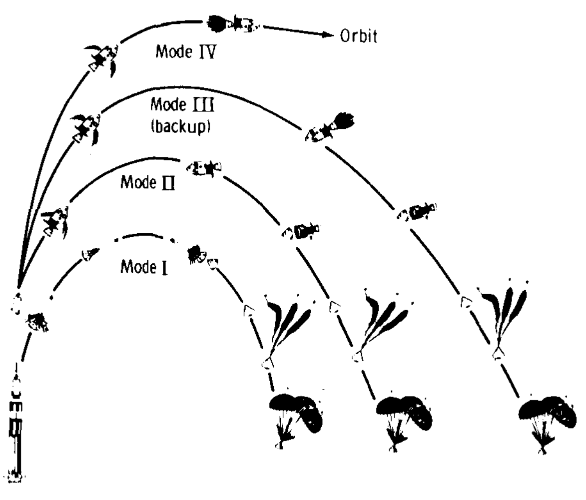

Figure 7. - Apollo launch-abort modes.

an altitude of 100 000 feet where the canard system was not effective and where the spacecraft tumble rate could be controlled manually by the crew. The options of jettisoning the tower and of reorienting the spacecraft manually for a manual (normal) entry were retained in mode IC. These options were allowable only when the body rates were under control and when the attitude reference system was usable. The flight procedures were written to follow the designed automatic abort modes with the crew monitoring all critical events. Thus, if the automatic sequence for abort failed, the crew would initiate an abort by manually executing the critical backup functions listed in the checklist procedures.

The SPS was to be used for abort modes during the portion of the launch phase occurring above the sensible atmosphere of the earth. Mode II consisted of spacecraft separation, reorientation, and entry with all events manually controlled by the CDR. Mode III involved a retroburn of the SPS. The retroburn was required to avoid a landing in Africa and to target the spacecraft for a planned recovery area. A mode III abort was considered highly unlikely because of overlaps between modes II and IV and because multiple system failures would be required for this type of abort. A mode IV abort was an insertion into earth orbit and was considered the most desirable of the abort modes because alternate missions could then be accomplished. The lower threshold of the mode IV abort was determined by mission control data and was based on the capability of the spacecraft to gain orbit from dispersed conditions during the boost phase. All data concerning attitude, time of ignition, and time of burn were to be supplied from the ground. The mode IV abort was a fixed-attitude burn on the Apollo 7, 8, and 9 missions.

Transfer of ground responsibility to flight crew: After the successful Apollo 7, 8, and 9 missions and the attendant increased confidence in the spacecraft systems, flight procedures were changed to allow the crew to control vehicle attitudes by considering trajectory information provided by the onboard navigational equipment. This change greatly increased the efficiency of the maneuver. The use of the SPS for abort was therefore advanced by approximately 1 minute for the nominal mission.

Early procedural problems, caused by late changes and corrections to launch-vehicle hardware, were solved, allowing the deletion of some abort criteria. For example, the loss of the launch-vehicle inertial guidance platform was not considered an abort criterion after demonstration of the capability of the crew to fly the launch vehicle by using the command module computer (CMC). A nominal launch-profile cue card (including pitch angle, inertial velocity, rate-of-change altitude, and altitude) was carried on board by the crew. These nominal values were adjusted by the crew during the flight by using values generated by the onboard computer. Before staging, the vehicle was guided by a programed tilt maneuver supplied by the CMC. Switchover to the backup guidance system was performed by the crew if indications were that the launch-vehicle guidance system had failed. During training simulations, each crew consistently demonstrated the capability to insert into orbits within 2 miles of the nominal altitude. The flight procedure also was expanded to allow the translunar injection (TLI) maneuver to be manually controlled following a guidance failure. Many conservative rules concerning the launch vehicle were relaxed as more flight data were gathered, and the probability of a successful mission was increased.

Translunar injection. - The primary crew task during the TLI maneuver was the same as during launch; monitoring the onboard displays. Procedures for aborts during TLI were simplified because the problem of an immediate earth entry did not exist. Criteria for mission termination still existed; however, more time was available for crew actions if an abort was necessary. The abort limits were excessive attitude rates and errors, and the error limits were larger than during launch because the SPS was capable of deactivating the earth-entry procedures or of executing maneuvers for alternate missions.

Malfunction procedures for TLI. - Loss of some spacecraft consumables or loss of power during the TLI maneuver would require a rapid return to earth, and these contingencies were covered by fixed-time aborts. Procedures and data supplied before launch were developed and included in the checklist for fixed-time aborts, which were planned for 10 minutes and for 90 minutes after the TLI maneuver. After the Apollo 10 mission, the abort after 10 minutes was deleted from the mission plans. The design of the 90-minute abort plan allowed the return to a contingency landing area in less than 18 hours. This period of time was considered sufficient for any foreseeable consumables problem. Other malfunctions occurring during or near the time of TLI were managed by using alternate mission plans. For failures of a rapid nature, the decisionmaking responsibility rested with the crew because ground-control data would probably be delayed too long for effective decisions.

If a complete guidance failure occurred during launch or orbital-coast phases, the primary method of starting the TLI maneuver would be inhibited. Backup procedures, using the onboard CMC to start the S-IVB engine, were incorporated into the checklist.

An approximation of the desired pitch-angle profile taken from the nominal trajectory was displayed on the attitude indicator by using the orbital-rate-drive capability. Thus, the flight commander's task was to keep the attitude rate under control and the attitude ball zeroed. If required by a dispersed initial orbit, the displayed profile could be updated before the maneuver by ground-supplied data. The crew was then responsible for controlling vehicle attitude and for shutting off the engine when proper inertial velocity was attained. The flight path was monitored continuously by using CMC displays, and attitude corrections could be made if necessary. The accuracy obtained during manned simulations required midcourse corrections of 100 to 300 ft/sec, well within the propellant budget for nominal missions.

Rendezvous

In the Apollo Program, the CSM was the rendezvous target for the ascending LM. Rendezvous procedures using a concentric flight plan proved to be safe, flexible, and economical. The concentric flight plan was developed as a series of maneuvers to maintain a planned flight trajectory. The flight crew operated the onboard guidance and navigation system during rendezvous and monitored its performance. The operation of the guidance and navigation system was governed by nominal system procedures, and performance monitoring was accomplished by backup charts. The rendezvous procedures were developed and verified by analyzing trajectories and errors by means of digital programs. Simple procedures using a minimum of sensor information and onboard data were developed for backup and for monitoring the onboard guidance and navigation system.

Concentric flight plan. - The role of the flight crew in space rendezvous operations consisted of controlling the vehicle attitude, evaluating the progress of the trajectory, and, when necessary, computing backup solutions for the rendezvous maneuvers. The concentric flight plan was a rendezvous procedure developed specifically to provide the flight crew with simplicity of operation, high reliability of achievement, and economy of propellant usage.

The concentric flight plan was initiated by a spacecraft maneuver called concentric sequence initiation. This maneuver was made to establish a desired ratio of relative height to phase angle between the active and passive vehicles at the second maneuver. This second maneuver, designated as constant delta height, resulted in a constant differential altitude. Concentric sequence initiation was performed one-half revolution before the constant delta height maneuver. A third maneuver, terminal phase initiation, was executed to establish an active-vehicle trajectory that would intercept the trajectory of the target vehicle. The sequence of maneuvers and the critical parameters of the concentric flight plan are shown in figure 8.

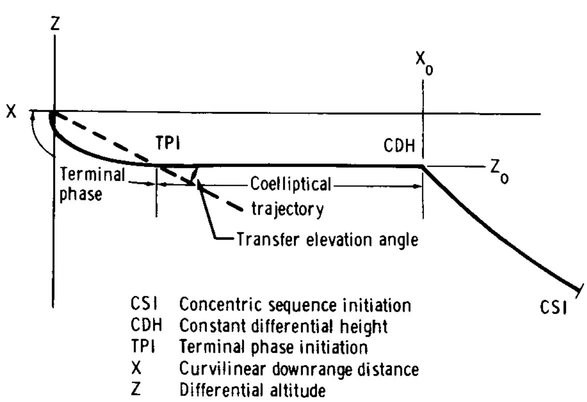

Figure 8. - Geometry for concentric flight plan.

Two parameters, transfer elevation angle and transfer interval (fig. 8), completely characterized the shape of the intercept trajectories of the concentric flight plan. These parameters were selected to reconcile conflicting requirements for optimum propellant economy, minimum error propagation, and maximum ease of operation. Because the time of arrival at a given elevation angle could be varied by changing differential altitude in the coelliptical phase, the transfer time for a given transfer elevation angle could be controlled, and the requirements for lighting, navigation, and ground tracking could be satisfied. By fixing the transfer elevation angle and the transfer interval and by selecting a coelliptical pretransfer condition, the shape of the rendezvous trajectory was held constant for various approaches. Thus, the flight crew could be trained to monitor rendezvous progress, to detect off-nominal conditions, and to develop a high degree of operational efficiency.

During the terminal phase, the transfer interval and elevation angle were chosen to reconcile fuel economy and ease of control. A transfer interval of 130° was chosen as a result of simulation and flight experience. Shorter transfer intervals were costly in terms of transfer and braking velocity, and longer intervals propagated initial velocity errors in the transfer maneuver to large misses at intercept. The transfer elevation angle was also selected to ensure that the apparent inertial motion of the target was near zero in the latter part of the intercept and to ensure that the transfer from a coelliptical trajectory was along the line of sight. For lunar orbit, a transfer elevation angle of approximately 26.6° was used; for earth orbit, the angle was 27.5°. The practical advantage of transfer-elevation-angle choice was a particularly simple, terminal-braking procedure. The CDR thrusted to null any apparent inertial motion of the target normal to the line of sight.

During the coelliptical phase, the time of transfer to the terminal phase was selected to satisfy operational constraints such as lighting and tracking. Under standard approach conditions, the coelliptical trajectory allowed the transfer time to be set by the appearance of a selected transfer elevation angle.

For a given time of the constant delta height maneuver, it was necessary to achieve a correct value for the ratio of relative height and position. Because two degrees of freedom existed and only one condition was to be satisfied, two procedures were possible. If a value of phase angle were given and the time of concentric sequence initiation were fixed, the height was constrained and could be obtained either by one two-axis maneuver at concentric sequence initiation or by two single-axis maneuvers at different times. Alternately, by letting the height be unconstrained, the correct ratio could be obtained by a single, horizontal, one-axis maneuver preceding the constant delta height maneuver. The horizontal maneuver was used to vary the value of differential height with the catchup rate to allow for dispersions in the orbit of the spacecraft.

The out-of-plane problem was found to be uncoupled from the in-plane rendezvous problem, and the computation and application of the solutions were handled separately. In practice, when the out-of-plane motion was established, a corrective maneuver was performed in conjunction with a scheduled in-plane maneuver (such as concentric sequence initiation). The corrective maneuver nulled the existing out-of-plane rate and forced a node to occur one-quarter of a revolution later. When the node was reached, the velocity was nulled again; and the active vehicle was placed in an in-plane trajectory. The corrective maneuver was repeated where necessary. Small residual errors in the out-of-plane direction were corrected easily during the terminal braking maneuvers.

Normal rendezvous procedures. - During rendezvous, crew attention was divided between operation of the primary guidance and navigation system (PGNS) and monitoring the progress of the rendezvous. One problem in developing rendezvous procedures was to devise a technique that would not overmonitor the PGNS when operations were normal but that would detect degrading system operations before maneuvers based on the degraded system were initiated.

Rendezvous monitoring procedures: Several approaches to the problem of rendezvous monitoring, differing somewhat in philosophy, were used on Apollo missions. In the yardstick method, a moderately accurate but highly reliable source of maneuver information (such as the CMC or the Mission Control Center) was selected as the yardstick. Based on the expected performance of the maneuver computing sources, acceptable tolerances were established; and each source was compared with the yardstick in a preestablished order. The first maneuver solution found to be within the specified tolerance of the yardstick was executed. If no solutions were within the tolerance of the yardstick, the yardstick information itself was used for the maneuver. The obvious shortcoming of the yardstick approach was that several valid solutions might be discarded, and the yardstick might be used when it was operating outside of expected accuracy limits.

A second technique was a comparison of the available maneuver solutions followed by a selection based on the agreement of a majority of the solutions. Acceptable tolerances for all types of solutions were established. When three solutions were available and any two solutions were within the specified tolerances, the acceptable solution with the highest priority was executed. The use of four solutions was considered the practical upper limit in rendezvous monitoring.

Another technique to obtain maneuver values was the calculation of a weighted average of all available solutions. The averaging technique had two major disadvantages: the solution of the PGNS was not used to execute the maneuver (although it was usually the most accurate solution), and obvious difficulties were encountered in selecting the weighting factor for each solution used in the averaging process.

The procedure that was finally established for monitoring rendezvous used the comparison technique. The priority for acceptable solutions was, first, the PGNS; second, the CMC; and, third, the abort guidance system (AGS). If no agreement occurred among the solutions that were within specified limits, then the CMC solution was used. If either guidance system failed, values from manual rendezvous charts were substituted in the logic for the failed system.

Crew task distribution: The procedures for operating spacecraft rendezvous systems were distributed as follows.

1. Tasks of the CDR

   a. Execution of all automatic and manual attitude and translating maneuvers

   b. Operation of the PGNS during thrusting maneuvers

   c. Operation of the rendezvous radar

   d. Operation of systems accessible only from the CDR crew station

2. Tasks of the LMP

   a. Operation of the AGS

   b. Operation of the PGNS in all cases not involving attitude maneuvers or translation

   c. Calculations and logging of data

   d. Operation of systems accessible only from the LMP crew station

The rendezvous data on board the spacecraft were in three books. The time line book contained the step-by-step operating procedures for both the nominal and the aborted mission from powered descent. The data card book contained the monitoring procedures and the provisions for all navigation data logging. The rendezvous chart book contained the manual backup charts for computing solutions to rendezvous maneuvers by using basic sensor data available to the flight crew.

Backup charts. - The backup solution for terminal phase initiation was computed by obtaining the differences between actual conditions observed just before terminal phase initiation and the conditions required at terminal phase initiation to achieve rendezvous. The observations needed for definition of the position of the two vehicles were range and range rate at a fixed time before terminal phase initiation and two measurements of the relative elevation angle at fixed times before terminal phase initiation. The solution obtained was resolved into a velocity component along the line of sight and a velocity component normal to the line of sight at terminal phase initiation. The measurement geometry is diagramed in figure 9.

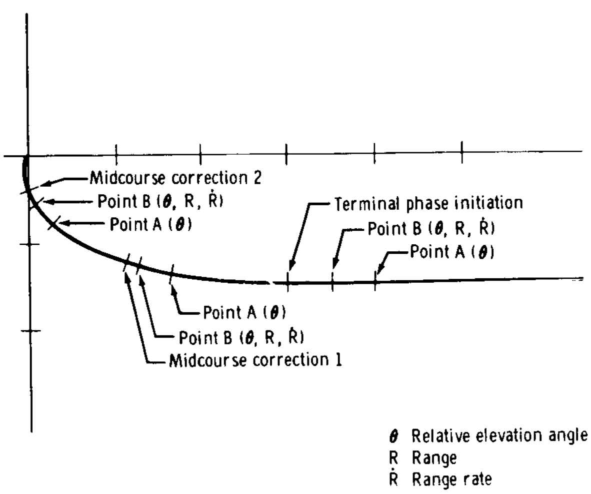

Figure 9. - Measurement geometry for terminal phase initiation backup.

The backup approach was feasible because the catchup rate of the active vehicle with respect to the passive vehicle was very nearly constant for coelliptical orbits, and range rate was a function of catchup rate and relative elevation angle. Thus, the values observed at a fixed time before terminal phase initiation could be used to infer the critical values (range rate and elevation angle rate) at terminal phase initiation. The differences between the estimated value and the values required at terminal phase initiation could then be used to obtain a backup maneuver solution.

The backup chart was graphical. The data used to plot the backup chart were computed by using a digital routine that generated the orbital parameters for a set of trajectories covering the region of expected dispersions about the nominal trajectory. The terminal-phase-initiation-backup chart carried on the Apollo 11 mission is shown in figure 10.

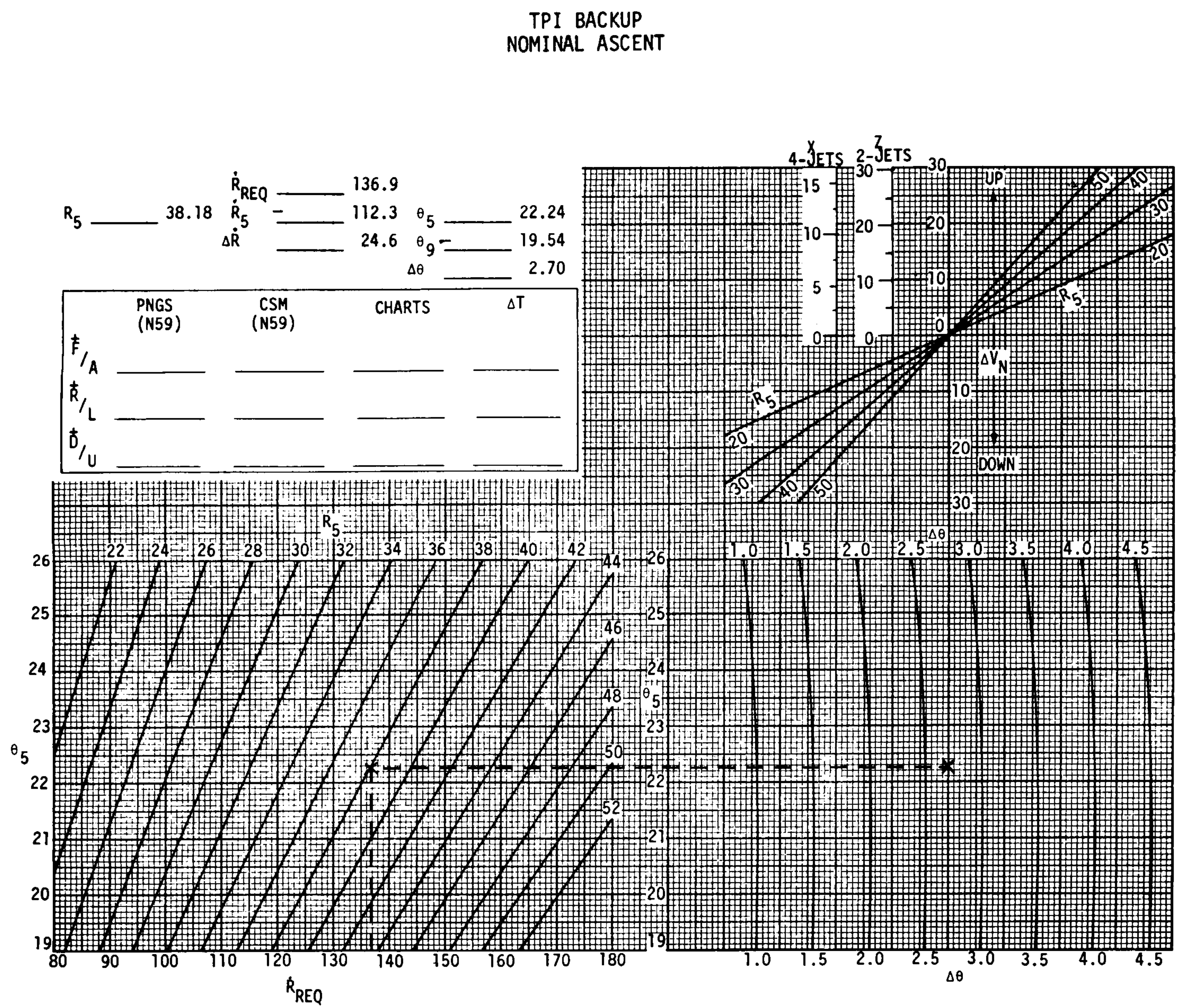

Figure 10.- Terminal phase initiation backup chart for Apollo 11 mission.

The midcourse correction charts were similar to the terminal phase initiation backup charts with the following exceptions.

1. The active vehicle was assumed to be on a collision course with the passive vehicle rather than in a coelliptical orbit.

2. The midcourse correction maneuver was assumed to occur at the instant of the second measurement point rather than at a later fixed time.

In all other respects, the midcourse correction charts were generated and used in the same manner as the terminal phase initiation chart.

Concentric sequence initiation backup: Because the velocity change needed at concentric sequence initiation was not directly available as a function of observable parameters, an approach to a backup maneuver solution different from that used to solve the terminal phase initiation problem was necessary. Of the mathematical techniques for approximating an unknown function, the simplest was the Taylor series. For concentric sequence initiation, only the in-plane problem was to be solved. Therefore, four independent measurements served to constrain the problem. The simplest equation was an uncoupled power series of the observable parameters, range or range rate or both. For the situation in which concentric sequence initiation occurred as a result of a nominal ascent from the lunar surface and for similar trajectories, this approach worked well. The resulting tabular data are presented in figure 11. In this case, the measurements were of range rate at concentric sequence initiation minus 30, 20, and 10 minutes; and of range at minus 10 minutes. As each measurement was obtained, the corresponding factor was determined from the table and logged in the space provided. At the last observation, the factors were summed to give the velocity change needed at concentric sequence initiation.

Constant delta height backup: Range rate in a nearly coelliptical orbit could be closely represented by a sinusoidal curve. Moreover, relative velocity changes, both vertical and horizontal, were sinusoidal functions of range rate. Because the constant delta height maneuver depended only on the relative velocity and height differences between the two spacecraft, three independent measurements were sufficient to define the sinusoidal curve. By using the sinusoidal functions of vertical and horizontal velocity changes, a nomographic solution of the constant delta height problem was constructed and carried as onboard data.

Performance analysis: After backup charts had been constructed, statistical analyses were made to determine how well the charts would perform. Data for the statistical analyses were generated by a computer routine that executed a large number of simulated rendezvous and calculated statistical parameters of interest.

One of the basic parameters examined in the analyses was the accuracy of the backup chart solutions. In addition, data were derived for miss distance at closest approach, for total fuel used in the rendezvous, and for arrival time at terminal phase initiation. The results of these analyses were used to establish source priority of maneuver solutions.

RDOT1	F1	RDOT2	F2	RDOT3	F3	R3	F4
-240.0	47.3	-140.0	45.2	-70.0	-27.6	120.0	-15.2
-241.0	48.4	-141.0	43.4	-71.0	-26.6	121.0	-15.5
-242.0	49.4	-142.0	41.6	-72.0	-25.6	122.0	-15.7
-243.0	50.5	-143.0	39.8	-73.0	-24.5	123.0	-15.9
-244.0	51.5	-144.0	37.9	-74.0	-23.5	124.0	-16.1
-245.0	52.5	-145.0	36.1	-75.0	-22.5	125.0	-16.3
-246.0	53.6	-146.0	34.3	-76.0	-21.4	126.0	-16.5
-247.0	54.6	-147.0	32.4	-77.0	-20.4	127.0	-16.7
-248.0	55.7	-148.0	30.6	-78.0	-19.4	128.0	-16.9
-249.0	56.7	-149.0	28.7	-79.0	-18.3	129.0	-17.1
-250.0	57.8	-150.0	26.9	-80.0	-17.3	130.0	-17.3
-251.0	58.8	-151.0	25.1	-81.0	-16.3	131.0	-17.5
-252.0	59.9	-152.0	23.2	-82.0	-15.2	132.0	-17.7
-253.0	60.9	-153.0	21.4	-83.0	-14.2	133.0	-17.9
-254.0	62.0	-154.0	18.6	-84.0	-13.1	134.0	-18.1
-255.0	63.0	-155.0	17.7	-85.0	-12.1	135.0	-18.4
-256.0	64.1	-156.0	15.9	-86.0	-11.1	136.0	-18.6
-257.0	65.1	-157.0	14.0	-87.0	-10.0	137.0	-18.8
-258.0	66.2	-158.0	12.2	-88.0	-9.0	138.0	-19.0
-259.0	67.2	-159.0	10.3	-89.0	-8.0	139.0	-19.2
-260.0	68.3	-160.0	8.5	-90.0	-6.9	140.0	-19.4
-261.0	69.3	-161.0	6.6	-91.0	-5.9	141.0	-19.6
-262.0	70.4	-162.0	4.8	-92.0	-4.8	142.0	-19.8
-263.0	71.4	-163.0	3.0	-93.0	-3.8	143.0	-20.0
-264.0	72.5	-164.0	1.1	-94.0	-2.8	144.0	-20.2
-265.0	73.5	-165.0	-.7	-95.0	-1.7	145.0	-20.5
-266.0	74.6	-166.0	-2.6	-96.0	-.7	146.0	-20.7
-267.0	75.7	-167.0	-4.4	-97.0	.4	147.0	-20.9
-268.0	76.7	-168.0	-6.3	-98.0	1.4	148.0	-21.1
-269.0	77.8	-169.0	-8.1	-99.0	2.4	149.0	-21.3
-270.0	78.8	-170.0	-10.0	-100.0	3.5	150.0	-21.5
-271.0	79.9	-171.0	-11.9	-101.0	4.5	151.0	-21.7
-272.0	81.0	-172.0	-13.7	-102.0	5.6	152.0	-21.9
-273.0	82.0	-173.0	-15.6	-103.0	6.6	153.0	-22.1
-274.0	83.1	-174.0	-17.4	-104.0	7.7	154.0	-22.4
-275.0	84.2	-175.0	-19.3	-105.0	8.7	155.0	-22.6
-276.0	85.2	-176.0	-21.1	-106.0	9.7	156.0	-22.8
-277.0	86.3	-177.0	-23.0	-107.0	10.8	157.0	-23.0
-278.0	87.4	-178.0	-24.9	-108.0	11.8	158.0	-23.2
-279.0	88.4	-179.0	-26.7	-109.0	12.9	159.0	-23.4
-280.0	89.5	-180.0	-28.6	-110.0	13.9	160.0	-23.6
-281.0	90.6	-181.0	-30.4	-111.0	15.0	161.0	-23.8

CSI BACKUP TABLE
NOMINAL ASCENT

TIME (Min)			NOMINAL
			DSKY>TM
-30	$\dot{R}1$	________	(-283.3) -1.4
-20	$\dot{R}2$	________	(-173.9) -.9
-10	$\dot{R}3$	________	(- 94.0) -.5
-10	R3	________	(154.1)
	F1	________	(93.0)
	+F2	________	(-17.3)
		========	(75.7)
	+F3	________	(-2.8)
		========	(72.9)
	+F4	________	(- 22.4)
		========	(50.5)
	+ΔΔVCSI	________	(0.0)
	ΔVCSI	[ ]	(50.5)

Figure 11. - Concentric sequence initiation backup table.

Onboard rendezvous evaluation: A primary crew function in manned space flight was the evaluation of the progress of rendezvous. Analyses of simulated rendezvous provided rule-of-thumb statements about the behavior of maneuver solutions after trajectory dispersions occurred. For example, the analyses indicated that an insertion dispersed behind the nominal phase angle (up-range distance) would propagate to similar off-nominal positions at each point, particularly at the point of the constant delta height maneuver. If the phase angle were too large, the spacecraft was too far up range, and a larger differential height was necessary to arrive at the transfer elevation angle at the correct time. Because orbital period was a function of energy, a shorter period (corresponding to a larger differential height) was required, implying a smaller change in velocity at concentric sequence initiation.

Similar statements apply to horizontal overspeed at insertion. Analysis indicated that after nearly one revolution (for example, at constant delta height) an overspeed placed the spacecraft up range from the nominal position. Converse statements apply to an insertion phase angle that is too small or to an insertion underspeed. If the insertion error was in altitude rate, the position of the spacecraft after one revolution was nearly coincident with the nominal position; but the spacecraft altitude-rate error was nearly equal to that at insertion. Thus, the vertical component of the constant delta height maneuver needed change to remove the error, although the resulting differential height was little affected. When the pilot had information on the dispersions resulting from a particular case, he inferred the trend of his maneuver solutions from comparison to nominal.

Lunar Descent and Ascent

Background. - Approximately 1 year before the Apollo 11 mission, work was begun on the developing of detailed flight procedures for the descent and ascent phases of a lunar landing. Onboard computer programs, spacecraft configuration, and preliminary mission planning were partially defined, and some work was completed on the capability of the crew to detect off-nominal guidance performance. The current mission planning was integrated with onboard computer requirements, with systems requirements and constraints, and with crew and ground capabilities. A detailed flight procedure was developed that would allow the crew to function without ground assistance except for maneuver and computer updates. Independence from ground support was desirable for the following reasons: effective communications at lunar distance were unproven; crew operations would be more efficient if coordination with the ground were not critical; and communication contacts from lunar orbit would be impossible when the spacecraft was behind the moon.

Development. - Initially, flight procedures were to be concerned only with the powered phases of lunar descent and ascent; however, the importance of certain preceding events soon became evident. The decision was made to include in the descent procedures all events in the 2.5-hour period from the time of undocking to lunar touchdown. The detail included in the first drafts of the flight procedures was sufficient for use on a simulator and for review and criticism. The onboard data were then condensed from the final flight procedures documents.

The initial development of the flight procedures involved determination of the sequence of mission events, attaching time tags to known mandatory events, and scheduling the support and highly desirable events in the best places possible. The mandatory events for the descent were undocking, descent orbit insertion, and powered descent initiation. Procedures that constrained the descent phase of the mission were an inertial measurement unit alinement within 2 hours of initiation of powered descent, AGS alinement to the PGNS within 5 minutes of the descent burn, and AGS state-vector update from the PGNS within 10 minutes of the descent burn. These constraints had been identified by the hardware manufacturers or from guidance performance studies.

Some proposed constraints could not be met realistically. For example, an early requirement was to aline the inertial measurement unit within 30 minutes (rather than 2 hours) of the descent burn. When it was determined that the alinement probably could not be conducted during lunar daylight, the constraint was dropped.

Some items that were not mandatory but served to increase crew confidence in vehicle performance were added to the flight procedures. For example, the AGS was configured to monitor the descent orbit insertion burn and to check performance of the PGNS. For resolving differences between observed guidance values, a technique was added to the flight procedure to verify the correct value by using the rendezvous radar. The technique involved measurement of the resultant trajectory relative to the CSM.

Other tasks were added to the descent procedures because they could not be performed before the vehicles undocked. For example, the rendezvous radar/transponder operation could not be verified in the docked configuration because of physical limitations of the spacecraft hardware.

Visual inspections, which were added to the flight procedures, included an inspection of the LM by the CMP immediately after undocking and a check of timed lunar landmark passage before powered descent initiation. The procedures for landing radar activation and self-test were added to the descent procedures because of time limitations in the LM-activation period.

Verification. - When the logical and complete sequence of mission events was established, the detailed descent procedure was written. The procedure was used to verify that all the events could be accomplished in the allotted time. A cockpit mockup was first used for time and motion studies; later, more realistic computer time requirements were simulated. No problems were encountered during these studies, although the schedule during descent was found to be very tight.

The Apollo 10 mission was planned to be flown exactly the same as the lunar landing mission, except for the final powered descent. The Apollo 10 mission verified that the general procedure was acceptable.

Changes for the Apollo 11 mission. - Some changes were made in the Apollo 11 flight plan, such as rescheduling the landing radar test to a more convenient time. Other technical changes in the computer programs and flight procedures included the following items.

1. Measuring the undocking maneuver on board to facilitate ground-based predictions of the LM orbit

2. Loading an abort maneuver program to be effective 12 minutes after a failure to initiate powered descent, should the maneuver be required

3. Verifying PGNS pitch alinement before powered descent initiation by computer-pointing the optics at the sun

4. Preloading a landing-site state vector into the AGS to ensure availability of a good state vector upon touchdown

5. Including a procedure by which the crew could time landmark passage and thus determine altitude on the basis of known velocity

These changes were made to prepare for contingencies that might arise and to obviate possible deficiencies in Manned Space Flight Network orbit determination. During most of the descent, the LM was under automatic control; the crew was involved only with monitoring and decisionmaking until shortly before touchdown. The powered descent trajectory (table VII) was designed to reduce the velocity of the LM from approximately 5500 ft/sec at an altitude of 50 000 feet to 0 ft/sec at touchdown. Constraints were designed to provide the crew with continuous visibility of the landing site from high gate (approximately 7000 feet altitude) to low gate (approximately 100 feet altitude). The range of velocities and attitudes below 500 feet facilitated crew takeover for a manually controlled landing. The LM was to be in a face-down attitude before powered descent initiation so that the crew could verify visually their position by sighting at preselected landmarks through marks on the LM left-forward window and their pitch attitude by sighting at the lunar horizon through marks on the overhead window. The inertial velocity, altitude rate of change, and total attitude could be compared between the displays of the two guidance systems and with predicted nominal values. Discrepancies could be identified by out-the-window checks and, when available, by landing radar information.

Because of the orientation of the radar antenna, the LM landing radar was not functional above 30 000 feet during descent. The crew had to maneuver the LM to a face-up position (Z axis radially up) to obtain radar data. When the radar data became available, the crew decided whether the data should be incorporated into the guidance system. This decision was based on reasonability and on precalculated limits. After the data were incorporated and convergence was verified, data from the AGS, not updated by the landing radar, would be in error, and thus would not be monitored closely. In addition to the trajectory parameters, the crew monitored vital spacecraft systems parameters (such as use of descent propulsion system propellant) but relied primarily on the absence of caution and warning lights and alarms to indicate safe performance.

TABLE VII. - GENERAL PROCEDURES DURING LUNAR POWERED DESCENT

Spacecraft position	Time relative to PDI[a], min:sec	Flight procedures
Approaching powered descent initiation at 50 000 ft and 270 n. mi. from landing site	-25:00	Call for automatic braking
	-20:00	Acquire Manned Space Flight Network
	-15:00	Manual control to attitude of PDI
	-10:00	Update AGS and load state vector
	-5:00	Check switches, go/no-go for descent, altitude, attitude, and position
Approaching high gate at 7000 ft and 4 n. mi. from landing site	+2:00	Check altitude
	+3:30	Check position
	+4:00	Yaw face up
	+5:00	Enable landing-radar updating
	+7:00	Evaluate manual control
	[b]+7:00	Monitor trajectory and systems
Between high gate and 500-ft altitude	+8:30 to +10:00	Monitor powered descent angles
		Evaluate landing site
		Redesignate landing site if necessary
		Update AGS altitude
Between 500-ft altitude and touchdown	+10:00 to [b]+11:30	Manual control rate of descent
		Select landing site
		Null horizontal velocity
		Monitor fuel

[a]Powered descent initiation.

[b]Approximate time.

At high gate, the LM pitched down so that the landing site was visible in the forward windows. The LM guidance computer calculated the angle between the plus Z axis of the vehicle (straight ahead) and the line of sight to the landing site. The angle was displayed on the display and keyboard and was called out by the LMP while the CDR sighted through the landing-point-designator markings on the window (fig. 12) to determine where the vehicle would land under full automatic guidance. If the landing site

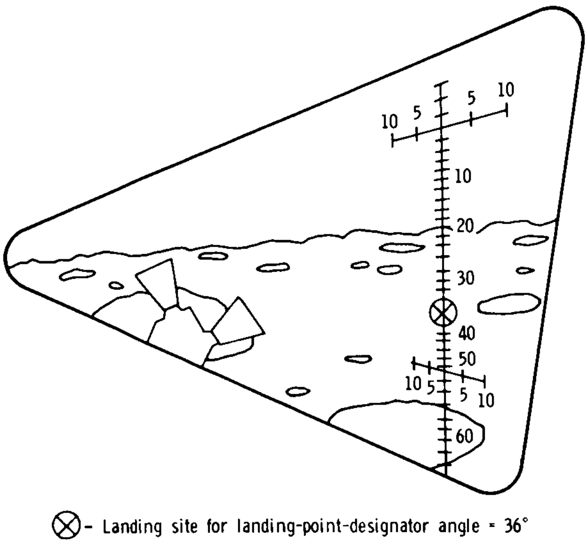

Figure 12. - View from LM window.

were unacceptable, the CDR would select a suitable site and redesignate the landing by using the attitude controller assembly. A forward or backward motion of the assembly shifted the approach to the landing site down range or up range by 0.5°, and a right or left motion shifted the site laterally by 2.0°. In addition to calling out the landing-point-designator angle, the LMP continued to monitor and report altitude, altitude rate, and propellant quantity.

Procedures for three types of landing modes were as follows: first, an automatic mode that required no crew action (with this mode, the vehicle might land on an uneven surface or in a crater); second, a semimanual mode, in which the CDR used the attitude controller assembly to fly to a suitable landing site, null the horizontal velocity, and control the rate of descent (activation of the rate-of-descent switch increased or decreased the rate of descent by intervals of 1 ft/sec); and, third, a completely manual mode, using the attitude controller assembly and the manual throttle. The manual mode was least desirable because of the possibility of propellant depletion before landing. Thus, the semimanual mode was selected as the prime mode for the Apollo 11 flight plan.

In summary, the division of crew tasks in the descent procedures was as follows. The CDR monitored and controlled the altitude and attitude of the spacecraft, using external visual sightings to verify a proper trajectory, and completed the landing. The LMP monitored LM displays and advised the CDR of vehicle and trajectory status.

Ascent procedures. - The procedures for powered ascent were similar to those for powered descent except that the landing radar was not available as a third source for altitude and altitude-rate data. However, these values were not as critical for ascent as for descent. If the nominal attitude profile was maintained and an established minimum velocity was attained, a safe orbit insertion was assured. The AGS was monitored only to verify that the system was functional.

For a condition in which neither guidance system was available for ascent, procedures were developed to fly manually to a safe orbit by using the attitude controller assembly. On the basis of simulations in the LM procedures simulator, a safe orbit would always be achieved by allowing the ascent engine to burn to propellant depletion. However, an orbit with an excessive apogee could be obtained. The CDR could maneuver by using the attitude ball for reference or by using a sighting on the horizon through the angle marks on the overhead windows. The parameters for both modes were contained on the ascent monitoring card (fig. 13). If neither an attitude-hold nor a rate-damped control mode was available, a direct control mode that included two four-step profiles (one for attitude-ball reference and one for overhead window-horizon reference) could be used. The two four-step profiles were added to the ascent monitoring card for the Apollo 11 mission (fig. 13).

SOURCE REV "K" JULY 9, 1969
DATE JUNE 27, 1969-CHG "D"

LM TIMELINE BOOK

APOLLO 11 FLIGHT DATA FILE PAGE 13

ABORT STAGE-PUSH
PRO
ENG ARM-ASC
ENG START-PUSH
N63, YAW
PITCH
BAL CPL-OFF

SBD P 134 Y -32

CHANGE 16 mm
FRAME RATE
TO 6 FPS

N76E VH Vv ΔR
V16 N77 E
N85 E, 500R
TM-R, R DOT

200 FPS MAIN SOV(2)-OPEN
ASC FEED 2(2)-CLOSE
50 FPS ENG ARM - OFF
0 FPS ABORT STAGE-RESET
ENG STOP RESET
MODE CONT (2)-ATT HOLD
2 JET
BAL CPL-ON
END APS CARD
ΔVX NULL, KEY REL
VI, HDOT, H
PRO ΔV'S
V82E, 315R, 403R, 313R
PRO PRO
P00, RR-AUTO TRACK
CRSFD - CLOSE

ASCENT

PITCH	OHW	TFI	VI	H DOT	H
		-0:05			
		0:00	15.0	0	0
		0:10	50.0	55.0	300
308	39	0:30	200.0	90.0	1800
305	37	1:00	400.0	125.0	5000
302	35	1:30	700.0	150.0	9200
299	33	2:00	1000.0	170.0	14000
296	31	2:30	1400.0	185.0	19300
292	29	3:00	1700.0	190.0	24900
289	27	3:30	2100.0	190.0	30600
285	24	4:00	2400.0	185.0	36300
281	22	4:30	2900.0	175.0	41600
277	19	5:00	3300.0	155.0	46700
273	16	5:30	3700.0	135.0	51000
269	13	6:00	4200.0	110.0	54800
265	10	6:30	4700.0	80.0	57500
260	7	7:00	5300.0	50.0	59500
		7:14	5540.0	32.0	60150

MANUAL ASCENT

CONFIGURATION-NOMINAL EXCEPT
MODE CONT-ATT HOLD
PROFILE-NOMINAL EXCEPT
4-STEP FOR DIRECT MODE,
BAL CPL-OFF AFTER PITCH
8-BALL 4-STEP:
:20 PITCH DN TO 300°
3:15 285
5:15 270
7:00 255

OHW 4-STEP
:15 PITCH DN TO 37
1:14 32
3:26 25
5:24 11

ASC QTY LITE-MAIN SOV(2)-OPEN
ASC FEED 2(2)-CLOSE
BURN TO PROP DEPLETION

MONITOR

PGNS		AGS
06 63	VI, H, Ḣ	500 VGX
16 77	TGO, VY	367 Ḣ
16 85	VGX, VGY, VGZ	433 VI

ASCENT MONITOR

7 6 4 3 2 1

Figure 13.- Ascent monitoring card.

Entry

Background. - The Apollo primary guidance and control system provided all the functions for determining and performing the proper maneuvers to return to earth with a safe entry. However, Mission Control Center personnel normally dictated the actual transearth corrections because the ground-tracking facilities provided better accuracy. If data were unavailable from either source because of equipment malfunctions, the onboard backup systems and charts could provide adequate displays for the flight crew to maintain the trajectory within the entry corridor and to guide the vehicle to a preselected target area. The checkout, monitor, and takeover criteria for spacecraft systems were incorporated into a single checklist together with the spacecraft attitudes and the flight techniques used during entry.

Entry procedures for Apollo missions were divided into entries from lunar return and entries from earth orbit. The monitoring checks are summarized in tables VIII and IX. In the event of a malfunction, take-over criteria were established so that the crew could use the remaining equipment to ensure a safe landing at a predetermined target. The monitoring points and limits and the alternate guidance and control techniques were incorporated into each procedure to provide a concise and convenient entry checklist.

TABLE VIII. - SUMMARY OF MONITORING CHECKS FOR LUNAR-RETURN ENTRIES

Time relative to entry interface, hr:min:sec, or event	Check	Effect of failure
-30:00:00	Verify entry monitor system (EMS) self-test.	If the EMS has failed, no range beyond 1800 n. mi. can be targeted. If all accessible targets have bad weather, a midcourse correction is indicated.
-01:00:00	Verify EMS self-test.	If the EMS has failed, the constant-g mode becomes the prime backup mode.
-00:30:00	Check horizon to test inertial measurement unit (IMU) alinement and displays.	If the IMU has failed, the guidance, navigation, and control system (GNCS) is no-go. Isolate the error source.
Entry initialization program	Monitor display of range to target.	If an improper target is loaded, the GNCS is no-go. Complete the entry using EMS mode.
At 0.05g	Verify automatic computer program sequence and automatic EMS initialization.	If the GNCS is no-go, complete the entry by using the EMS mode. Manually initiate the EMS at predicted time plus 3 sec. If manual initialization is unsuccessful, use the constant-g backup mode.
+00:01:00	Check corridor and initial lift-vector orientation.	If the EMS is commanding proper attitude, reverse initial attitude and return to automatic control at 1.5g.
Continuous EMS check	Verify that EMS g-level is within +1g of g-meter value.	Check the g-level with the computer callup and fail the system in disagreement with the other two sources.
Continuous GNCS checks	Verify that vehicle attitude is responding to displayed roll commands.	Switch to backup roll thrusters to isolate failure. If no effect and the GNCS is go, manually fly roll commands. If the GNCS is no-go, complete the entry with manual control and the EMS.
	Verify that roll commands avoid violation of onset and offset lines with g-V trace on EMS scroll.	If the GNCS is no-go, complete the entry with the EMS and manual ranging.
	Verify automatic program sequencing.	If the GNCS is no-go, complete the entry with the EMS and manual ranging.
	For long-range targets, verify specified control constants displayed to ensure a safe ballistic trajectory.	If the GNCS is no-go, complete the entry with the EMS and manual ranging.

TABLE IX. - TYPICAL MISSION TIME LINE FOR A NOMINAL RANGE TARGET

Time relative to entry interface, hr:min:sec	Event
--	Initial stowage
--	System checks
-06:00:00	Last midcourse correction decision
-03:00:00	Last midcourse correction
-01:15:00	Maneuver to entry attitude
-01:00:00	EMS go/no-go tests
-00:55:00	Gyro display coupler drift check
-00:45:00	Navigation update and entry-pad data
-00:35:00	Roll indicator set for EMS initialization
-00:25:00	Separation checklist
-00:19:00	Entry preparation program inception
-00:18:00	CM/SM separation and preentry maneuver program inception
-00:17:00	Horizon attitude check
-00:15:00	CM/SM separation
-00:12:00	Entry initialization program with sequences for lift-up entry (horizon tracking) inception
-00:05:00	Pitch-error needle converging to zero (0.05g attitude hold) notation
-00:01:30	Pitch-error needle converging to zero (horizon tracking) notation
00:00:00	Entry interface at 400 000 ft
+00:00:28	Post-0.05g program inception
+00:00:31	Manual EMS initialization (if required)
+00:02:08	Velocity equal to satellite velocity
+00:02:08	Final phase program automatically sequenced
+00:08:16	Drogue parachutes deployment
+00:09:04	Main parachutes deployment
+00:13:59	Splashdown

Lunar-return entries. - Lunar-return entry procedures for Apollo missions were based on the following criteria.

1. The timespan between the maneuver establishing entry conditions and the actual entry into the earth atmosphere

2. The level of crew activities

3. The routine tasks requiring procedures executed earlier in the mission

4. The monitoring capabilities of the hardware and crew

5. The identification of malfunctions and contingencies

6. The operational alternatives available to the crew

The procedures in the entry checklist included only the general category of activity until several hours before entry because detailed procedures were available in the general onboard checklist data. As crew workload increased while approaching entry, use of a detailed checklist became necessary to monitor specific checkpoints and to determine associated alternatives in case of a contingency. The use of simulations for entry training covering this critical period of heavy activity verified the organization and detail in the flight procedures.

Crew tasks and takeover criteria: Preparation for lunar-return entry began with the transearth injection (TEI) maneuver performed using the SPS. After the TEI maneuver was completed, the crew prepared for entry by performing alinement checks, trajectory corrections, and system management duties similar to those performed throughout the mission. Duties unique to the entry task began after the time designated for the final midcourse correction (approximately 3 hours before entry). The events for the nominal lunar-return entry are shown in table IX. Crew tasks during this period were as follows.

1. General system management and entry preparation

2. Entry-pad and computer-data up links from the Mission Control Center

3. Entry monitor system (EMS) self-checks

4. Entry-attitude alinement and horizon checks

5. Entry program preparation and checks

Guidance checks associated with entries initially consisted of star-tracking techniques performed throughout the flight. For guidance checks as the spacecraft approached entry, a second method was recommended that involved measuring the earth-horizon alinement with a designated window mark to provide a reliable fix on the entry attitude and a checkpoint on the guidance data. It was desirable to perform several of these checks, the last of which was a final check on the automatically commanded attitude just before entry. If the final check were satisfactory, the spacecraft control was placed on automatic steering. The horizon checks had an advantage over the star and sextant attitude checks because they could be performed while the crewmen were secured in their couches and while the spacecraft was in the entry configuration.

The primary guidance accelerometers sensed the first indication that the entry phase had begun, and this information was displayed by an onboard computer read-out. As spacecraft acceleration reached 0.05g, the initial entry-control program of the primary guidance system commenced automatically, an 0.05g acceleration in the EMS was indicated by a display light, the display change was noted by the crew, and the integration process for determining the decreases in range and velocity was activated. If the program change was not accomplished within a predicted time, the primary guidance was considered unusable. If the 0.05g indication did not occur within several seconds of predicted time, the crew started the EMS manually to preserve monitoring capability.

The EMS also provided an entry-corridor check by indicating whether a lift-up or a lift-down attitude should be flown. The corridor check was performed by sensing the g-level 10 seconds after 0.05g initiation and comparing this g-level to a reference constant. This gross check did not allow for lift-to-drag and atmospheric variations but was available if loss of both communications and primary guidance eliminated a more accurate indication. A lift-down attitude on the initial entry was required only for extremely shallow entry angles in the corridor, but the safeguard of having the gross check available from an independent source was desirable to reduce further the chances of skipout.

A real-time trace of the spacecraft load factors as a function of spacecraft velocity (g-V) was made by the EMS on a scroll that contained predetermined parameters for safe entry and for landing-point targeting (fig. 14). This display served as a check on the automatic guidance system and provided sufficient information for safe manual control to intermediately ranged targets.

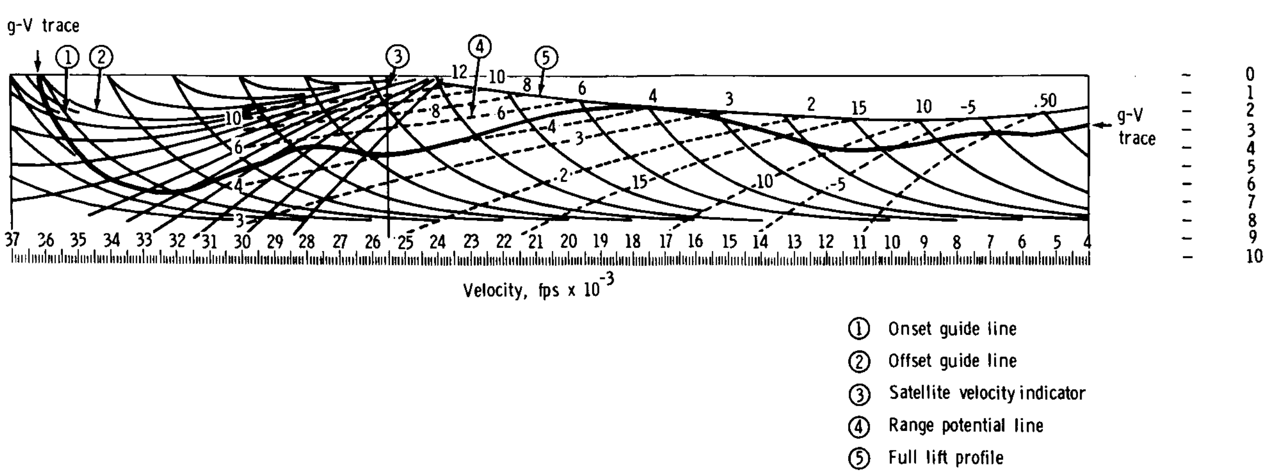

Figure 14.- Entry monitor system g-V scroll.

The most critical phase of entry occurred from the time TEI began until the spacecraft velocity became subcircular. During this phase, the mandatory monitoring tasks (to ensure against skipout or excessive g-loads) were the initial-g onset control, the peak-g control, and the energy control. Normally, a lift-up vector was held from entry interface through the peak-g period for the majority of entry conditions. If shallow entry conditions dictated a lift-down vector, the initial lift-down control was held only long enough to ensure atmospheric capture (too long a hold would cause excessive g-loading).

Peak-g control monitoring ensured that guidance commands were not initiated to increase g-loading. A full lift-up attitude was maintained until the time for energy-control maneuvering. Any other command from automatic steering would necessitate manual takeover.

The energy-control maneuvering resulted in the safe expenditure of spacecraft energy until a subcircular velocity was reached. A constant-g level was maintained, and the crew monitored convergence to a g-value by observing g-level and roll commands. The required constant-g level was a function of initial entry velocity and was available to the crew from the data pad. If the value of the constant could not be obtained because of an equipment failure, the crew could fly manually at a predetermined g-level, which was nearly constant and which had been well established during training. Energy-control maneuvering also allowed retention of sufficient energy in reserve for target ranging. Targets ranging from approximately 1500 to 2500 nautical miles required a proportional up-vector control phase that approached skipout conditions and, therefore, increased the monitoring tasks. The capability was retained because weather conditions could dictate changes in target area; however, the longer the range, the greater the monitoring task and the more difficult the task of flying manually to the target. Because a near-skipout condition had to be avoided, the reliability of targeting with manual control for points at distances over 1600 nautical miles decreased substantially with increased range.

Although the trajectory to the target was calculated during the early phases of the entry, ranging to a selected target usually began when the trajectory became subcircular. The g-V trace indicated the range capability by intersection of the trace with the range-potential lines. The range-potential lines were generated for the scroll by plotting the distances that could be covered at various constant-g levels. By noting the current range potential and the remaining EMS range, the crew could determine if steering were adequate for proper targeting.

Backup procedures: The nominal lunar-return entry checklist incorporated many checkpoints and criteria for switchover to manual control of the entry. Because the checklist was abbreviated, some detail in backup technique was omitted; but backup techniques were thoroughly covered in crew training. Malfunctions were covered by the following alternatives.

1. Loss of communications: The onboard targeting program was available if entry parameters could not be relayed from the Mission Control Center. Other pertinent information was available in the routine entry programs and could be used for EMS initialization and final targeting criteria.

2. Loss of primary guidance: The EMS not only served as an entry monitor display but also indicated sufficient information for a crew-controlled entry to a predetermined target. If the primary guidance system failed, the spacecraft would initially be manually controlled to nearly the same criteria and checkpoints that the automatic system would have provided. Once suborbital velocity was reached, the crew would use the ranging technique practiced in simulations (i. e., matching range-to-go with range potential). This training was necessary because the crew had only the range-to-go integration and the range-potential traces as guidelines. The crewmen would attempt to match these values by rolling the spacecraft to control the lift vector.

3. Loss of primary guidance and entry monitor system: Although the probability of loss of primary and backup systems was extremely remote, training established a safe procedure by using the onboard gravity meter. Although ranging capability would be lost, the technique of controlling the vehicle to a predetermined constant-g level allowed for a safe entry and a good splashdown-point prediction to the recovery forces.

CONCLUDING REMARKS

The complex nature of the Apollo spacecraft systems and missions required the participation of many engineering specialists to determine effective crew procedures. The development of procedures was required along two distinct lines: systems procedures and flight procedures. Systems procedures, largely independent of the mission plan, were developed with the assistance of the prime contractors and encompassed all the systems operating modes. Flight procedures produced an optimized crew time line for each mission phase by incorporating mission constraints and requirements with appropriate system operating modes.

Procedures documentation, like procedures development, was accomplished in two categories. Systems procedures were recorded in the Apollo Operations Handbook, which became the source of approved operating modes and provided a vehicle for officially distributing procedures changes resulting from hardware and software modification and testing. Flight procedures were recorded in flight procedures documents with one volume for each of several critical mission phases. Portions of the Apollo Operations Handbook and flight procedures documents were included in the flight data file for use by the crew in flight.

During the Apollo Program, it was found that a procedures control board was necessary to maintain correct crew procedures when various mission and systems changes were made. This board ensured that every organization concerned with mission operations was provided with current and complete information on crew operation of the spacecraft, that all proposed procedural changes received a thorough review, and that management had sufficient information concerning the number and nature of procedural changes.

A significant fact learned during procedures development for the Apollo Program was that the crew, given certain basic flight displays, could perform the following functions: monitor and assess the performance of automated systems during normal operation; accomplish the primary mission objectives despite many kinds of subsystem failures or degraded situations; and make real-time decisions during emergencies to abort the primary mission and return safely to earth, to accomplish alternate missions, or to continue the primary mission by using manual backup techniques, thereby enhancing both crew safety and mission success.

Manual backup procedures were developed for the following critical mission phases.

1. Launch into earth orbit: In the event of booster malfunction, the crew could terminate the ascent or take control of the booster attitude and manually guide to earth orbit.

2. Translunar injection: If the booster guidance failed, the crew could take control and continue the translunar injection thrusting by guiding to the nominal attitude-angle profile.

3. Rendezvous: The best procedure for rendezvous monitoring was to compare maneuver solutions from the lunar module and command and service module guidance systems with chart solutions obtained manually by using raw data from radar and angle sensors. A significant fact learned during the Apollo Program was that all rendezvous maneuvers could be calculated and performed with simple manual techniques by using basic sensor displays and onboard charts with an accuracy only slightly degraded from that of the primary guidance and navigation system.

4. Lunar descent: The crew could successfully monitor the descent by observing the spacecraft attitude, altitude, and position relative to known landmarks through the spacecraft windows and by comparing these observations with computer displays. During the final 10 000 feet of descent, the crew could adjust the flight-path angle for clearance of terrain obstacles and control touchdown velocities to within acceptable limits.

5. Lunar ascent: Display monitoring and out-the-window monitoring were found adequate to detect and recover from most types of failures. However, lack of a third source of altitude information required participation by ground-based tracking to identify certain guidance system component failures. Successful procedures were developed for achieving near-nominal lunar-orbit conditions for any single guidance and control failure except failure of the ascent propulsion system.

6. Entry: The automatically guided entry was monitored by use of the entry monitor system. It was found that the skipout margin could be continuously observed and, if necessary, the spacecraft attitude could be manually controlled to obtain a safe splashdown. A second backup procedure, using only an attitude indicator and a gravity meter, was also developed for use in case of failure of both the primary guidance system and the entry monitor system.

On the basis of experience gained through the time of the Apollo 11 mission, the following general conclusions relating to crew procedures can be made.

1. Automated modes designed into the Apollo systems proved successful in performing complicated mission plans using a minimum of propellant and in relieving the crew of many tedious tasks.

2. Onboard monitoring of automatic functions was best accomplished by crew observation of basic flight data such as velocity, attitude, and range rate; or of overall system outputs such as attitude errors and maneuver solutions; or of all these.

3. Given accurate sensor display information, successful manual backup procedures could be developed for completion of the primary mission or for an abort to an alternate mission for all mission phases.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
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"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

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